GROUND COVER PLANTS FOR WEED CONTROL IN AMENITY HORTICULTURE

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Abstract

Aspects of the establishment and use of ground cover plants for urban weed control were investigated. Established ground cover populations of different taxa were monitored over 1 year at 14 sites for their ability to block light from the soil and prevent weeds from establishing. Field trials compared 12 ground cover species of widely differing growth form for rate of establishment and ability to block light and suppress weeds. Another field trial compared various types of mulch with selective herbicides and hand weeding as techniques for establishing ground cover species. No single growth form was superior to others, and it was the density of the foliage that was key to suppressing weeds. Ground cover plants should be selected for having persistently dense canopies throughout the year, such as *Coprosma acerosa* 'Taiko' and *Juniperus procumbens*. Deciduous species like *Persicaria capitata*, evergreen species which become sparser in winter like *Pimelea prostrata*, and plant canopies which open up during flowering like *Grevillea lanigera,* all allow weeds to germinate while the ground is exposed. Ground cover plants appear to deter weeds mainly by keeping weed seeds dormant through preventing red light from reaching weed seeds and triggering a phytochrome response leading to germination. Keeping the ratio of red to far-red light below 0.3 appeared to give best inhibition of weed seed germination. Presence of mulch and spot application of selective herbicides can help prevent weeds causing problems should gaps appear within ground covers, and these may be preferable to hand weeding. Little herbicide tolerance information exists for ornamental ground cover plants, so herbicide tolerance trials were conducted on eight ground cover plant species. This work showed that herbicides can aid in ground cover plant establishment and subsequent maintenance to selectively spot-treat weeds that appear. Ground cover species were assessed which grow low enough to be mowed but which seldom need mowing, to replace grass turf in situations where mowing is inconvenient such as under trees, on slopes, or roadsides. *Dichondra micrantha* and *Soleirolia soleirolii* showed the most potential, forming dense low growing swards that tolerated a wide range of herbicides.

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Table of contents

Abstract i

Acknowledgements iii

Dedications v

Table of contents vii

List of Figures xii

List of Tables xiv

Chapter 1 Introduction 1

Chapter 2 Literature Review 5

2.0 Introduction 5

2.1 Use of ground cover plants and popularity of turf grass 5

2.2 Limitations of turf grass as ground cover 6

2.3 Benefits of ground cover plants in landscape and amenity horticulture 7

2.4 Competition by ground cover plants over weeds 11

2.5 Plant cover effects on seed germination 12

2.6 Importance of light for seed germination 13

2.7 Phytochrome action in seed germination 13

2.8 Emergence of ground cover plants for weed control in agriculture 17

2.9 Ground cover plant research in the urban environment 19

2.10 Production of ground cover plants 20

2.11 Establishment of ground cover plants 20

2.12 Mulches 22

2.12.1 Organic mulches 23

2.12.2 Inorganic mulches 26

2.13 Applications of ground cover plant in plant production 29

2.13.1 Considerations for ground cover plants in revegetation 29

2.13.2 Considerations for ground cover plants in agroforestry 30

2.13.3 Current use of ground cover plants in orchards and crop farms 30

2.13.4 Effects of ground cover plants on bare soil 32

2.14 Summary 33

Chapter 3 Assessing ground cover plants of various forms and growth habits 35

3.1 Review 35

3.2 Trial objectives 35

3.3 Materials: Species introduction 36
3.4 Methods 44
3.4.1 Methods: Establishment of 12 ground cover plant species 44
3.4.2 Methods: Rate of establishment -- Measuring diameter and height 45
3.4.3 Methods: Visual estimate of plot coverage of ground cover plants 46
3.4.4 Methods: Light quality under the ground cover foliage 46
3.4.5 Methods: Weed germination in plots with established ground cover plants 47
3.4.6 Methods: Data Analysis 48
3.5 Results 48
3.5.1 Results: Diameter of the plants 48
3.5.2 Results: Visual estimate of plot coverage of ground cover plants 50
3.5.3 Results: Height of the plants 52
3.5.4 Results: Visual estimate of canopy foliage density of ground cover plants 54
3.5.5 Results: Light quality under ground cover foliage 56
3.5.6 Results: Mean dry mass of weeds growing within each plot and under ground cover foliage 58
3.6 Discussion 60
Chapter 4 Comparing canopy covers of established ground cover species 65
4.1 Introduction 65
4.2 Objectives 65
4.3 Sites monitored and species introduction 65
4.4 Methods 70
4.5 Results 71
4.5.1 Result data by species over one year 71
4.5.1a Data from *Agapanthus x hybrid* population 71
4.5.1b Data from *Ajuga reptans* population 73
4.5.1c Data from *Coprosma* population 75
4.5.1d Data from *Cotyledon orbiculata* var *oblonga* population 77
4.5.1e Data from *Gazania rigens* hybrids population 79
4.5.1f Data from *Grevillea lanigera* population 81
4.5.1g Data from *Hebe chathamica* population 83
4.5.1h Data from *Hedera helix* population 85
4.5.1i Data from *Juniperus procumbens* in Palmerston North City 87
4.5.1j Data from *Juniperus chinensis* at Massey University 89

4.5.1k Data from *Muehlenbeckia axillaris* population 91
4.5.1l Data from *Pimelea prostrata* population 93
4.5.1m Data from *Plectranthus ciliatus* population 95
4.5.1n Data from *Viola sp.* population 97
4.5.2 Light quality data across all populations by quarterly interval 99
4.6 Discussion 101
4.7 Conclusion 107
Chapter 5 Herbicide trials for three ground cover species of different growth forms 109
5.1 Introduction 109
5.1.1 Objective 109
5.2 Herbicide trials 110
5.2.1 *Persicaria capitata* herbicide trials 111
5.2.1a *Persicaria capitata* herbicide trial: Materials and methods 111
5.2.1b *Persicaria capitata* herbicide trial: Results 112
5.2.1c *Persicaria capitata* herbicide trials: Discussion 115
5.2.2 *Sedum mexicanum* herbicide trials 115
5.2.2a *Sedum mexicanum* herbicide trials: Materials and methods 115
5.2.2b *Sedum mexicanum* herbicide trial: Results 117
5.2.2c *Sedum mexicanum* herbicide trials: Discussion 119
5.2.3 *Coprosma acerosa* 'Taiko' herbicide trials 120
5.2.3a *Coprosma acerosa* 'Taiko' herbicide trial 1: Materials and methods 120
5.2.3b *Coprosma acerosa* 'Taiko' herbicide trial: Results 120
5.2.3c *Coprosma acerosa* 'Taiko' herbicide trial: Discussion 123
5.3 Conclusion 123
Chapter 6 Comparison of establishment methods for ground cover plants of three different growth forms 125
6.1 Introduction 125
6.2 Objective 126
6.3. Mulch and cover materials 126
6.4. Methods: Establishment trial 126
6.5 Rates of growth 130
6.5.1 Results: Rates of growth -- *Coprosma acerosa* 'Taiko' 131
6.5.2 Results: Rates of growth -- *Persicaria capitata* 132
6.5.3 Results: Rates of growth -- *Sedum mexicanum* 'Acapulco Gold' 133

6.5.4 Discussion: Rates of growth in various treatments 134
6.6 Soil moisture and temperature 134
6.6.1 Results: Soil moisture and temperature 134
6.6.2 Discussion: Soil moisture and temperature 135
6.7 Assessment of weeds found in plots 136
6.7.1 Results: Mean weed numbers found in plots 136
6.7.2 Results: Standardised weed mass found in plots 137
6.7.3 Discussion: Assessment of weeds found in plots 139
6.8 Overall Discussion 141
6.9 Conclusion 143
Chapter 7 Herbicide trials for five ground cover species suitable for companion planting with turf grass 145
7.1 Introduction 145
7.1.1 Objective 145
7.1.2 Species introduction: *Dichondra micrantha* 145
7.1.3 Species introduction: *Hydrocotyle microphylla* 146
7.1.4 Species introduction: *Sagina procumbens* 146
7.1.5 Species introduction: *Soleirolia soleirolii* 147
7.1.6 Species introduction: *Veronica serpyllifolia* 147
7.2 *Dichondra micrantha* herbicide trials 147
7.2.1 General comments on herbicides used and application method 147
7.2.2 *Dichondra micrantha* trials: Methods 148
7.2.3 *Dichondra micrantha* trials: Results 150
7.2.4 *Dichondra micrantha* trials: Discussion 153
7.3 Hydrocotyle trials 155
7.3.1 Hydrocotyle microphylla trials: Methods 155
7.3.2 Hydrocotyle microphylla trials: Results 156
7.3.3 *Hydrocotyle microphylla* herbicide trials: Discussion 159
7.4 *Sagina procumbens* herbicide trial 159
7.4.1 *Sagina procumbens* herbicide trial: Methods 159
7.4.2 *Sagina procumbens* herbicide trial: Results 160
7.4.3 *Sagina procumbens* herbicide trial: Discussion 162
7.5 *Soleirolia soleirolii* herbicide trials 162
7.5.1 *Soleirolia soleirolii* herbicide trials: Methods 162

7.5.2 *Soleirolia soleirolii* herbicide trials: Results 163
7.5.3 Field observations of *Soleirolia soleirolii* 167
7.5.4 *Soleirolia soleirolii* trials: Discussion 167
7.6 *Veronica serpyllifolia* herbicide trials 168
7.6.1 *Veronica serpyllifolia* herbicide trials: Methods 168
7.6.2 *Veronica serpyllifolia* herbicide trials: Results 169
7.6.3 *Veronica serpyllifolia* trial: Discussion 172
7.7 Conclusion 172
Chapter 8 Field trials with turf-compatible ground cover species 173
8.1 Introduction 173
8.2 Establishment of initial ground cover plots at Fruit Crops Unit (FCU) 173
8.2.1 Determining rate of growth by point analysis 175
8.2.2 Determining rate of growth by point analysis: Results and discussion 175
8.3 Herbicide trial 1 at FCU 176
8.3.1 Herbicide trial 1 at FCU: Materials and methods 176
8.3.2 Herbicide trial 1 at FCU: Results 177
8.3.3 Herbicide trial 1 at FCU: Discussion 182
8.4 Herbicide trial 2 at FCU 183
8.4.1 Herbicide trial 2 at FCU: Materials and Methods 183
8.4.2 Herbicide trial 2 at FCU: Results 184
8.4.3 Herbicide Trial 2 at FCU: Discussion 186
8.5 Ground cover trial under poplar trees 186
8.5.1 Ground cover trial under poplar trees: Materials and methods 186
8.5.2 Ground cover trial under poplar trees: Results 190
8.5.3 Ground cover trial under poplar trees: Discussion 194
8.6 Conclusion 196
Chapter 9 Conclusion 199
9.1 Project overview 199
9.2 Thesis findings 200
9.3 Promoting use of ground cover plants in landscape decision-making 204
9.4 Threat of species new to cultivation being invasive 205
References 209

List of Figures

Figure 2.1 Schematic showing conditions for the conversion of phytochrome isomers...................... 13
Figure 3.1 The trial site at 2 weeks after planting (left); and 4 months after planting (right)............. 36
Figure 3.2 *Acaena inermis* 'Purpurea', whole plant (left) foliage close-up (right)............................... 37
Figure 3.3 *Ajuga reptans* 'Caitlin's Giant', whole plant (left) foliage close-up (right) 38
Figure 3.4 *Coprosma acerosa* 'Taiko', whole plant (left) foliage close-up (right)................................ 38
Figure 3.5 *Grevillea lanigera* 'Little Drummer Boy', whole plant (left) foliage close-up (right) 39
Figure 3.6 *Juniperus procumbens* 'Nana', whole plant (left) foliage close-up (right).......................... 39
Figure 3.7 *Lithodora diffusa* 'Grace Ward', whole plant (left) foliage close-up (right)......................... 40
Figure 3.8 *Muehlenbeckia axillaris*, whole plant (left) foliage close-up (right) 41
Figure 3.9 *Ophiopogon planiscapus*, whole plant (left) foliage close-up (right).................................. 41
Figure 3.10 *Persicaria capitata,* whole plant (left) foliage close-up (right) 42
Figure 3.11 *Pimelea prostrata* 'Anatoki'*,* whole plant (left) foliage close-up (right)........................... 42
Figure 3.12 *Sedum mexicanum* 'Acapulco Gold', whole plant (left) foliage close-up (right)............... 43
Figure 3.13 *Veronca peduncularis* 'Oxford Blue'*,* whole plant (left) foliage close-up (right) 43
Figure 3.14: Planting layout of the 12 species in a randomised complete block design. Triangles at the top indicating planting position for the column 45
Figure 3.15 (left) Top view of *Sedum mexicanum* in vegetative state 63
Figure 3.16 (middle) Top view of *Sedum mexicanum* in flowering state.. 63
Figure 3.17 (right) Sample flowering stem on left side, placed next to sample vegetative stem on right side. Note the tighter whorled foliage on the vegetative stem on right side 63
Figures 4.1, 4.2, 4.3 (L-R) Agapanthus x hybrid; Cotyledon orbiculata var oblonga; Coprosma kirkii.. 67
Figures 4.4, 4.5, 4.6 (L-R) Gazania rigens hybrids; Hebe chathamica; Hedera helix............................ 68
Figures 4.7, 4.8, 4.9 (L-R) Juniperus chinensis; Plectranthus ciliatus; Viola sororia 70
Figure 4.10 Mean R:FR of *Agapanthus x hybrid* population over one year; with lines showing standard errors; and squares not on line representing conditions where weeds were found. 73
Figure 4.11 Mean R:FR of *Ajuga reptans* population over one year; with lines showing standard errors; and squares not on line representing conditions where weeds were found. 74
Figure 4.12 Mean monthly red to far-red light ratio under *Coprosma kirkii* canopy, over full year of 2010. 76
Figure 4.13 Mean red to far-red light ratio under canopy; with lines showing standard errors, over full year of 2010. 78
Figure 4.14 Mean R:FR of *Gazania rigens* population over one year; with lines showing standard errors; and square symbols not on line representing conditions where weeds* were found. 80
Figure 4.15 Mean R:FR of *Grevillea lanigera* population over one year; with lines showing standard errors; and square symbols not on line representing conditions where weeds were found. 82
Figure 4.16 Mean R:FR of *Hebe chathamica* population over one year; with bars showing standard errors; and square symbols not on line representing conditions where weed* was found. 84

Figure 4.17 Mean R:FR of *Hedera helix* population over one year; with bars showing standard errors; and square symbols not on line representing conditions where weeds* were found. 86
Figure 4.18 Mean R:FR of *Juniperus procumbens* population over one year; with bars showing standard errors. 88
Figure 4.19 Mean R:FR of *Juniperus chinensis* population at Massey University over one year; with bars showing standard errors; and square square symbols not on line representing conditions where weeds were found. 90
Figure 4.20 Mean R:FR of *Muehlenbeckia axillaris* population over one year; with bars showing standard errors. 92
Figure 4.21 Mean R:FR of *Pimelea prostrata* population over one year; with bars showing standard errors; and square symbols not on line representing conditions where weeds were found. 94
Figure 4.22 Mean R:FR of *Plectranthus ciliatus* population over one year; with bars showing standard errors; and square symbol not on line representing conditions where weed* was found. 96
Figure 4.23 Mean R:FR of *Viola sororia* population over one year; with bars showing standard errors; and square symbols not on line representing conditions where weeds were found. 98
Figure 5.1 Hand held pump sprayer similar to the one used for herbicide application in trials 111
Figure 5.2 Sample of scores in herbicide trial (from left): *P. capitata* plants with scores 1, 3, 6, 9 112
Figure 5.3 Sample of scores in herbicide trial (from left): *S. mexicanum* plants with scores 1, 3, 6, 9 116
Figure 5.4 Sample of scores in herbicide trial (from left): *C. acerosa* plants with scores 1, 3, 6, 9 120
Figure 6.1 The establishment trial four months after setup 127
Figure 6.2 Plot layout of combinations of ground cover species and eight establishment treatments 128
Figure 7.1 (from left to right) *Dichondra micrantha* damage rating 1, 3, 6, 9 148
Figure 7.2 (from left to right) *Hydrocotyle microphylla* damage rating 1, 3, 6, 9 155
Figure7.3 (from left to right) *Sagina procumbens* damage rating 1, 3, 6, 9 160
Figure 7.4 (from left to right) *Soleirolia soleirolii* damage rating 1, 3, 6, 9 163
Figure 7.5 (from left to right) *Veronica serpyllifolia* damage rating 1, 5, 9 168
Figure 8.1 Layout plan of planting plots at Massey University Fruit Crops Unit 174
Figure 8.2 Planting layout of ground cover plants under poplar trees. 187
Figure 8.3 *Dichondra micrantha* under poplar tree, nine months after transplanting. 188

List of Tables

Table3.1 Assessment of data set skewness to determine best transformation, if necessary, on plot coverage by ground cover plants prior to ANOVA. 46
Table 3.2 Mean diameter (cm) of ground cover plants at 2 weeks, 3 months, 5 months, 7months and 9 months after planting (MAP). Column means sharing the same letter are not significantly different at p>0.05. 49
Table 3.3 Mean diameter (cm) of ground cover plants at 11 months; 13 months; 18 months; and 24 months after planting (MAP). Column means sharing the same letter are not significantly different at p>0.05. 49
Table 3.4 Plot coverage (%) by all ground cover plants within the plot at 3 months; 5 months; 7 months; 9 months; and 11 months after planting (MAP). Column means sharing the same letter are not significantly different at p>0.05 51
Table 3.5 Plot coverage (%) by all ground cover plants within the plot at 13 months; 18 months; and 24 months after planting (MAP). Column means sharing the same letter are not significantly different at p>0.05. 51
Table 3.6 Mean height (cm) of ground cover plants at 3 months; 5 months; 7 months; and 9 months after planting (MAP). Column means sharing the same letter are not significantly different at p>0.05. 52
Table 3.7 Mean height (cm) of ground cover plants at 11 months; 13 months; 18 months; and 24 months after planting (MAP). Column means sharing the same letter are not significantly different at p>0.05. 53
Table 3.8 Mean estimated foliage density (%) of individual ground cover plants at 3 months; 5 months; 7 months; and 9 months after planting (MAP). Column means sharing the same letter are not significantly different at p>0.05. 54
Table 3.9 Mean estimated foliage density (%)of individual ground cover plants at 11 months; 13 months; 18 months; and 24 months after planting (MAP). Column means sharing the same letter are not significantly different at p>0.05 55
Table 3.10 Mean reduction (%) of red, far-red and total light through foliage canopy in June 2010, and the mean ratio of red to far-red light (R:FR) . Column means sharing the same letter are not significantly different at p>0.05. 56
Table 3.11 Mean reduction (%) of red, far-red and total light through foliage canopy in Nov 2010, and the mean ratio of red to far-red light (R:FR). Column means sharing the same letter are not significantly different at p>0.05. 57
Table 3.12 Mean dry mass of weeds growing from 18 May – 2 Nov 2010 both within and out of ground cover canopy and mean R: FR in June and November, by species. Column means sharing the same letter are not significantly different at p>0.05. 59
Table 3.13 Weeds found growing within the ground cover plant canopy in November 2010, with the most common listed first. 60
Table 3.14 Comparison between mean weed mass and recorded R:FR. 61
Table 4.1 Estimated ground coverage; plant height; mean visible light (400-700 nm) transmission; mean red light (660 nm) transmission; and mean far-red light (730 nm) transmission; in *Agapanthus x hybrid* over one year. 72

Table 4.2 Weeds found within *Agapanthus x hybrid*, in ascending order of R:FR value for the month listed. 72
Table 4.3 Estimated ground coverage; plant height; mean visible light (400-700 nm) transmission; mean red light (660 nm) transmission; and mean far-red light (730 nm) transmission; in *Ajuga reptans* over one year. 74
Table 4.4 Weeds found within *Ajuga reptans*, in ascending order of R:FR value for the month listed. 75
Table 4.5 Estimated ground coverage; plant height; mean visible light (400-700 nm) transmission; mean red light (660 nm) transmission; and mean far-red light (730 nm) transmission; in *Coprosma kirkii* over one year. 75
Table 4.6 Estimated ground coverage; plant height; mean visible light (400-700 nm) transmission; mean red light (660 nm) transmission; and mean far-red light (730 nm) transmission; in *Cotyledon orbiculata* var *oblonga* over one year. 77
Table 4.7 Estimated ground coverage; plant height; mean visible light (400-700 nm) transmission; mean red light (660 nm) transmission; and mean far-red light (730 nm) transmission; in *Gazania rigens* hybrids over one year. 79
Table 4.8 Estimated ground coverage; plant height; mean visible light (400-700 nm) transmission; mean red light (660 nm) transmission; and mean far-red light (730 nm) transmission; in *Grevillea lanigera* 'Little Drummer Boy' over one year. 81
Table 4.9 Weeds found within *Grevillea lanigera,* in ascending order of R:FR value for the month listed. 82
Table 4.10 Estimated ground coverage; plant height; mean visible light (400-700 nm) transmission; mean red light (660 nm) transmission; and mean far-red light (730 nm) transmission; in *Hebe chathamica* over one year. 83
Table 4.11 Estimated ground coverage; plant height; mean visible light (400-700 nm) transmission; mean red light (660 nm) transmission; and mean far-red light (730 nm) transmission; in *Hedera helix* over one year. 85
Table 4.12 Estimated ground coverage; plant height; mean visible light (400-700 nm) transmission; mean red light (660 nm) transmission; and mean far-red light (730 nm) transmission; in *Juniperus procumbens* over one year. 87
Table 4.13 Estimated ground coverage; plant height; mean visible light (400-700 nm) transmission; mean red light (660 nm) transmission; and mean far-red light (730 nm) transmission; in *Juniperus chinensis* over one year. 89
Table 4.14 Weeds found within *Juniperus chinensis*, in ascending order of R:FR value for the month listed. 90
Table 4.15 Estimated ground coverage; plant height; mean visible light (400-700 nm) transmission; mean red light (660 nm) transmission; and mean far-red light (730 nm) transmission; in *Muehlenbeckia axillaris* over one year. 91
Table 4.16 Estimated ground coverage; plant height; mean visible light (400-700 nm) transmission; mean red light (660 nm) transmission; and mean far-red light (730 nm) transmission; in *Pimelea prostrata* over one year. 93
Table 4.17 List of weeds found within *Pimelea prostrata*, in ascending order of R:FR value for the month listed. 94

Table 4.18 Estimated ground coverage; plant height; mean visible light (400-700 nm) transmission; mean red light (660 nm) transmission; and mean far-red light (730 nm) transmission; in *Plectranthus ciliatus* over one year. 95
Table 4.19 Estimated ground coverage; plant height; mean visible light (400-700 nm) transmission; mean red light (660 nm) transmission; and mean far-red light (730 nm) transmission; in *Viola sororia* over one year. 97
Table 4.20 Weeds found within *Viola sororia*, in ascending order of R:FR value for the month listed. 98
Table 4.21 Mean visible Light transmission (% quality) in January, April, July and October 2010 99
Table 4.22 Mean red light (660 nm) transmission (% quality) in January, April, July and October 2010 100
Table 4.23 Mean far red light (730 nm) transmission (% quality) in January, April, July and October 2010 100
Table 4.24 Mean red to far red light ratios (R:FR) under the ground cover canopy in January, April, July and October 2010 101
Table 5.1 Product list and description of herbicides used in trials for Chapter 5 110
Table 5.2 Mean scores (1 = healthy, 10 = dead) of herbicide treatments on *Persicaria capitata* trial 1 at 1-18 weeks after treatment (WAT) 113
Table 5.3 Mean scores (1 = healthy, 10 = dead) of herbicide treatments on *Persicaria capitata* trial 2 at 3-21 weeks after treatment (WAT) 114
Table 5.4 Mean scores (1 = healthy, 10 = dead) of treatments on *S. mexicanum* Trial 1 at 1-18 weeks after treatment (WAT) 117
Table 5.5 Mean scores (1 = healthy, 10 = dead) of herbicide treatments on *Sedum mexicanum* trial 2 at 3-20 weeks after treatment (WAT) 118
Table 5.6 Mean scores (1 = healthy, 10 = dead) of herbicide treatments on *Persicaria capitata* trial 1 at 3-15 weeks after treatment (WAT) 121
Table 5.7 Mean scores (1 = healthy, 10 = dead) of herbicide treatments on *Coprosma acerosa* trial 1 at 2-20 weeks after treatment (WAT) 122
Table 6.1 Herbicides applied for herbicide treatment plots 129
Table 6.2 The change in mean plant diameter of *Coprosma acerosa* cv Taiko for different establishment techniques. Column means sharing the same letter are not significantly different at p>0.05. 131
Table 6.3 The change in mean plant height of *Coprosma acerosa* cv Taiko for different establishment techniques. Column means sharing the same letter are not significantly different at p>0.05. 131
Table 6.4 The change in mean estimated ground coverage (%) of *Coprosma acerosa* cv Taiko for different establishment techniques. Column means sharing the same letter are not significantly different at p>0.05. 131
Table 6.5 The change in mean plant diameter of *Persicaria capitata* for different establishment techniques. Column means sharing the same letter are not significantly different at p>0.05. 132
Table 6.6 The change in mean plant height of *Persicaria capitata* for different establishment techniques. Column means sharing the same letter are not significantly different at p>0.05. 132

Table 6.7 The change in mean estimated ground coverage (%) of *Persicaria capitata* for different establishment techniques. Column means sharing the same letter are not significantly different at p>0.05. 133
Table 6.8 The change in mean plant diameter of *Sedum mexicanum* cv Acapulco Gold for different establishment techniques. Column means sharing the same letter are not significantly different at p>0.05. 133
Table 6.9 The change in mean plant height of *Sedum mexicanum* cv Acapulco Gold for different establishment techniques. Column means sharing the same letter are not significantly different at p>0.05. 133
Table 6.10 The change in mean estimated ground coverage (%) of *Sedum mexicanum* cv Acapulco Gold for different establishment techniques. Column means sharing the same letter are not significantly different at p>0.05. 134
Table 6.11 Soil moisture content sampled over two summers and the mean maximum and minimum temperatures in summer and winter of soil under various treatments. Column means sharing the same letter are not significantly different at p>0.05. 135
Table 6.12 Mean weed numbers per plot found within *Coprosma acerosa* cv Taiko plot boundaries that had established since removal following the previous assessment. Column means sharing the same letter are not significantly different at p>0.05. 136
Table 6.13 Mean weed numbers per plot found within *Persicaria capitata* plot boundaries, built up after weed removal from previous observations. Column means sharing the same letter are not significantly different at p>0.05. 136
Table 6.14 Mean weed numbers per plot found within *Sedum mexicanum* cv Acapulco Gold plot boundaries, built up after weed removal from previous observations. Column means sharing the same letter are not significantly different at p>0.05. 137
Table 6.15 Dry weed mass (g m^{-2}) of each treatment plot by species, with differentiation between weeds found within and beyond the ground cover canopy. Column means sharing the same letter are not significantly different at p>0.05. 138
Table 6.16 Weeds found in the establishment trial plots 138
Table 7.1 Product list and description of herbicides used in trials reported within this chapter. 149
Table 7.2 Mean scores of plant damage (1 = healthy, 10 = dead) for the first herbicide screening of *Dichondra micrantha* 1-18 weeks after treatment (WAT). 151
Table 7.3 Mean scores of plant damage (1 = healthy, 10 = dead) for the second herbicide screening of *Dichondra micrantha* 3-20 weeks after treatment (WAT). 152
Table 7.4 Mean scores of plant damage (1 = healthy, 10 = dead) for the first herbicide screening of *Hydrocotyle microphylla* 1-18 weeks after treatment (WAT). 156
Table 7.5 Mean scores of plant damage (1 = healthy, 10 = dead) for the second herbicide screening of *Hydrocotyle microphylla* 3-11 weeks after treatment (WAT). 157
Table 7.6 Mean scores of plant damage (1 = healthy, 10 = dead) for the third herbicide screening of *Hydrocotyle microphylla* 1-7 weeks after treatment (WAT). 158
Table 7.7 Mean scores of plant damage (1 = healthy, 10 = dead) for the herbicide screening of *Sagina procumbens* 1-9 weeks after treatment (WAT). 161
Table 7.8 Mean scores of plant damage (1 = healthy, 10 = dead) for the first herbicide screening of *Soleirolia soleirolii* 3-19 weeks after treatment (WAT). 164
Table 7.9 Mean scores of plant damage (1 = healthy, 10 = dead) for the second herbicide screening of *Soleirolia soleirolii* 1-17 weeks after treatment (WAT). 166

Table 7.10 Mean scores of plant damage (1 = healthy, 10 = dead) for the first herbicide screening of *Veronica serpyllifolia* 1-18 weeks after treatment (WAT). 169
Table 7.11 Mean scores of plant damage (1 = healthy, 10 = dead) for the second herbicide screening of Veronica serpyllifolia 3-21 weeks after treatment (WAT) 170
Table 7.12 Mean scores of plant damage (1 = healthy, 10 = dead) for the third herbicide screening of *Veronica serpyllifolia* 3-19 weeks after treatment (WAT). 171
Table 8.1 Mean plot coverage by ground cover species 1- and 9-months after planting 175
Table 8.2 Herbicide damage scores of *Dichondra micrantha* plants and main weeds present in plots at various days after treatment (DAT), with overall weed mortality after 40 days. 178
Table 8.3 Herbicide damage scores of *Hydrocotyle microphylla* plants and main weeds present in plots at various days after treatment (DAT), with overall weed mortality after 40 days. 179
Table 8.4 Herbicide damage scores of *Sedum mexicanum* plants and main weeds present in plots at various days after treatment (DAT), with overall weed mortality after 40 days. 180
Table 8.5 Herbicide damage scores of *Sagina procumbens* plants and main weeds present in plots at various days after treatment (DAT), with overall weed mortality after 40 days. 181
Table 8.6 Herbicide damage scores of *D. micrantha* plants at various days after treatment (DAT) 184
Table 8.7 Herbicide damage scores of *H. microphylla* plants at various days after treatment (DAT) 184
Table 8.8 Herbicide damage scores of *S. procumbens* plants at various days after treatment (DAT) 185
Table 8.9 Herbicide damage scores of *S. mexicanum* plants at various days after treatment (DAT) 185
Table 8.10 Herbicide damage scores of *V. serpyllifolia* plants at various days after treatment (DAT) 185
Table 8.11 Herbicides for broad-leaved weeds used during establishment of ground cover plants under poplar trees. 189
Table 8.12 Percentage (%) of ground cover plots under poplar trees occupied by ground cover species, the perennial weed *Ranunculus* repens, other weeds and bare soil in March and April 2010. Column means sharing the same letter are not significantly different at p>0.05. 190
Table 8.13 Percentage (%) of ground cover plots under poplar trees occupied by ground cover species, the perennial weed *Ranunculus* repens, other weeds and bare soil in May, June, August, and October 2010. Column means sharing the same letter are not significantly different at p>0.05. 191
Table 8.14 Percentage (%) of ground cover plots under poplar trees occupied by ground cover species, the perennial weed *Ranunculus* repens, other weeds and bare soil in May, June, August, and October 2010. Column means sharing the same letter are not significantly different at p>0.05. 192
Table 8.15 Weeds found under poplar trees in April and May 2010. 193

Chapter 1 Introduction

In an increasingly stressed out world constantly getting smaller as people become better connected, with a concurrent deluge of information received as technology improves, being close to nature offers a refuge of calm to sort out our senses which may be in disarray (Relf 1998). Indeed, 69% of hospital patients and university students found that the presence of plants significantly contributed to a reduction in stress and improving moods (Cooper-Marcus & Barnes 1999). Office workers reported being in a better mood when plants were present (Ulrich 1999), and having a window with a view of nature improved office staff's well-being (Leather et al. 1998).

In urban landscapes, one of the most commonly seen plants is probably regularly-mown grass. Its popularity may be attributed to its ability to withstand repeated human traffic, and many people even enjoy the feeling of grass underfoot. It allows for a convenient surface for games and recreation, and covers the soil necessary for maintaining the health of trees and garden plants which would otherwise be deemed unsightly and uncomfortable to play on (Williamson 1964a).

Yet for all its established popularity, there are some instances where grass lawns may not be the best option. For instance, if turf is planted upon a steep slope, or along soggy banks, operating a mower will be difficult. Also, for large tracts of land in urban areas in-between development pending regulatory procedures, managers may balk at the regular mowing and weeding requirements (van der Spuy 1976).

An alternative solution to these scenarios would be the use of ground cover plants instead of turf grass. Ground cover plants play a major supporting role in any garden environment. These are plants usually defined as being low in stature and having a preference for horizontal growth, so as to obscure the view of the soil or planting media.

Another big advantage of well-established ground cover plants is that they offer a garden with easy maintenance as weeds are prevented from establishing so can lead to reduced herbicide use, and upkeep is restricted to occasional pruning without the need for regular mowing. In addition, they can assist in erosion prevention from strong winds and running water; and many species are available to suit local site conditions. For the garden designer, they add welcome variety and expand the possibilities for aesthetic amenity horticulture (Fish 1970).

For urban landscapes, plants typically serve an important aesthetic function on top of other benefits which are accorded to the environment. Ground cover plants selected for urban planting often include aesthetics as a criterion in its introduction (Pieroni 1994). The function of weed control further enhances this aesthetic contribution to the landscape. Alternatives to weed control in urban environments may involve mulching, which is not equitable to a live plant for the sense of psychological well-being and mental healing conferred by a natural landscape (Bisgrove 2010); hand-weeding by itself, which is a time-consuming operation and cannot be recommended even for agriculture (Hussain et al. 2008; Gianessi 2009); and regular herbicide application, which raises concerns of perceived adverse effects to health and environment, being especially contentious in densely populated urban areas (Page et al. 2010; Meyer et al. 2011). An integrated weed management plan which involves ground cover plants in tandem with the above methods might prove to be a feasible alternative which synergises all the benefits while downplaying the disadvantages (Helfer 2008; Wang et al. 2011).

There has been some recognition in recent years that live ground cover plants could offer a more preferable solution to urban weed problems. For example, ground cover plants have been suggested instead of pavers or other artificial materials, to suppress weeds along roadsides (Eom et al. 2005) and slopes (Amoroso et al. 2011). Past studies about the introduction of ground cover plants in landscape design have focused largely on their aesthetic appeal and ability to overcome urban environmental constraints, such as cold winters (Bell 2009); drought-tolerance (Jiang et al. 2009) which can minimise irrigation and watering needs (Pittenger et al. 2001); or salinity tolerance for planting in coastal cities (Eom et al. 2007) or desert areas (Gerhart et al. 2006).

Ground cover use has been better studied in the agricultural context. However, the commercial nature of agriculture leads to selection criteria with potential enhancements to profit, such as using additional ground cover plants as a secondary cash crop, or using leguminous ground cover to reduce fertiliser costs (Snapp et al. 2005). The widespread use of grass or leguminous cover in fruit orchards is a carefully considered option to prevent weedy competition which may reduce crop yield, in addition to maintaining tidiness and reduce harbouring of pests and disease organisms (Korte & Porembski 2010; Atucha et al. 2011a). The ability of ground covers to stop establishment of more competitive weed species has led to their use in agriculture for weed control (Tixier et al. 2011).

This thesis aims to show that ground cover plants can also reduce the presence of weeds in the urban landscape. If so, is this accomplished mainly by blocking light from reaching dormant weed seeds? Which characteristics of the ground cover plants will best block this light? If ground cover plants are to be widely used, what is the best way to assist their establishment, so that they may deter weeds sooner? Can herbicides help ground cover plants to grow better during the establishment phase? What are some of the challenges in the use of ground cover plants? How can further research promote the use of ground cover plants and improve their effectiveness as a weed control measure?

A selection of ground cover plant species with different growth forms and habits will be assessed for their weed suppression ability. Several establishment techniques will be compared to determine which produces the best growth response to achieve a dense foliage canopy rapidly over a large area. The light characteristics under the canopy will be studied to see what conditions prevent weed seed germination from occurring. Herbicide use on the ground cover plants will be studied to determine optimal treatments for judicious weed control within the ground cover plant canopy, and also as a control measure to prevent the ground cover plants becoming invasive nearby.

To promote the use of ground cover plants in problem areas which prove challenging to turf grass, plant species which are prostrate and low growing enough to be used as companion plantings will be evaluated. These problem areas could be slopes which are difficult for mowing machines to manoeuvre around, or under mature trees with heavy shade where low branches make mowing difficult. A few plant species currently considered as weed species will be evaluated for their growth and establishment in this context, perhaps allowing them to become useful ground covers to replace mown turf within amenity horticulture. Herbicide trials will also be conducted for these species to facilitate their establishment next to turf or under trees. The attempt to introduce uncultivated or weedy species as turf compatible plantings is not a novel concept and promising species from the wild have been evaluated before (Dou et al. 2006).

It is hoped that the contributions of such studies will raise the profile of ground cover plants in the horticultural industry. Currently, ground cover plants are treated much the same as bedding plants during establishment. With better knowledge of how best to quickly establish ground cover plants, it may become feasible to grow larger areas of ground covers within the financial constraints currently limiting their use. Ground cover plants may also become options for covering waste-land as an interim landscape between developments, replacing unsightly long grass with high pollen production that normally covers such areas.

Herbicide application in ground cover plants is envisioned as an aid during the establishment phase to keep opportunistic weeds at bay before the ground is fully covered. Such information will be useful for grounds managers establishing ground covers who wish to reduce reliance on labour for weeding in the early stages. This is currently lacking and not available for many ground cover plants. This thesis will attempt to determine herbicide compatibility for some of these ground cover species; especially those which may be grown as companion plantings alongside turf grass, to further extend the usability of ground cover plants.

Chapter 2 Literature Review

2.0 Introduction

In modern society, bare soil is a rare sight and is unlikely to be the intended end result. In nature, the ground is quickly covered with vegetation as the basis to support local fauna. In rural settings, a planted surface cover is usually established for cattle grazing, or to prevent soil erosion and buffer against extremes in the environment in non-cropped areas. A plant cover in the urban environment plays an important role in safeguarding and maintaining the quality of human life by contributing to stress management, social cohesiveness via recreational opportunities, returns on economic investments, and even direct physical health through air pollution control, glare reduction (using both plant material and tilled bare soil), noise abatement, heat dissipation, and dust prevention (Beard & Green 1994).

In many cases, the predominant vegetation used will be turf grass and shrubs in mulched beds, with ground cover plants used occasionally. For an urban setting or residential property with space for a garden, this alternative to bare soil has become the norm. A well implemented lawn or ground cover plant bedding serves as a connection between the indoors and the outdoors, or a link between private and public spaces.

2.1 Use of ground cover plants and popularity of turf grass

A turf grass lawn is perhaps the most common plant feature found in any urban landscape to fill up space otherwise taken up by bare soil which most people find unappealing visually and to walk upon. Turf may have become pervasive since early history when it was out of utilitarian necessity to graze livestock close to one's dwelling; evolving over time to become a status symbol and venue for recreation (Robbins 2007). A recent study also showed that humans have an innate preference for a savannah-type habitat, characterised by a largely grassy landscape and few trees (Falk & Balling 2010). Indeed, various authors have described turf lawns and ground cover plants present in ancient gardens, such as in China 157-87 BC (Malone 1934), and Persia around 550 BC (Turgeon 2008).

For a grass species to be used as a turf species it must form a green carpet on the ground that is tolerant of wear from traffic and mowing (Burton 1992). Turf grass popularity may be attributable to the relatively quick establishment of turf, resistance to wear, and multiple species to choose from which affords varying degrees of desirable traits to suit local climes, selective resistances to pests, weeds, or herbicides as required by the grounds manager (Williamson 1964b).

2.2 Limitations of turf grass as ground cover

Despite its popularity and ubiquitous presence, there are detractors to the use of ever-more turf grass as ground cover plants. The current (2011) Director of Tower Hill Botanic Garden in Boylston, Massachusetts, is quoted to have said "Life is too short to be spending purposeless moments mowing your lawn" (Trexler 1993), in tacit acknowledgement of the chore that lawn mowing can be. Survey results in America also show that people who maintain lawns feel pressured to use chemicals to keep up with their peers' lawns, but are also concerned about possible negative effects on the environment and water supply (Robbins 2007).

Some site conditions also prove challenging for turf grass establishment and maintenance. For instance, about 20% of turf grass is grown under partial shade, which may be a 50% or more reduction in light levels (Vengris & Torello 1982). Shading reduces the ability of turf grass to photosynthesise, and if this shade is contributed by trees, may introduce competition by tree roots to water and nutrients, hence reducing turf grass vigour (Dudeck & Peacock 1992; Gardner & Taylor 2002). In addition, mowing around tree bases will prove to be a challenge, and attachments for the mower (Gates 1991) or around the tree trunk (Beckham 1994; Flasch Jr 1996) may be necessary to safeguard the tree trunk when mowing the lawn around trees. Furthermore, there will need to be extra consideration before applying herbicides for weed control within turf under trees, as feeder roots of trees may absorb even non-leaching herbicides close to the soil surface (Perry 1989).

When poor turf establishment due to shading is combined with soil compaction and poor drainage, it will also lead to unsightly patches of moss and algae; which may be slimy if wet, or peel off in layers if dry (Baldwin & Whitton 1992). On its own, soil compaction from heavy traffic tends to reduce soil porosity which chokes grass roots leading to thinning out of turf, and invasion by opportunistic weeds (Canaway 1975).

Steep slopes pose another problem for turf maintenance. Fertilisers and lime face the risk of runoff and need to be applied little but often, and staking the slopes or other engineering feats may be required to enhance stability and reduce runoff (Sotir & Gray 1989). Mowers risk skidding off slopes and even a slight incline may prove hazardous in moist or dew conditions, necessitating the use of devices to stabilise mowers for safety-conscious operators (Williams 1988), and likely resulting in reduced maintenance frequency if the grounds manager can get away with it. In New Zealand, north-facing slopes may face increased temperatures and drought-like conditions detrimental to turf development (Carroll 1943).

By its very nature, turf grass naturally forms a thatch layer which is an intermingled layer of living and dead grass tissues, mainly stems which are more lignified and do not decompose as rapidly as leaves. A thin layer (1cm or less (Vengris & Torello 1982)) of thatch is tolerated for its physical cushioning properties, and buffering against excessive drying out and reducing temperature fluctuations. However, its adverse effects tend to outweigh these benefits.

In cases with extremely thick thatch, grass roots may be hindered from growing into the soil layer below; and may accentuate diseases due to the stresses introduced. Thick thatch may also elevate grass foliage, and coupled with mowers which sink into thatch may lead to turf scalping (Gray & White 1999).

A unique aspect of turf maintenance is its requirement for regular mowing to maintain the aesthetics and function of the turfed areas. A survey in 2006 (Haydu et al. 2008) estimated that contractor fees by the entire sports turf industry in New Zealand, including councils, school properties and dedicated sports groups, for various maintenance jobs amounted to $63.4 million or 17.8% of total annual operating expense. Of this figure, 12% is solely for the purpose of mowing. Bearing in mind that this figure is likely an under-estimate as in-house mowing costs are not reflected, the promotion of ground cover plants which do not require mowing could save an operator of an amenity horticulture facility substantially in its annual contractor fees, less maintenance costs for ground cover plants. In an environment where investors and managers are increasingly focused on returns, alternatives not requiring mowing which perform the same function bear consideration.

2.3 Benefits of ground cover plants in landscape and amenity horticulture

Ground cover plants can be suitable replacements which overcome some of the challenges faced by turf grass. Ground cover plants may be described as those which tend to grow horizontally rather than upright, and have a dense profusion of leaves (van der Spuy 1976). The use of ground cover plants to suppress weeds is not a new concept and was reportedly used in Sumatra as early as the 17th century (Buckles et al. 1998). In cropping systems for maize and beans, cover crops have been reported as being as effective on weeds as herbicides (Hartwig & Ammon 2002). Ground covers may have a trailing or bushy form, and some may be partially deciduous while others are evergreen. Compared to the approximately 30-40 grass species commonly cultivated for turf grass use (Wiecko 2006), alternative ground cover plants offer a multitude of species across multiple plant families outside of the Poaceae.

This botanical diversity means that there are ground cover plants which are suited to overcome many site constraints on grass growth (Anon. 1968). For instance, van der Spuy's (1976) book lists dozens of species within each of the following categories: quick to establish; frost-hardy; suited for tropical and sub-tropical climates; drought-resistant; for alkaline soils; coastal conditions; and shade-tolerant. Other authors such as Thomas (1977) and Fish (1970) have listed further selections of ground cover plants to suit various needs. In general, ground cover plants may serve as both a surfacing alternative, and as a conservation measure against erosion risk (Drain 1968). Their wide variety of forms and colours make designing with them limited only by the imagination as illustrated in the books fore-mentioned in this paragraph.

Some plant traits suggested as desirable for the ideal ground cover plant may include: perennial growth or the ability to persist by self-seeding; good weed suppressing ability; extensive rooting or spreading stems; height of about 20cm; occupying a different ecological niche than trees and shrubbery to avoid competition; does not require mowing; able to regenerate if mown; ease of establishment; ease of eradication, if necessary; drought tolerant; non-climbing; tolerates wear from traffic; and resistant to pests and diseases (Firth & Wilson 1995). The lack of a mowing requirement lifts a substantial financial burden from grounds managers, and may also encourage planting in areas not normally mowable such as indoor patios, narrow pathways and courtyards, or around ornamental structures (MacKenzie 1997).

Ground cover plants tend to be shallow-rooted and this benefits more deeply-rooting trees and shrubs grown in conjunction with them by increasing porosity nearer the soil surface which increases aeration and contributes nutrients from valuable organic content deposited at the surface. The increased competition from shallow-rooted ground cover plants may also encourage deeper-rooted shrubs and trees to develop deep rooting systems sooner (Haynes 1980).

Soil temperature may be slightly reduced by the presence of ground cover plants. Winter temperatures in citrus orchards were found to be about 3-5^{o}C lower than orchards with bare soil (Jordan & Jordan 1985). This is attributed to the evapotranspiration effect of ground cover, and also the prevention of heat re-radiation from bare soil. The result may or may not be advantageous, depending on the use of the site. However, a possible advantage of this effect is that plants achieve cold-hardiness sooner with ground covers present than those growing in bare soil, especially for plants growing in climatic conditions bordering on their respective cooler limits (Calkins & Swanson 1998).

Ground cover plants may confer other benefits to plants grown in harsh winter conditions. Cold winters often lead to alternate thawing and re-freezing of soil moisture. This causes relative movement between soil and plant roots, known as heaving. For tree saplings, such heaving during winter may cause extensive root breakage. Planting ground cover plants around tree saplings during establishment can ameliorate this effect by reducing temperature differences and slows the thawing/freezing cycles (Goulet 1995).

Another advantage to having ground cover plants at the base of trees instead of bare soil is when there is concern about soil erosion. Where the soil layer is thin, ground cover leaf foliage serves to reduce the impact of raindrops, and ameliorates soil particle detachment. Water flow is also impeded as the flow has to meander around ground cover plants. As water slows, the likelihood that it may percolate into the soil rather than across the soil surface increases, helping to stay the erosive effects of rain (Sarrantonio & Gallandt 2003). Research done on a 10% slope suggests that a minimum of 15% plant cover in an area is required for any effect on erosion prevention (Rogers & Schumm 1991).

Due to the difficulty of establishing turf around tree bases, most grounds managers choose to leave those areas bare. To maintain a tidy appearance, herbicides have to be applied regularly around tree bases. This poses a potential hazard to tree health if mismanaged, and concerns also arise of groundwater contamination from chemical runoff. However, if plant cover is present, the fibrous plant root system leads to richer organic matter content. Recent research (Gan et al. 2003) suggests higher microbial activity facilitates faster herbicide break-down which in turn reduces risk to tree health and may reduce the likelihood of potential contamination from runoff. Since turf will not do well around tree bases, planting shade-tolerant ground cover species will be an elegant solution to this conundrum.

As a landscape design element, ground cover plants help unify unrelated elements by serving as a visual transition (MacKenzie 1997). It also adds interest to built structures by breaking monotony using foliage textures with softening effects; and flower or leaf colours which sets the mood and ambience for a planted space. Its low-growing nature also helps to hide exposed foundations of buildings. Foundations are often where snow and rainwater can accumulate and heat is reflected, leading to poor plant growth and looking unpleasant. Suitably spreading ground covers can be more suitable than common shrubs or turf to remedy this potential flaw in the landscape.

The earlier reference to Falk and Balling's (2010) recent work that savannah-type landscapes are preferred by most people, confirms the Habitat Theory first proposed in 1975 (Appleton 1996).

This theory states that the aesthetics of our surroundings are determined largely by the environment which first served our biological needs, which is theorised to be the African savannah where the cradle of human civilisation is believed to have arisen. The savannah look may not be faithfully reproduced, but landscape designers do break it down to its components for application in everyday urban locales. Many textbooks in landscape studies advocate moderate to high degrees of openness with a smooth or uniform surface, punctuated with scattered trees or tree clumps, as an internationally preferred design ideal in the landscape (Porteous 1996; Green 2010). This is actually a tacit allusion to the savannah-type scene most preferred by people; and a look which ground cover plants are well-suited to produce when planted *en masse*.

In an urban setting, modern construction materials such as concrete, steel, and glass rapidly form heat sinks in the environment (Mueller & Day 2005). The use of ground cover plants within the urban environment not only helps to cool down the environment, but will also boost performance of other landscape plants by lowering air, soil, and surface temperatures; raising relative humidity; and reducing air vapour pressure deficits better than concrete and asphalt surfaces (Montague et al. 2000). Additionally, succulent ground cover plants may even act as a firebreak (MacKenzie 1997).

Built-up areas also have less area for water infiltration and rates are lower when water infiltration does occur. In contrast, surface runoff greatly increases and flow speeds are rapid across smooth urban surfaces and straight drainage canals. This necessitates extensive investment in drainage systems, and urban hydrology studies point out that a consequence is decreased lag time between precipitation events and the occurrence of flash floods in the urban area (Sanders 1986). Replacing paved areas with ground cover plants could thus reduce the occurrence and severity of flash floods in urban areas.

Additional vegetation in urban environments can provide beneficial alterations to air quality when there is substantive planting. Evaporative transpiration can lower air temperature by 1-3^{O}C depending on plant density, and vegetation provides additional surface area to adsorb pollutants and particulate matter (Taha et al. 1997). Ground cover plants represent an easy method to increase vegetation cover to reap benefits described above by using suitably less-demanding species in areas which otherwise may not support trees, shrubs, or turf.

New Zealand has recognised the importance of plant cover in urban settings for many decades, and none more so than the famed Garden City of Christchurch. A survey of the public plantings in Christchurch undertaken by Drain (1968) had a chapter focusing exclusively on ground cover plants. It illustrated the myriad roles ground cover plants may fill in a local urban setting. Drain cited the Ferry Road Bridge, and river banks adjacent to Fitzgerald Avenue in Christchurch; as well as the London Transport railway tracks using ground cover plants to beautify and stabilise steep slopes. The presence of ground cover plants on a slope also reduces surface runoff, thereby reducing wastage of applied fertilisers and herbicides (Hartwig & Ammon 2002). Public buildings in Christchurch back in 1968 had already used ground cover plants nearby for reducing dust nuisance and providing relief from glare.

Alongside roads and highways, planting is desirable to clearly delineate road boundaries for safety purposes, and also to reduce surface glare to motorists (Mok et al. 2006). Local city councils depend on plants of varying heights to achieve this purpose, with considerations for aesthetics and ease-of-maintenance. Ground cover plants are prime candidates to meet these criteria. For example, ground cover plants are explicitly stated for use in the Hamilton City Road Reserve Planting Strategy 2007 (Lea & Cartwright 2007).

2.4 Competition by ground cover plants over weeds

The use of ground cover plants as a landscape surface inevitably implies the occasion arises where weed species may grow amongst them, since "it is impossible to sow a crop without the certainty that other plants will appear" (Brenchley 1917). This immediately raises the prospect of competition between plant species, stated thus: "Two plants are in competition with each other when the growth of either one or both of them is reduced or their form modified as compared with their growth or form in isolation (Bleasdale 1960)". However, due to differences in interpretation of the term 'competition' amongst various disciplines, Harper (1961) proposed the adoption of the term 'interference' which broadly blankets various effects between plants such as allelopathy. Following that, Donald (1963) also worded the definition of competition to encompass all living things: "Competition occurs when each of two or more organisms seeks the measure it wants of any particular factor or thing and when the immediate supply of the factor or thing is below the combined demand of the organisms". However, competition is not the only possible interaction between two or more plant species. Symbiosis is also possible, for example, between grass and legume (Ledgard & Steele 1992; Cadisch et al. 1994). Grime (1977) discusses these and various other types of relationships between plants as a strategic approach to best ensure species survival.

Interaction effects during plant competition may produce a "winner-takes-all" outcome, leading to rapid decline of the suppressed species. A study showed that while competition for one resource may result in concurrent yield decline for the aggressor species, when two or more factors are being competed for, yield levels are restored to non-competitive scenarios for the aggressor but have a severe decline of the weaker species (Donald 1958). Hence, the effects of competition for multiple resources exceed the sum effects for individual factors. This means that should established ground cover plants successfully out-compete weed invaders, there is a good chance that weeds will find it consistently difficult to gain a foothold in planted areas.

Even if one or few weeds do germinate under the canopy of ground covers, weed numbers need to gain critical mass and numbers before significant ill-effect manifests on the ground cover plant. Cropping models show that yield declines in a curvilinear fashion as weed density increases (Roberts et al. 1977), with only very slight declines at low weed densities.

Resources for which competition occurs are usually pooled and drawn upon as needed by competing individuals (Donald 1963). This is easily applied to water and soil nutrients, but a different approach is required for light. Light must be used as and when available or lost (Donald 1963), hence plant dimensions such as height, breadth, foliar arrangement and canopy density become paramount in light competition (Huston & Smith 1987).

2.5 Plant cover effects on seed germination

In theory, a well-established ground cover plant should have a good chance to hinder weed seed germination and if not, to outcompete weed seedlings by virtue of the ground cover plant's larger size and longer establishment time.

The presence of a ground cover plant creates a competitive environment from both its underground roots and aerial foliage. Biotic activity from micro-organisms as a result of ground cover plant root presence may intensify germination-inhibiting substances in the soil such as methane (Crill 1991; Danish & Ansari 2007), acetaldehyde, ethanol, and acetone; and may also even lead to less aerobic environments (Drew & Lynch 1980) which are germination unfriendly. Some plant genera are also believed to emit growth inhibitory substances from their roots (McCalla & Haskins 1964), such as acetaldehyde, ethanol, and acetone (Holm 1972).

The foliage canopy from ground cover plants may insulate the soil and reduce diurnal temperature fluctuations (Mueller & Day 2005). This constancy in temperature helps to keep some weed seeds dormant and reduce germination (Thompson & Grime 1983; Pons & Schröder 1986; Ekstam et al. 1999). Additionally, foliage cover also acts as a light filter. Leaf filtration of sunlight removes more red light than far-red light and this may have an inhibiting effect on weed seeds (Taylorson & Borthwick 1969), as a result of phytochrome activity. The efficiency of red light filtration by leaves, but allowance of far-red light to pass through, is attributable to chlorophyll properties (Johnson 1980).

Some seeds may experience dormancy cycles whereby there are periods that germination will not occur even when light is not limiting. Such cycles have been studied for both their physiological and ecological significance (Vleeshouwers et al. 1995). However, most weed seeds have a light requirement for germination. A study by Wesson and Wareing (1969a) showed that only 10% of weed seeds in the soil germinated without light under laboratory conditions and none germinated without light in field conditions. This light sensitivity could be inherently present upon seed formation or induced by soil (Wesson & Wareing 1969b; Scopel et al. 1991).

2.6 Importance of light for seed germination

The first observations that light plays a positive role in seed germination are attributed to Caspary in 1860 (Gardner 1921). Further work on the role of light during germination led Heinricher in 1903 to note conclusively the key supporting role of light on triggering germination (Evenari 1984). Subsequent work discovered that light effects work in tandem with temperature ranges and plant hormones to trigger or inhibit germination responses (Toole 1973).

The wavelength of light which best promotes germination was determined to be red light at around the 6700Å (670nm; 1 ångström = 0.1nm) band (Flint & McAlister 1937); and far-red light at a band around 7600Å inhibits germination (Flint & McAlister 1935). A model postulating that light triggering a reversible photoreaction is the mechanism for controlling germination was eventually proposed (Borthwick et al. 1952). A pigment with two mutually reversible stable forms in a dynamic flux dependent on light wavelength was isolated and observed in 1959 and later named phytochrome (Butler et al. 1959). It should be noted that peak absorption wavelengths published by different authors differ slightly due to the dynamic reversibility of the pigments, and a wavelength band may be more realistic. For instance, Butler *et al.* (1959) observed that peak radiation absorbance by phytochrome occurred at 655nm and 735nm.

2.7 Phytochrome action in seed germination

It is now widely accepted in many textbooks that phytochrome (P) responds to light as represented in Fig 1.

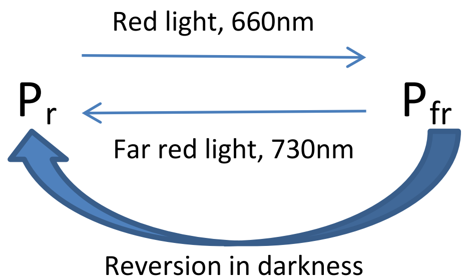

Figure 2.1 Schematic showing conditions for the conversion of phytochrome isomers

The schematic shows that the P_r form of phytochrome absorbs red light strongly and stabilises into P_{fr}. In turn, the P_{fr} form absorbs far-red light strongly and stabilises as the P_r form. Additionally, in the absence of any radiation, the P_{fr} form gradually reverts to the P_r form. The two forms of phytochrome also do not appear to be equally susceptible to conversion when exposed to the appropriate light. In red light, only 81% of P_r is converted to P_{fr}. Conversely, P_{fr} is 98% converted to P_r when exposed to far-red light. This is due to the overlap in wavelength sensitivity for both forms of phytochrome (Toole 1973). Reversion to P_r in darkness was also shown to be encouraged at temperatures higher than optimal for germination (Borthwick et al. 1954).

In seeds requiring light for germination, it is the P_{fr} form which triggers germination (Borthwick & Hendricks 1960; Hodson & Bryant 2012). However, because seeds of different species contain differing amounts of phytochrome, sensitivity to light also varies. Seeds with high amounts of phytochrome will require less red-light to germinate. In some cases, high phytochrome content in seeds, coupled with incomplete P_r conversion under far-red light, leads to possible germination even under poor red-light conditions (Koller et al. 1964; Toole & Borthwick 1968).

Phytochrome is a resource formed only when needed. The conditions under which phytochrome may form was shown by Kendrick *et al.* (1969) using *Amaranthus caudatus,* a species which germinates readily in darkness (>90% germination) so long as far-red light is not present to inhibit germination. Dry *Amaranthus caudatus* seeds did not exhibit any photoreversible absorption activity, suggesting a lack of phytochrome. Evidence of P_{fr} activity was detected only in imbibed seeds, allowing germination even in darkness. Initial levels of phytochrome remain constant for about 5 hours, after which another increase in phytochrome level is observed until 72 hours after imbibition. It is postulated that the initial appearance of phytochrome may be due to a rehydration of inactive phytochrome after imbibition. The subsequent increase is hypothesised to be due to active metabolic processes. To test if seeds actively produce phytochrome *de novo*, seeds were exposed to $0^{o}C$ after imbibition. The cooled seeds did not exhibit the second phase of phytochrome increase. The second surge in phytochrome levels was also found to occur in seeds kept in darkness but exposed to far-red light to inhibit germination; hence it is present in seeds which were not even germinating. Furthermore, this second increase in phytochrome levels occurred 10 hours before rapid water uptake of seeds as part of the germination processes were noted, indicating that it was not due simply to simple rehydration of more inactive phytochrome.

Whilst phytochrome plays an important role in signalling readiness for germination, seeds still need to be fully mature to respond to its effect on germination. Should there be ample red light formation of P_{fr} when the seed is not physiologically ready to germinate, it will have no effect (Fujii

1969). Seed readiness to germinate may involve factors such as presence of water, suitable temperature, and duration of suitable conditions. When seed readiness is not met, decline of total phytochrome or conversion to P_r isomer may occur to keep seeds dormant; the rate of P_{fr} decay is influenced by the proportion of P_{fr}:P_{total} (Kendrick & Frankland 1969).

It is widely demonstrated that the typical phytochrome reaction to having red light triggering germination is negated by a subsequent flash of sufficient far-red light. However, if seeds are exposed to far-red light too long after the red light exposure, there is no inhibition of germination. Hence P_{fr} can be deduced to require a minimum period of time for it to complete the germination triggers before conversion to P_r will no longer prevent germination. This period of time before germination cannot be prevented and varies according to species (Toole 1973), temperature (Yaniv & Mancinelli 1968), possibly pH (Anderson et al. 1969), and an aerobic environment (Fujii 1963).

Seeds which do not have light requirements for germination may also be under the effects of phytochrome. This was shown by red and far-red light effects on the germination of tomato seeds consistent with phytochrome behaviour (Mancinelli et al. 1966). Subsequent experiments with seeds of tomato mutants deficient in the phytochrome gene confirmed the role of phytochrome for germination in seeds which are light-independent (Appenroth et al. 2006). The presence of P_{fr} in dark-germinating seeds led to some speculation that there was a form of phytochrome which had an "inverse reversion" in the dark where P_{fr} was the preferred isomer in the absence of irradiation (Spruit & Mancinelli 1969). This is inconsistent with thermodynamics since the P_{fr} isomer was unstable in the absence of radiative energy. The presence of P_{fr} in dark germinating seeds is now known to be derived from incomplete reversion of P_{fr} to P_r , with the process unable to proceed beyond the first intermediate compound due to dehydration. This intermediate slowly reforms P_{fr} in darkness (Kendrick & Spruit 1974). In effect, seed dehydration acts to "store" P_{fr} during dark periods by preventing reversion. It therefore appears that phytochrome is present in seeds regardless of whether germination for that species is dependent on light.

Some seeds are inhibited from germination by light exposure. Well-known examples of this anomaly are *Phacelia sp., Nemophilia sp.,* and *Nigella sp.* This is an adaptation to dry summers and wet mild winters of their respective native regions (Baskin & Baskin 1971; Cruden 1974). The mechanism was postulated to be purely physical resistance from the hard endosperm, whereby light prevents necessary development by the embryo from exerting sufficient force to break out (Chen 1968). However, Rollin *et al*. (1970) showed that maximum inhibition occurred upon exposure to 717 nm far-red light, which strongly indicates phytochrome involvement, although the study did not offer any proposed mechanism. Similar results for *Nigella* seeds with 720 nm far-red exposure are documented (Pamukov & Schneider 1978).

Underneath a leaf canopy, soil level light is typically filtered through foliage above. As most leaves contain pigments which strongly absorb red light for photosynthetic purposes, it is the norm for leaf-filtered light to be richer in far-red light and deficient in red light. With the low height levels of many ground cover plants, the likelihood of ambient light to be reflected in under the canopy from nearby surfaces is also reduced. Thus the area under ground cover foliage is likely to have low overall light levels which are particularly poor in red light content after filtration by leaves, producing an environment in which light-sensitive seeds would be starved of the light trigger needed for germination.

In addition, research has shown that many plant species, including those which have demonstrated an ability for their seed to germinate in total darkness, can be induced to a state of seed dormancy when placed in otherwise suitable conditions under leaf shade (King 1975; Górski & Górska 1979; Fenner 1980; Silvertown 1980). This shows phytochrome to be sensitive not only to the detection of light, but also to the quality of ambient light, especially the ratio of red to far-red light (R:FR) (Batlla et al. 2000). This sensitivity to poor light quality is also extended to detection of incipient canopy encroachment as shown by Batlla's (2000) work where seeds of some species failed to germinate despite conditions where leaf area index of shading canopy was less than 1 and R: FR of ambient light was above 0.8. In addition, inhibition by plant shade seems to be conditional upon prolonged exposure similar to a photoperiod rather than by short pulses or intermittent exposure (Batlla et al. 2000; Benech-Arnold et al. 2000).

Such a development might prevent a seed from germinating not only when there is insufficient light, but also when the seed is likely to be under shade from other plants, unless the species has developed adaptations for a shady understorey habitat. King (1975) further postulated that it would be of particular advantage for smaller-seeded plant species to possess this germination safeguard, given the smaller food store in smaller seeds, and that most species identified in his study are smaller-seeded. As many weed species are opportunistic in reproductive strategy and may also be wind-dispersed, being smaller-seeded is common. The environment under ground cover foliage shade may thus prove additionally challenging for species which have discriminatory seed preferences for germination. The complexity of phytochrome responses to light is not fully understood, but molecular research has shown at least two different forms of phytochrome coded by different genes and differing in protein sequences (Bewley & Black 1994).

While being principally a light-sensitive protein molecule, phytochrome is the principal determinant with regards to germination response when seeds are confronted by multiple combinations of dynamic environmental factors. An understanding of phytochrome response and its underlying mechanisms may be usefully manipulated to assist in weed control, by avoiding weed seed germination altogether.

2.8 Emergence of ground cover plants for weed control in agriculture

Farmers have long realised that weeds represent significant competition for plant nutrients which draw these valuable resources away from their crops. Prior to the development of synthetic herbicide options, soil tillage was seen as the best option for weed control on a large scale. It could kill sprouting weeds, and was considered to improve soil productivity, hence reducing the use of manure with its attendant weed seeds embedded within (Paine & Harrison 1993).

However, tillage was not without its drawbacks. It required expensive investments in equipment and continual consumption of costly fuel. It also required skilled labour not only to operate the machinery, but also to determine the best timing for tillage. This is because annual weeds have to be controlled before the seeds form, otherwise tillage will only serve to spread the seeds. In addition, the process may also turn up buried weed seeds. If in an orchard, the heavy equipment may injure shallow tree roots which affect tree health and productivity, or even cause soil compaction. Near harvest time, fruit trees heavily laden with fruit may have low lying branches which may break off during the tillage operation (Jordan & Jordan 1985).

The discovery and subsequent mass-production of synthetic herbicides, with the corollary rise in use of synthetic fertilisers in the 1950s and 1960s led to intensified crop production but is also associated with environmental pollution. Concerns about impact on the environment grew in the 1970s and the synchronous rise in fuel prices led to an economic re-evaluation of cropping practises (Hartwig & Ammon 2002).

The impetus to move away from tillage practises and chemical applications arose from both environmental and economic fronts. In light of these concerns, the use of cover crops and living or 'green' mulches, though previously known, gained new favour in the 1970s and 1980s (Paine & Harrison 1993). The primary functions of these cover crops or live mulches were to reduce weed competition; prevent soil erosion; improve soil structure by adding organic matter and supporting soil microbes; and through the use of leguminous species, reduce the reliance on nitrogenous fertilisers (Miller et al. 1989; Upadhyaya & Blackshaw 2007). As research in this area grew, a priority was to screen and identify plant species suitable for use as a ground cover plant. Qualities considered desirable in a ground cover plant included rapid spread and establishment to suppress weeds early; tolerance to traffic and persistence on site; tolerance to drought and poor soils; low maintenance requirements; be self-regenerating; provide enhancement to crop yield and quality; will not compete with the crop species for resources; will not harbour pests and diseases; will not be a fire hazard; and will not impede cropping operations (Jordan & Jordan 1985; Paine & Harrison 1993).

For some time, the focus was on identifying an alternate cover crop which provided additional benefit to yield, such as legumes for their nitrogen-fixing ability or an alternate/concurrently harvestable crop. However, screening of plant species for ground cover which evaluated grass species or non-leguminous dicotyledonous species has been gradually conducted and is still being researched (Lal et al. 1978; Brown & Glenn 1999). This represents a shift in the philosophy of ground cover planting towards the intention of regulated planting with no consideration to direct crop yield enhancement, as being preferable over uncertain weedy outcomes. Weed suppression through the use of cover planting or intercropping has been demonstrated successfully by various cropping studies (Akemo et al. 2000; Ross et al. 2001); as has improved soil mineralisation in orchards and forestry plantations using both grass and leguminous cover (Atucha et al. 2011a; Balota & Auler 2011; Lin et al. 2011).

Despite documented weed control and other benefits of cover cropping over the last few decades, a recent survey showed poor adoption of this technique by US farmers (Singer et al. 2007). The authors of the survey concluded that agricultural extension on cost, crop selection, and management techniques will overcome the inertia in adoption.

In orchards, mown grass is often used between tree rows as this is better than bare soil for a number of reasons including increased soil organic matter from mown clippings, weed suppression, and the prevention of soil erosion and compaction (Ferree & Warrington 2003). However, grass cannot be planted up to the base of trees due to difficulties with mowing within the tree rows, so regular herbicide applications are required to maintain a grass-free region next to the trees. Grass alternatives have been investigated that do not need regular mowing and thus can be grown right to the base of trees (Elmore 1989; Hartley et al. 2000; Harrington et al. 2005).

2.9 Ground cover plant research in the urban environment

While research into ground cover plants as an alternate harvest or crop-soil management aid has been motivated for several decades by potential commercial gain, attention to its use in the urban environment has been comparatively sparse. Ground cover plants are seen primarily as an aesthetic addition to the urban landscape. However, with greater attention now focused on improving quality of life in many parts of the world, this is set to change as plants are recognised for their less tangible contributions to the environment and the human psyche.

Additional ground cover plants for urban landscapes are being developed or recommended not just for aesthetic beauty (Noack 1993; Pieroni 1994) but also evaluated for persistence in built-up areas through tolerance to various environmental constraints such as drought (Sacamano & Feldman 1984; Starr 1988; Roberts 1989; Pittenger et al. 2001; Sun et al. 2009; Yang et al. 2009); salinity (Niu & Rodriguez 2006; Eom et al. 2007; Niu et al. 2007); heat (Zheng et al. 2009); disease resistance (Owings et al. 2010); alkalinity and pollution (Wang & Chen 1990); traffic stress (Cheng et al. 2008); and winter hardiness (Fortgens & Laar 1989).

The potential use of ground covers to suppress weeds has often been listed to promote its usefulness in landscape use (Fish 1970; Foley 1972; Thomas 1977; MacKenzie 1997). Yet studies to evaluate the effectiveness of ground cover plants in weed suppression have been few. This looks set to change as urban densities build up and specific scenarios have proven increasingly challenging to manage. A recent paper has evaluated 15 ground cover species for weed suppression along roadsides, primarily motivated by the need to reduce the inherent safety hazard of grass mowing along roads (Eom et al. 2005). This paper identified four species (*Alchemilla mollis, Nepeta x faassenii, Phlox subulata,* and *Solidago spacelata*) to be strongly weed suppressive, chiefly due to the very low light transmittance to the soil surface under these plants. Another paper tested 25 ground cover species for side slope planting which also evaluated weed biomass after planting; it was aimed at combining improved aesthetics with ease-of-maintenance (Amoroso et al. 2011). Results showed that ground cover planting in bare soil was preferable to mulched planting and the paper recommended *Deutzia scabra* 'Pride of Rochester' and *Philadelphus* x *virginalis* 'Minnesota Snowflake'.

A possible reason that ground cover planting is not more popular for weed suppression may be the impression that effective ground cover takes too long to establish, necessitating hand-weeding and herbicide applications during the initial stage. One possible solution to overcome this drawback is to use mixed species of ground cover planting, combining a fast-spreading ground cover to out-compete weeds, and which could be removed later if it overextended its boundaries, with a slower-growing plant which provides dense and effective foliage cover to suppress weeds (Quigley 2003). Whilst results for weed suppression were encouraging, there is concern that public reaction to mixed planting would be one of untidiness, which is akin to the perception of a weedy plot. The author concludes that site-specific or customised combinations of ground cover plants will need to be developed and produced for this option to succeed.

2.10 Production of ground cover plants

In commercial practice, the production of ground cover plants may adopt a system similar to bedding plants (Kessler 2004). Traditionally, seeds are sown directly into the ground or growing containers such as seedflats (Rathmel & White 1976), and then transplanted into pots or containers when the first pair of true leaves emerges (Rathmel 1976). An alternative technique is to produce plants as plugs, a system popularised in the 1970s (Armitage & Kaczperski 1994).

A major advantage of the plug method of production is the ease of transplanting even with relatively inexperienced staff and the faster speeds with which the transplanting can be completed. The design of the plug trays also makes mechanisation viable, and the opportunity arose to reduce the labour-intensiveness of production horticulture (Cantliffe 2009). Furthermore, because the plugs are transplanted with a small amount of soil still attached to the roots, transplanting shock is reduced, leading to minimised losses for the producer, as compared to the bare-root transplants when seedlings are planted in high density within seed flats (Armitage 1994).

2.11 Establishment of ground cover plants

For best weed control effects by ground cover plants, it is advantageous for them to rapidly establish a dense foliage cover over the desired area. In most amenity horticulture scenarios, a most critical step for the establishment of ground cover plants is to completely clear the planting area of all weeds and vegetation, including roots in the soil (MacKenzie 1997). This can be facilitated by the use of a non-selective translocated herbicide such as glyphosate, which is deactivated by soil contact and harmless to planned transplants or seedlings, followed by residual pre-emergent herbicides to extend the weed-free period, if information on compatible herbicides is available (Elmore 2000); and a combination of mulch and herbicide use during establishment may prove to be the most effective method (Elmore et al. 1997). At the same time, herbicides may need to be applied when the ground cover plants are actively growing, so selectivity of action becomes paramount. Currently there is a relative dearth of information on herbicide compatibility with ground cover plants, which this thesis will be addressing.

Selective herbicides kill weeds without harming the intended planting. Such selectivity may be accomplished through deactivation where the protected plant is able to rapidly metabolise the active ingredient (commonly through dealkylation, deamination, or conjugation of the ingredient molecule with another metabolite such as glutathion) before it accumulates to concentrations high enough to be damaging; whereas the weed lacks this ability (Copping & Hewitt 1998). Selectivity may also be achieved through physical properties. For example, diuron does not harm trees because it does not move deeply enough into the soil profile to reach tree roots.

Herbicides can also be classified based on when they should be applied to weeds. Pre-emergence herbicides refer to those which are applied to the soil before the weeds germinate. To use pre-emergence herbicides effectively, one should have knowledge of which weeds are likely to be a problem at the site and apply suitable pre-emergence herbicides to target that weed (Silvy 2012). Examples include oxyfluorfen and oxadiazon. They should be applied when the soil is moist in spring, but to avoid contact damage with trees and deep-rooting shrubs, it may be necessary to apply in early spring before new foliage appears. Oxyfluorfen and oxadiazon can selectively control weeds around trees and large shrubs due to their low solubility in soil, so very little herbicide moves into the rooting zone of these species.

In contrast, post-emergence herbicides are applied to the weeds after they have germinated. Some of the earliest such herbicides to be developed were 2,4-D and MCPA in the 1940s, and they are still widely used today. These are synthetic hormone herbicides which can selectively remove dicotyledonous weeds from cereal crops (LeBaron et al. 2008). Post-emergence herbicides are further differentiated to those which only damage those parts of the foliage that they contact, and those which translocate throughout the plant within the phloem system after absorption. Contact post-emergence herbicides, such as bentazone and ioxynil, typically do not damage grass species or broad-leaved species with waxy leaves, since the herbicides do not stay on such foliage for long. Translocated herbicides can be absorbed by the plant and be mobilised to kill other parts of the weed such as the root system not in contact with the spray (Monaco et al. 2002). Clopyralid and MCPA are examples of translocated herbicides.

While herbicides are generally safe and cost effective (Prichard et al. 1989; Gianessi & Reigner 2007; Wibawa et al. 2010; Jat et al. 2011) when used within appropriate guidelines, there are detractors who prefer consumption of organically grown products. Organic growers may use natural plant extracts such as clove oil and vinegar (acetic acid) for weed control, but will have to rely on hand weeding or other mechanical means to supplement these methods (Evans & Bellinder 2009). A comparison between herbicides and hand weeding concluded that hand weeding produced superior yield in rice production (Parmeet et al. 2008) and brinjal (aubergine) production (Meena et al. 2006) but unremarkable results in groundnut fields (Chaudhari et al. 2007). Yet another study showed that a combination of hand weeding and herbicide treatment produced greatest seed yield and protein content in soybeans (Geet et al. 2007). Unfortunately, the high time consumption and labour intensiveness of hand weeding operations mean it is not a feasible option on a large scale (Hussain et al. 2008).

Site conditions need to be assessed so that the right choice in species selection can be made (Hirshfield 2006). This planning includes ensuring that other landscape plants do not share the same rooting depth and foliage height to avoid competition. Planting of ground cover plants require consideration of their mature size so there will be the right allowance in spacing for healthy plants and optimal weed control. Once a decision is made, the plants may be positioned in rows with plant centres staggered at the mid-points of neighbouring rows (MacKenzie 1997).

Ground cover establishment may be assisted by adding fertiliser after planting to encourage leafy growth. To ensure ground cover plants can easily gain the benefits of fertiliser, planting should preferably coincide with the rainy season of the local climate. If dry fertilisers are applied, it would be useful to follow with watering to wash off any fertiliser stuck to foliage to avoid burns, and to promote availability of fertiliser nutrients. The addition of fertiliser is however subject to diminishing returns (Spillman 1923; Chavas et al. 2010) and the bioavailability of the nutrients subject to formulation or origin of added fertiliser (Toole 2004). There may also be concerns of ecological disruption due to leaching (McDowell & Koopmans 2006).

After planting and fertilising ground cover plants, mulch can be added over the exposed soil surfaces to discourage germination of weed seedlings (Thomas 1977; Brown & Tworkoski 2004; Jodaugienė et al. 2006). Should opportunistic weeds still occur during the establishment phase of the ground cover plant, post-emergent herbicides may be judiciously applied. If weed numbers are not high, hand weeding may be a feasible option.

2.12 Mulches

A common problem during plant establishment is warding off weed invasion. Since the dense foliage necessary for weed suppression has yet to be developed in young ground cover plants, alternative intervention is needed. Mulching is an option which helps to reduce the frequency of hand-weeding or herbicide application.

Mulch is a layer of material laid uniformly across exposed soil. This material may be plant-based, or gravel, mineral, recycled paper, fabric, or plastic. It can be used in the early stages of ground cover plant establishment to stop weed invasion in the interim before ground cover plant foliage canopy is fully grown. Mulch serves a variety of purposes such as reducing weed growth (Hembry & Davies 1994; Penny & Neal 2003), conserving soil moisture, reducing soil temperature variations (Bussière & Cellier 1994; Ramakrishna et al. 2006), minimising soil erosion (Maass et al. 1988), and improving aesthetics (Skroch et al. 1992). These effects have the potential to improve plant growth, and thereby reduce management costs of fertilisers and herbicides as well (Masiunas et al. 1997). If the mulch material is organic in origin, it may also serve to increase the organic matter content of the soil (Rose & Smith 1996). For amenity purposes, organic mulches are usually deemed more attractive (Skroch et al. 1992).

2.12.1 Organic mulches

Examples of organic mulch materials include: bark shredded or cut into chunks of various sizes; wood chips or shavings; sawdust; compost; grass clippings; leaves; peat from stem material of various waterside plants; pine needles; and straw (Anon. 2006).

Since organic mulches are derived from plants, and are commonly used as garden composts, their decomposition over time may enrich or otherwise alter the properties of soil. For instance, adding organic mulch may improve soil structure. This is achieved by the decomposition of the organic mulch where by-products of microbial organisms such as *Actinomycetes sp.* and *Azotobacter sp.* promote the stability of granules in soils (McCalla 1950). Mulches also help preserve soil structure by acting as a cushion against compaction (Trowsdale & Simcock 2011). The use of compost as mulch if properly done, has the additional benefit of killing weed seeds which may be present in the mix (Duryea et al. 1999a).

Soil pH can also be modified by organic mulches. Wood-based mulches may reduce soil pH (Billeaud & Zajicek 1989) but not in all conditions (Cregg & Schutzki 2009); using sphagnum moss could exacerbate this effect due to the acidophilic nature of associated microbial activity (Pankratov et al. 2008). However, if compost mixes are used as mulch, a slight increase in alkalinity may be observed as the decomposed mixture 'ripens' (Lalande et al. 1998).

Organic mulch supports soil microbial populations as it acts as a nutrient source, conserves moisture and maintains a relatively constant temperature (Almeida et al. 2011). Whilst the increase in soil biodiversity may be encouraged for promoting nutrient cycling, using poor quality mulch may risk the introduction of pathogens and pests (Miyasaka et al. 2001; Jordan & Jones 2002).

Urban soils may be more prone to toxic contaminants as by-products from industrial activities. The application of organic mulches such as from leaf (Salim & Abu El-Halawa 2002) and wood (Kiikkilä et al. 2002) materials may serve to decontaminate soils by forming stable complexes with heavy metal ions. This efficacy of mulch in soil decontamination has been comparable to the use of activated carbon. Such decontamination effects not only benefit plant life directly, but also represent another way that mulch bolsters soil ecology.

Application of mulch is usually done in late spring before the soil gets too dry. However, adding mulch during the rainy spring season may cause soil to be too wet and not provide sufficient root aeration (MSU Extension 1998). A second application in autumn is often necessary before cold winters to reduce heaving of tree saplings during the freezing and thawing cycles which damages plant roots (Goulet 1995). The recommended mulching depth using organic mulches should be maintained at 5.0-7.5 cm for effective weed control (Greenly & Rakow 1995; Jordan & Jones 2002; Penny & Neal 2003).

Commercially sold organic mulches are often formulated from materials unavailable to the public in large quantities. These are often by-products from cropping processes and hence may be limited in availability and also localised to the immediate community after prior arrangements were made.

Cocoa bean shells are an example which have been popular where they are available, as they have an attractive appearance, and many people enjoy the aroma of cocoa as it decomposes and adds nutrients to the soil. Unfortunately, there is concern that pet dogs may develop a taste for this mulch and eat it in quantities that lead to gastro-intestinal upsets or even fatal toxicity (Hansen et al. 2003).

Waste wood from sawmills, fallen or pruned trees, unwanted crates and pallets may be traditionally bound for landfills but a modern focus of recycling gives these sources of wood a new lease of use in the form of mulch. These may range from sawdust, wood chips, shavings, and chunks of wood of varying sizes. Bark mulch is sold separately from wood mulch, and may be more popular due to perception its appearance is more natural.

There has been some controversy that the use of wood-based mulches will lead to induced nitrogen deficiency (Bollen & Lu 1957) as a result of the proliferation of soil microorganisms metabolising cellulose. Recent work by TerArvest *et al.* (2011) showed that soils under wood chip mulch had a high cumulative carbon mineralization and a high C:N ratio, which resulted in some nitrogen immobilisation due to microorganisms using up soil nitrogen for their growth. However, the same paper also found that apple trees in the two wood chip treatments ranked in the top four of the 13 treatments in both fruit yield and tree growth. This favourable outcome of wood chip mulching in apple orchards was repeated by Choi and Rom (2011) who reported higher leaf nitrogen content and greater trunk diameters of apple trees after 2 years under wood mulch. Atucha *et al.* (2011b) also reported a positive nitrogen balance in fruit, leaves, and wood prunings from apple trees mulched with wood chip, despite not being supplemented with nitrogen fertiliser for two years, compared with trees receiving herbicide treatments in bare soil. The literature to date appears to indicate nitrogen immobilisation within five months of using wood mulch, but after two years or more, the nitrogen is made available for plant assimilation.

Another concern raised against the use of wood mulch is the possibility that it may lead to a termite infestation (Schroth et al. 1992); increased population of invertebrates (Jordan & Jones 2007); or even promote fungal growth by harbouring spores and providing a suitable substrate (Brantley et al. 2001), some may find these fungal growths interesting while others find them unsightly. A survey of 2,500 wood chip samples to be processed into mulch led to 114 species of fungi being found (Hoover-Litty & Hanlin 1985).

The claim of termite infestation is disputed by some researchers, who argue that termites are not attracted to wood due to high carbon and lower nutrient content (Long et al. 2001). This backs up findings which confirmed that termites prefer a diet with higher nitrogen and phosphorus content, and will consume wood mulch which satisfy this criterion (Duryea et al. 1999b). To minimise termite infestation in areas of known risk, high carbon wood mulch such as bark material can be used if desired.

Bark mulch may also serve a protectant function against herbicides when applied around the base of trees with shallow roots. This is due to adsorption of herbicide to mulch which reduces the availability, persistence and phytotoxicity of some herbicides (Grover 1971; Smith & Skroch 1995). However, it is hoped that the application of mulch will minimise the need to apply herbicides at all, not only protecting the environment but also reducing management costs as well (Gardiner & Yeiser 1998).

Paper is a highly processed material made from wood, and can be used as mulch when collected from recycled material. It can be used simply by laying down old newspapers on the ground, or purchased as a dedicated landscape product (Crown Zellerbach Corp 1954). Plain newspapers have proven effective in weed suppression (Shogren & David 2006), for more than 3 months and up to two seasons per application (or 16 weeks as determined by Runham *et al.* (2000)), provided they are wetted after laying, and pressed down with a lawn roller to prevent being wind-blown and better resist weathering (Pellet & Heleba 1995). The drawback is of course in aesthetics, which necessitates the covering of newspaper mulch with other materials to improve its appearance and to keep it in place. The natural degradation (Brault et al. 2002) of paper mulch may or may not be an advantage, depending on management viewpoint. Oiled paper is available as an alternative which retards the natural degradation of paper (Andersen et al. 1996; Shogren 1999).

To improve aesthetics, paper mulch can also be used in combination with other mulches. Schonbeck (1999) found that two layers of newsprint under straw mulch significantly enhanced weed suppression.

In New Zealand, a commercially available product known as EcoCover is available. This has been tested to give good weed suppression ability for up to 6 months. The degradable nature of this produce is deemed to be advantageous when laid around trees, as compared to black weed mat (Harrington & Bedford 2004).

Being wood-based, there is concern for the potential of induced nitrogen deficiency from the use and subsequent breakdown of paper mulch, as was discussed above for wood mulch. Some research found no conclusive evidence for this (Pellet & Heleba 1995; Jenni et al. 2004); another found that any adverse effect to plant growth was only observed when paper pellets were applied as a layer 50 mm thick but not when only 25 mm thick (Smith et al. 1997). Follow-up research also reiterated that effective weed control was achieved when paper pellets were added at 25mm depth to containerised plants (Smith et al. 1998). Prevention of weed germination by paper pellets was achieved by the absorbance of water which caused the pellets to swell and form an interlocking mat. This effect is contingent on the pellet being of an optimal size and the absorbance property of the paper material used. Separate research in container plants found that paper mulch "retained" nitrogen if fertiliser was top-dressed over paper mulch; but this effect was eliminated if the fertiliser was incorporated into the potting mix instead (Glenn et al. 2000). This again suggests that wood-based mulches have no harmful effect when applied only to the soil surface.

2.12.2 Inorganic mulches

Inorganic materials used as mulches include minerals in the form of stones, chips, pebbles or gravel; black polyethylene or other plastic sheets; landscape fabrics or geotextiles which may be woven or sheets of synthetic materials such as polypropylene polymers; recycled rubber strips, and aluminium foil.

Plastic sheets used as mulch can be an effective weed control measure provided the unbroken physical barrier can be maintained (Ricotta & Masiunas 1991). Some work has also been done to show that increased red and far-red light from surface reflection from variously coloured plastics can alter the red to far-red light ratios, which affect phytochrome responses in the crop plants for assimilate partitioning, hence potentially improving crop yields (Decoteau et al. 1989). As such, the use of plastic sheets affects both underground condition via heat conductance, and above ground conditions by light reflectance. Another note-worthy consideration when using plastic is the non-porous and non-permeable property of unwoven plastic sheets which may trap excess moisture. This has been linked to higher incidences of bacterial soft rot than other mulch types (Davis 1994). Users are advised to consider the holistic effects these may have on the plants around which plastic mulch is laid (Tarara 2000).

Landscape fabrics and geotextiles were invented following the development of the petrochemical industry. They were promoted as being able to suppress weeds, conserve moisture by re-condensing evaporated water vapour, and raising soil temperature through reflectivity, heat absorbance and conductivity (Lalitha et al. 2010). Non-porous plastic geotextiles are also used as a soil fumigation aid for weed, insect pest and disease control when first developed (Johnson 1952; Kopitke & Langford 1952; Marvel 1952) and are still in use today for similar purposes (Fennimore & Ajwa 2011; Qin et al. 2011). Weed control results using plastic geotextiles have been steadily improving. Derr and Appleton (1989) recommended it on a qualified basis for annual weeds. Previously, the nature and manufacturing method of the landscape fabric could affect weed control, with meshed fabrics using more elastic polymers permitting weeds through more easily, compared to spun-bound non-woven fabrics (Martin et al. 1991). Spun-bound fabrics have polymer filaments extruded in a random pattern on a collecting belt before the web-like mass goes through a binding process to fix the polymer fibres in place. Another problem with weed control using landscape fabric, and plastic weed mats too, is that weeds will still grow around the edges or through the centre planting hole (Appleton & Derr 1990). Appleton and Derr also recommend supplementing the use of landscape fabrics with herbicides and hand weeding. An advantage recognised early on of using plastic in general is a slight reduction in herbicide (Wilson et al. 1995) or nitrate (Romic et al. 1996; Romic et al. 2003) runoff, which helps to allay concerns by the public. Some early types of plastic-based geotextiles were prone to photodecomposition, and allowed light through to the soil surface as time passes. This necessitated another mulch layer on top of the geotextile for better weed control (Derr & Appleton 1989; Ito & Nagai 2008). Improved technology has led to better UV-resistance in polymers through the use of additives during manufacture, which helps to reduce this problem in newer materials (Yildiz et al. 2010).

Now, plastic mulch cover is among the best performing materials in weed control. It is possibly better than sand, cardboard, wheat stem mulch and glyphosate applications (Ustuner &

Ustuner 2011). Plastic cover is also widely recognised in agriculture around the world (e.g. Croatia (Dudas & Kaufmann 2010); China (Li & Yang 2009); Turkey (Urems et al. 2009)) for its positive effects on plant growth; and being cost-competitive, in addition to providing superior weed control. Darker colours of plastic cover may also be used if raising the soil temperature is desired (Lamont 1993; Gordon et al. 2010). Another method to increase soil temperature would be to use infra-red transmitting (IRT) plastic mulch (Loy 1991) which raises soil temperature more than black plastic but less than clear plastic, useful for soil solarisation. This produces conditions conducive for better plant growth but not for weed growth since photosynthetically active radiation is blocked. IRT plastic mulch has been shown to be effective against noxious weeds such as *Cyperus rotundus* (Patterson 1998). IRT plastic mulch is now considered as a viable weed control method in scenarios where soil warming is also desirable (Mathieu & Jeremy 2004; Lamont 2005). The increased soil temperature from use of plastic mulch may lead to beneficial precocity in some plants, hastening harvest time (Ashrafuzzaman et al. 2011; Zribi et al. 2011); or even allow double cropping in one growing season (Ngouajio & Ernest 2005). Some woven polyethylene sheets with high reflectance are used as ground cover and have been shown to improve photosynthetic ability and fruit colouration in orchards (Hanrahan et al. 2011).

Following the success and continual popularity of plastic use in agriculture, criticism has been laid against plastics as being environmentally pollutive due to their persistence (Albertsson 1978; Thompson et al. 2004). In response, polymers have been developed which are degradable by light exposure (Lemaire et al. 1996; Kwabiah 2003), and/or microorganisms in aerobic and anaerobic conditions (Hadad et al. 2005; Roy et al. 2008; Mumtaz et al. 2010). However, the debate continues with critics claiming that degradation to smaller particles, even those invisible to the naked eye continues to harm various life-forms (Betts 2008). Satisfactory degradation to dedicated environmentalists will see plastics successfully re-enter ecological cycles through bioassimilation or conversion to CO_2 and H_2O in an acceptably short time frame (Roy et al. 2011).

Mineral-based mulches such as gravel also persist in the environment but do not come under criticism as they are naturally occurring. This is a good option which reduces the need for replacement. In regions with risks of termite infestation, mineral mulches will be safe from potential attack (Myles 2008). However, with such mulches, minerals could be leached into the soil and may potentially increase alkalinity which may or may not be desirable. Stones also tend to absorb more heat during the day, which are released at night; and day-time heat may also be reflected back at plants, so the additional heat factor need to be taken into account (Boyer 2007).

Rubber mulches tend to be recycled from used tyres, but they may be processed to resemble wood, bark, or gravel. Hence they can claim not to require any further addition of organic mulches to improve aesthetics. Manufacturers also claim the lack of natural decomposition to be another advantage since there will be no thinning or associated undesirable odours. Rubber also yields under compression, and does not have sharp edges, so may be preferred where there may be foot traffic and concerns for safety of pedestrians or young children (Byrne 1993). However, rubber mulch may not be a good choice for hot climates, as risk of ignition is high, even when compared against mulch materials like straw and bark (Steward et al. 2003). Use of improved rubber formulations in mulch may solve this problem (Derouet et al. 1994; Wang & Chen 2008).

Aluminium foil is used primarily in vegetable plots, where the high light reflectance of the material has been found to be an effective deterrent of insect pests and the viruses associated with some insect vectors (Loebenstein et al. 1975; McLean et al. 1982; Basavarajappa & Rajasekhar 2001; Greer & Dole 2003) but not for the western black flea beetle (*Phyllotreta pusilla*) (Demirel & Cranshaw 2005) nor thrips (*Thrips tabaci*) (Van Toor et al. 2004). The benefits of increased light reflectance discussed earlier with woven polyethylene sheets is also well documented with aluminium mulch in apple orchards (Mika et al. 2007; Tahir & Gustavsson 2010).

2.13 Applications of ground cover plant in plant production

This project is mainly focused on ground cover plant applications for weed control in amenity horticulture. However, ground covers have also been used in forestry, production horticulture and for erosion control. These uses are briefly discussed below as some lessons can be learned from these situations when looking at how best to improve use of ground covers within amenity horticulture.

2.13.1 Considerations for ground cover plants in revegetation

Ground cover plants have been advocated for use as an aid in re-vegetation, which frequently includes land on slopes. The main aim of using ground cover plant is to minimise the risk of soil erosion due to storm run-off while re-vegetation takes place, with the secondary benefit of improving soil structure and building up organic matter (Marston 1952). This has been advocated by the Appalachian Regional Reforestation Initiative (ARRI) in the United States, following the cessation of coal-mining activity. However, being mindful of the potential competition which might be unduly imposed on the establishing forest, some guidelines have been suggested which seek to combine the advantage of ground cover plants without compromising sapling development. These include using less-competitive ground cover species; using a lower seeding rate for sparser cover; minimising fertiliser to prevent reduce aggressiveness of ground cover growth; and accepting partial vegetation cover in the initial years of re-forestation (Burger et al. 2009). The ground cover plants proposed initially include annual grasses for their rapid growth, but will mainly comprise legumes as understorey plants when the forest matures. It is hoped that the low seeding rates of ground cover plants will also allow the gradual re-introduction of native plant species. It is expected that the ground cover plants will gradually thin out when the forest canopy closes overhead.

The intention to introduce ground cover planting by the ARRI may produce better results than traditional reforestation efforts. A recent report which examined reforestation in 1860 using high density sapling planting concluded that it did not lead to sustainable self-renewal of the replanted trees, possibly due to the lack of native ecology rehabilitation (Vallauri et al. 2002).

2.13.2 Considerations for ground cover plants in agroforestry

Weed invasion during the establishment of tree saplings may lead to suppression of tree growth, adversely affecting future yield (Watt et al. 2003a). Ground cover plants have been used to good effect in weed control in plantation establishments of *Eucalyptus dunii (Little & Berg 1999)*; rubber trees (*Hevea brasiliensis*) (Grist et al. 1999); *Bactris gasipaes* (for heart-of-palm production)(Clement & DeFrank 1998); ash trees (*Fraxinus excelsior*) and Douglas fir (*Pseusotsuga menziesii*). Ground cover plants were also successfully used to check soil erosion in hardwood plantations of *Liquidambar styraciflua* (Malik et al. 2000). In New Zealand, *Pinus radiata* plantations face major competition from broom (*Cytisus scoparius*), especially for water and soil nitrogen at the sapling stage (Watt et al. 2003b). The use of ground cover less competitive toward pine saplings, such as *Lotus pedunculatus* (formerly *L. uliginosus*) (Richardson et al. 1996; Harrington & He 2010), can help to reduce competition and minimise losses to the industry.

2.13.3 Current use of ground cover plants in orchards and crop farms

Planting ground covers in an orchard is an alternative to keeping the ground bare through mowing and herbicide applications. When used as part of a weed suppressant strategy in cropping systems, ground cover planting can reduce reliance on potentially damaging herbicides. This is achieved by the ground cover plants' competition for growth resources and also through purported allelopathic effects (Hartwig & Ammon 2002; Shiraishi et al. 2002). Trials involving different ground cover species and establishment methods have been carried out (Harrington 1995).

Ground cover plants used in orchards are often leguminous, for the additional benefit of soil nitrogen fixing (green manure) (Sarrantonio & Gallandt 2003). The legumes can spread quickly, for example, a Florida study involving *Arachis glabrata* (perennial groundnut) showed that it achieved 89% ground cover after three years with good weed suppression without the need of any fertiliser or herbicide during this time (Rouse & Mullahey 1997). Species selection will also need to consider the flowering periods of ground cover plants. This ensures there will be no competition for pollinating insects between the ground cover and trees (Firth & Wilson 1995). An example would be the use of strawberry clover (*Trifolium fragiferum*) in apple orchards as ground cover where the trees out-yielded those trees inter-planted with white clover (*Trifolium repens*) (Stinchcombe & Stott 1983). This was probably due to the later flowering of *T. fragiferum* from July – October which did not compete for pollinators with apple trees flowering from spring onwards depending on variety; as opposed to the May-August flowering of *T. repens* which overlapped with later flowering apple varieties (Harper & Clatworthy 1963).

A non-leguminous alternative for ground cover use in orchards is *Dichondra micrantha*. Research has shown that it provides good cover with easy establishment using selective herbicides and demonstrates good weed suppressing properties (Harrington & Zhang 1997; Harrington et al. 2002). In a bid to diversify the plant species available for ground cover away from grasses and legumes, attention has turned to characteristics of some weed species, which may be deemed desirable in a ground cover plant. These traits include continued growth throughout the year with little sign of dormancy; moderate biomass which is acceptable without mowing; excellent horizontal growth to discourage other weeds and prevent soil erosion; and the ability to self-seed. Herbicide selectivity for species commonly regarded as weeds, such as *Poa annua,* mouse-ear chickweed (*Cerastium vulgatum*)*,* chickweed (*Stellaria media*), and storksbill (*Erodium sp.*), have been assessed (William 1990). In New Zealand, other non-leguminous ground cover species, such as *Sagina procumbens* and *Pratia pedunculata* have also being considered for orchard use with research being carried out on their herbicide compatibility to encourage interest by orchardists (Harrington & Grant 1993).

One of the indirect benefits of ground cover planting in orchards is the earlier promotion of cold-hardiness. It has been noted that ground covers may lower temperature, due to less heat reflectance and evapotranspiration. This may be advantageous or disadvantageous depending on the on-site climate and the specific crop. However, it was shown that in a tree nursery of *Acer sp.* and *Gleditsia sp.* with companion planting of *Lotus corniculatus* and grass, the saplings suffered from less winter injury (frost cracking, sunscald, branch tip dieback, crown dieback, and complete plant mortality) than those planted in a bare soil environment (Calkins & Swanson 1998). However, this may become a disadvantage in warmer climates. When the perennial peanut, *Arachis pintoi*, was planted in a banana plantation, the cooling effect on soil temperature led to decreased fruit yield (Johns 1994). Other general indirect effects are discussed below.

2.13.4 Effects of ground cover plants on bare soil

Despite seemingly the easiest and cheapest option, having bare ground is a costly proposition when risk of the loss of potential natural resources is considered. The use of ground cover plants can be a cost-effective method to ward off soil erosion from rainfall as described earlier in this chapter. For instance, there is evidence from data taken in Zimbabwe, then known as Rhodesia, that plant cover is the key factor in predicting soil erosion effects, and may be used to adequately quantify soil erosion estimates (Elwell & Stocking 1976). More recent research in Spain continues to reinforce the relationship between plant canopy cover and soil erosion due to runoff (Quinton et al. 1997). In some parts of the world, soil erosion may also stem from wind effects on bare ground. For commercial growers, planting ground cover plants is the most effective method at their disposal to mitigate erosion from wind effects. Scenario modelling in Western Australia has shown that wind erosion effects may be mitigated exponentially as the proportion of ground covered by prostrate plants increases (Findlater et al. 1990).

Ground cover plants are also preferable to bare soil even where trees are present, as is commonly the case of roadside trees or urban parks. A study found that *Cercis canadensis* trees had greater height and trunk diameters when planted with ground cover plants than on bare soil (Arnold & McDonald 2009). This was despite potential competition from ground cover plants for water and nutrients. The authors note that the two treatments with the smallest height and trunk diameters were also the weediest. Treatments with better weed suppression in the study, including living ground cover (St. Augustine grass, *Stenotaphrum secundatum*) produced larger trees. On the other hand, pavers were found to have a detrimental effect on tree survival and growth.

Another way ground cover plants may improve plant growth is through increased contributions of organic matter. A study conducted in an orchard showed that when crown vetch (*Securigera varia*) cover or grass sod was planted, soil organic matter was highest compared to other treatments (Merwin et al. 1994); and live grass mulch improved strawberry yield similarly (Univer et al. 2009). Merwin's study also concluded that the long-term soil fertility and productivity declined under pre-emergence herbicides and mechanical cultivation relative to the other treatments which included live ground cover.

The presence of live cover over bare soil was also shown to mitigate soil compaction. This effect may be attributable to the presence of plant roots and being able to support a thriving community of micro-fauna which creates spaces in the soil for transport and gaseous exchange. A recent study found that when 'spontaneous vegetation' were eradicated through herbicide use, soil compaction increased (Fidalski & Tormena 2007). Soil aeration will expectedly suffer under vehicular traffic common in many urban areas. A study in Brazil showed that when *Paspalum notatum* was planted, soil aeration was better maintained under truck movement than when bare soil was maintained with herbicide application. The resistance to soil compaction was attributed to root presence (Fidalski et al. 2007). Careful selection of non-grass ground cover species planting may reproduce similar benefits, since lawnmower traffic is also found to lead to compaction (Oliveira & Merwin 2001).

The effect of ground cover plants to soil pH is less consistent, and appears to vary depending on vegetation type. In an urban tree environment with assorted soil covers both organic and inorganic, the soil pH did not vary significantly from bare soil (Arnold & McDonald 2009). However, soil pH became less acidic as ground cover biodiversity increased under plots of pine (*Callitris glaucophylla)* (McHenry et al. 2006).

2.14 Summary

Ground cover plants can be used as living mulch in both cropping and amenity situations. They are not only aesthetically pleasant, but afford a potential ease-of-maintenance while being able to confer all the attendant benefits of mulch to soil conservation and plant growth. Ground cover plants are effective as a weed control strategy as they compete against weeds not only for underground nutrient and water resources but can also hinder access to light and cause phytochrome in weed seeds to remain in a physiologically inactive form. Ground cover plants are especially useful in urban environments because the high resident population density means greater emphasis will be placed on concerns of inconvenient disruptions to daily routine and hazards to public health from chemical contamination of air and water through the use of herbicides or petrol-based mowing. However, more research is required to enable astute decision-making in terms of species selection, establishment and subsequent management of ground cover plants to ensure maximum benefits will be reaped at minimal cost to environment and fiscal budgets.

Chapter 3 Assessing ground cover plants of various forms and growth habits

3.1 Review

For ground cover plants to prevent weeds from growing, they must essentially outcompete them. Grounds managers must therefore attempt to confer the maximum advantage for growth towards desirable ground cover plants.

Ross and Harper (1972) showed that the seedlings which emerged earlier were better able to outcompete their later neighbours by claiming more resources available to them in the 'biological space' that their larger size due to earlier emergence has afforded them. Taller plants may also have an unfair advantage over their shorter competitors by causing wind turbulence which may dry out the soil surface around the smaller plant more, adding stress to the younger plant (Harper 1977b). This effect would be significant in arid regions or during dry seasons.

The spatial arrangements of ground cover plants and weeds also play an important role in determining the outcome of competition. Harper's (1977a) experiments showed that if two different species are grown together, the greater the 'interface' or area of contact between two different species, the more pronounced the competitive effect of the stronger species. In the scenario where weeds may germinate amongst the gaps of establishing ground cover, such interspecific contact will likely be maximised. By having a vigorously growing ground cover plant early on, weeds will more likely be outcompeted.

In fact, competition may serve to magnify the competitive advantage of the stronger species as a result of the marginal advantage in resource capture being used to further the growth of the advantageous plant characteristic. Such a positive feedback loop has been termed 'snowball cumulation' (Newman 1973). As such, it is imperative that ground cover plants get a head start in establishment at the desired areas where weeds are to be kept out. This thesis now looks at the natural capabilities of twelve selected species to establish themselves in an area before weed invasion sets in.

3.2 Trial objectives

This trial put together ground cover plant species with different growth forms, habits and modes of reproduction in adjoining plots of land (Fig 3.1). The aim was to compare how well these different traits enabled the plant species to cover the ground, and if they were able to keep weeds out of the area they covered.

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Figure 3.1 The trial site at 2 weeks after planting (left); and 4 months after planting (right)

3.3 Materials: Species introduction

Twelve species of ground cover plants were chosen as a representation of various growth forms and reproductive habits. Their inclusion also took into consideration the availability and suitability for the Palmerston North climate. All plants are low-growing, ranging from 10-60 cm in various parts of the year. It was envisaged that these 12 species were suitable as companion planting with shrubbery in amenity horticulture situations.

The 12 species were:

i. *Acaena inermis* 'Purpurea';
ii. *Ajuga reptans* 'Caitlin's Giant';
iii. *Coprosma acerosa* 'Taiko';
iv. *Grevillea lanigera* 'Little Drummer Boy';
v. *Juniperus procumbens* 'Nana';
vi. *Lithodora diffusa* 'Grace Ward';
vii. *Muehlenbeckia axillaris;*
viii. *Ophiopogon planiscapus;*
ix. *Persicaria capitata;*
x. *Pimelea prostrata* 'Anatoki'*;*
xi. *Sedum mexicanum* 'Acapulco Gold'*;*
xii. *Veronica peduncularis* 'Oxford Blue'.

Acaena is a genus of about 100 species found mainly in the temperate southern hemisphere, with many species also found in Australia and South America. Only two species are noted in the northern hemisphere; *Acaena exigua* in Hawaii is thought to have developed from seeds dropped by migratory birds (Gynn & Richards 1985), and *Acaena pinnatifida* is a rare plant native to California, although it has been recently described as *Acaena pinnatifida* var. *californica* (Crain & White 2011). Commonly known as piripiri in New Zealand or bidibidi, 18 species of *Acaena* are regarded as New Zealand natives (Lloyd et al. 2002). Many species are low-growing (about 10 cm high), mat-forming plants in various attractive hues which spread quickly over a radius of a metre or more (Laing & Blackwell 1964). *Acaena* species produce fruit-heads full of seeds easily but can also be propagated by lifting and separating rooted stems to ensure that the desired foliage colour is maintained (Matthews 1993). Due to the ability of many *Acaena* stems to root at the nodes, and the bur-like seed heads which may attach to passing animals and human apparel, some *Acaena* species are regarded as weeds. An example is *Acaena novae-zelandiae,* which was offered for sale as an ornamental in the UK, but has now established feral populations (Gynn & Richards 1985). It is also considered an introduced weed in California (DiTomaso & Healy 2007).

Acaena inermis is a New Zealand native that is found from central to southern North Island and also widespread east of the Main Divide in South Island from Nelson to Otago (Lee et al. 2001). *A. inermis* is a grey-leaved form, but the 'Purpurea' variety selected for this project is highly sought after for its more colourful purple foliage (Eadie 2008). This is a carpet-forming species (Fig 3.2) which will eventually fill up all space around the plant. It is tolerant of most soils but a well-drained soil in a sunny position is recommended. Propagation is easy with either stems cuttings or seeds.

Despite their known weedy nature, cultivated forms of *Acaena sp.* continue to be developed as ornamentals for their colourful foliage and often contrasting seedheads, but carefully selected for a propensity to be less weedy. *Acaena caesiiglauca* and *Acaena microphylla* are examples of species available for sale in New Zealand (online plant catalogue by Naturally Native http://www.naturallynative.co.nz).

Figure 3.2 *Acaena inermis* 'Purpurea', whole plant (left) foliage close-up (right)

Ajuga reptans originates from Europe forming clumps of leafy stems which creep on the ground surface forming a dense canopy in semi-shade to shady conditions (Odenwald & Turner 2006). The plant is stoloniferous with waxy or metallic-looking leaves and grows best in porous well-drained soil. The variety 'Caitlin's Giant' has larger leaves than is usual for the species, the leaves also have a bronze hue with a purple tinge (Fig 3.3). While the leaves and stems are prostrate when mature, the flowering spikes may be more than half a metre tall. It spreads easily by rooting stolons, which can be cut off and transplanted.

Figure 3.3 *Ajuga reptans* 'Caitlin's Giant', whole plant (left) foliage close-up (right)

Coprosma is a genus of 111 species which is widespread over the Pacific Ocean from Borneo, to Australia, to various Pacific Islands, up to Hawaii (Moore & Irwin 1978). Of these, 47 species are found in New Zealand , of which 45 species are native (Heads 1996). While some *Coprosma* species may be shrubs (eg *C. crassifolia*) or even small trees (eg *C. australis*) a few metres tall, *Coprosma acerosa* is a prostrate ground cover plant with small leaves (Fig 3.4), traits which are not uncommonly found amongst the other native *Coprosma* (eg *C. atropurpurea, C. petriei*). Plants of the *Coprosma* genus are often dioecious and reproduce by wind pollination, which contributes to many natural hybrids in the genus (Taylor 1961). The hybridised nature of many *Coprosma* taxa is confirmed by Wichman's nuclear ribosomal DNA investigations (Wichman et al. 2002).

Figure 3.4 *Coprosma acerosa* 'Taiko', whole plant (left) foliage close-up (right)

C. acerosa 'Taiko' is commonly listed as a variety of *C. acerosa*, although Oratia Native Plant Nursery (http://www.oratianatives.co.nz) lists it as a hybrid possibly parented by the prostrate *C. propinqua* var 'martinii', a claim which is also supported by the website of a landscape design company (http://www.o2landscapes.com). It is sometimes listed simply as *Coprosma* 'Taiko' (Cave &

Paddison 1999), a tacit acknowledgement of its possibly hybrid origins. This thesis will refer to it as *C. acerosa* 'Taiko'.

C. acerosa 'Taiko' has drooping stems which occasionally roots, and glossy leaves growing densely. It grows well in full-sun with sandy or well-drained soil, and produces dark blue to black berries in autumn.

A member of the Proteaceae family, the genus *Grevillea* is widespread in Australia, and also in the islands of New Guinea and areas in Indonesian provinces and Papua New Guinea. *G. lanigera* is native to the Australian states of Victoria and New South Wales. The species epithet means "wool-bearing" and alludes to the hairy, grey-tinged leaves of the plant (Fig 3.5). All cultivars grow best in sunny positions with well-drained soils, and are tolerant of drought once established. The plants may be propagated by stem cuttings (Elliot 2008). *Grevillea lanigera '*Little Drummer Boy' has attractive bright red flowers from winter through to summer, with a low growth form and a cascading habit which makes it ideal as a ground cover plant or planted over slopes (MacKenzie 1997).

Figure 3.5 *Grevillea lanigera '*Little Drummer Boy', whole plant (left) foliage close-up (right)

Junipers are usually majestic trees 20-40 m tall, but in contrast, *Juniperus procumbens* is a low-growing ground cover plant (Fig 3.6). Other examples of species suitable to be ground cover

Figure 3.6 *Juniperus procumbens '*Nana', whole plant (left) foliage close-up (right)

include *J. conferta* and *J. horizontalis*. *J. procumbens* is native to the Japanese island of Kyushu and some other smaller islands in southern Japan. This is a dioecious species, shedding pollen in spring and producing dark-coloured cones containing 2-3 seeds each (Adams 2011). The cultivar 'Nana' is believed to have originated in the wild along the coastal areas of Kyushu (Bloom & Bloom 2001), and thus grows well in sandy soils. *J. procumbens* 'Nana' has a slightly more squat stature than the species, with slightly bluish foliage which may deepen to purplish in winter (MacKenzie 1997).

Lithodora diffusa was formerly known as *Lithospermum diffusum*. The name *Lithodora* was proposed in 1844 by Grisebach to accommodate six species of shrubs found mainly in the Mediterranean but was used largely as being synonymous with *Lithospermum*, although Johnston (1953, 1954) highlighted its differences and proposed revaluations of *Lithospermum*. The main differentiating features of *Lithodora* are an overall shrubby habit, absence of faucal scales and annulus, with unusual mericarp morphology. Genetic investigations of its ribosomal and chloroplast DNA deemed it sufficient to warrant its own polyphyletic group (Thomas et al. 2008). The present day *Lithodora* genus now encompasses nine species around the Mediterranean, with diversity centred on the western side. *Lithodora diffusa* is popularly grown as a low-growing plant for its ability to produce attractive blooms to accent the landscape (Fig 3.7). It is often used in rock gardens as it is drought tolerant, or well-drained soils are preferred. *L diffusa* also prefers slightly alkaline soils for best results (Tenenbaum 2003). The 'Grace Ward' variety has a more intense blue colour than the species with slightly larger flowers from summer to autumn (MacKenzie 1997; Hillier & Coombes 2007).

Figure 3.7 *Lithodora diffusa* 'Grace Ward', whole plant (left) foliage close-up (right)

Muehlenbeckia is a relatively small genus of 15 dioecious species (Hillier & Coombes 2007) with mostly vine-form species and some shrubs (eg *M. astonii*) (Eadie 2008). The genus is distributed over South America, and Australasia including New Zealand (Laing & Blackwell 1964), though the *M. axillaris* species (creeping pohuehue) can be found naturally in New Zealand south of the lower North Island and Tasmania (MacKenzie 1997) in rocky or gravelly soils (Wardle 1991). *M. axillaris* makes a good ground cover plant as it is less vigorous and aggressive than other *Muehlenbeckia* species, usually described as a mat-forming, trailing species (Fig 3.8); in contrast to *M. complexa* which is a strong climber (Smith-Dodsworth 1991; Cave & Paddison 1999). *M. axillaris* has conspicuous, albeit tiny, creamy white flowers (Eadie 2008). It is also deep rooting and has the advantage of being able to bind sandy or loose soil (Matthews 1979).

Figure 3.8 *Muehlenbeckia axillaris*, whole plant (left) foliage close-up (right)

Ophiopogon is a genus of monocotyledonous plants native to Asia that spans the tropical south-east Asia to the warmer temperate zones up to Japan. *O. plansicapus* is typical of the genus with its tufted growth habit (Fig 3.9), and is native to Honshu in Japan (Levy-Yamamori & Taaffe 2004).

Figure 3.9 *Ophiopogon planiscapus*, whole plant (left) foliage close-up (right)

The deep green leaves of *O. planiscapus* arches over the ground and it produces dainty bell-shaped flowers in pale lilac to white on a flowering stalk, which mature into black fruits. It is rhizomatous and also produces stolons which terminate in plantlets. It initially has a clumped appearance when newly established, but as plantlets gradually form around it, adopts a more patchy appearance. It grows best in moist, well-drained soils with partial shade (Schmid 2005).

Persicaria capitata (pink knotweed) (formerly known as *Polygonum capitatum*) is a herbaceous creeper that easily roots at its nodes. It rapidly forms a carpet cover like *A. inermis* and *M. axillaris*, with a habit of producing profuse pink flower-heads on red-toned stems and leaves (Fig 3.10), which makes it an attractive landscape feature (Fish 1970). However, it needs to be protected from frost. It is tolerant of poor soils and has been found growing on moist rocky surfaces in Nepal at altitudes up to 2200 m (Kantachot et al. 2010). It is thought to be of east Asian origin (Groves 1994), but is now naturalised outside this region, including in nearby Tasmania (Baker 2007). It can be easily propagated by its rooting stolons or seeds.

Figure 3.10 ***Persicaria capitata,*** **whole plant (left) foliage close-up (right)**

Pimelea is a genus of about 80 species with 24 which are New Zealand natives (Smith-Dodsworth 1991). Most other species are native to eastern Australia (Moore & Irwin 1978). *P. prostrata* 'Anatoki' (New Zealand Daphne), a native plant, is a low growing woody plant with a drooping habit with bluish-green leaves (Fig 3.11), often growing in rocky or sandy soils throughout New Zealand as it can tolerate dry conditions (Cave & Paddison 1999). It is also versatile enough to adapt to any free-draining soil in a sunny position (Matthews 1993). The flowering inflorescences are eye-catching in pinkish-creamy-white with a slight fragrance, later forming waxy white fruits (Spencer & Pearson 2002; Eadie 2008). *P. prostrata* will root easily from semi-woody stem cuttings, and rooting hormone may be used if required. However, self-rooted stems frequently occur in established plants, and these may be used for propagation (Metcalf 1995).

Figure 3.11 ***Pimelea prostrata*** **'Anatoki',** **whole plant (left) foliage close-up (right)**

Sedum is a genus of succulent plants found around the world, commonly known as stonecrop. Many species are ideal in situations with bright light, little water in well-drained soils, and are tolerant of short-term extremes in temperature within zones of hardiness (MacKenzie 1997). *S. mexicanum* despite its name, is not from Mexico, and is thought to be more closely related to Asian species. It probably acquired the name due to the many *Sedum* species which are truly native to Mexico (Cave 2002). *S. mexicanum* 'Acapulco Gold' is a low growing plant with dense interlocking bright yellow needle-like leaves in whorls (Fig 3.12) which flowers from late spring to summer with tiny flowers in the same bright yellow hue. As it spreads on the ground, it occasionally develops roots from its trailing stem nodes. The species has been used as a roof cover in various parts of the world due to its hardiness and dense foliage cover. A local example of roof cover planting using *S. mexicanum* 'Gold Mound' is at the Pipitea Plaza in Wellington (Hopkins & Goodwin 2011).

Figure 3.12 *Sedum mexicanum* 'Acapulco Gold', whole plant (left) foliage close-up (right)

Veronica is a genus with species spread throughout the world, though the greatest diversity appears around the Mediterranean region (Albach et al. 2004). There are approximately 300 species found throughout the world except in the polar region. The genus is adaptable to most habitats and lighting conditions (Kelaidis 1993). *Veronica* is prized in amenity horticulture for its blue-violet flowers, though white and pink flowers, like those found in *V. spicata* cultivars, are also represented (Foley 1972). The *Veronica* genus also varies in form, ranging from small shrubs up to 1m tall when in bloom to creeping carpeters growing less than 0.1m above the soil surface (Ellis 1998). Some of these carpeting species also root easily from stolons, which enables them to spread quickly and makes them difficult to eradicate. Hence *Veronica* species are also on the weed list for lawn managers and gardeners (Christians & Ritchie 2002; Schrock 2004; Clarke 2007). Examples of *Veronica* weeds include *V. officinalis, V. arvensis, V. persica, V. hederaefolia,* and *V. filiformis.* In Europe, *V. officinalis* is also recorded as a medicinal herb for its diuretic and expectorant properties (Foster & Duke 2000).

In Australasia, there are about 90 species of the *Veronica* species present (Mabberley 2008). However*, V. peduncularis* has its origins in the Turkish Mediterranean region, growing long trailing stems with evergreen leaves, and a loose scatter of blue flowers from spring onwards which fade to pale violet with blue veins (Fig 3.13). If cut back after its first flowering, a subsequent flowering flush may follow (Grey-Wilson 2009). *V. peduncularis* 'Oxford Blue', also known as 'Georgia Blue', has expectedly deeper blue flowers and also leaves which are sometimes tinged purple at the margins.

Figure 3.13 *Veronca peduncularis* 'Oxford Blue', whole plant (left) foliage close-up (right)

3.4 Methods

3.4.1 Methods: Establishment of 12 ground cover plant species

A site within farmland maintained by Massey University at Poultry Road near Palmerston North (40°22’57.5’’S, 175°36’19.9’’E) was used for establishing these species. The site measuring 12m by 12m was on Manawatu fine sandy loam.

Manawatu fine sandy loam is categorised as a soil composed of alluvium material found along river levees. The top layer is about 25 cm deep and described as “dark greyish brown fine sandy loam; friable; with a moderate nutty texture”. It is also considered to be a well-draining soil type which occurs on “infrequently flooding river flats”. It may also dry out in summer, and topsoil structure could deteriorate if frequently cultivated (Cowie & Rijkse 1977). Prior to use for the trial, the site was used for grazing by sheep and dairy cows. Pre-existing vegetation was removed by rotary hoeing.

The ground cover species were planted using a randomised complete block design with three blocks. Each block contained all 12 species in separate plots. Within each 2m by 2m plot, three plants of the same species were planted in an equidistant triangle pattern 1.0 m apart from each other. The apical position of the triangle alternated between neighbouring plots to reduce the risk of overcrowding when the plants expanded (Fig 3.14).

Each plot received 200 kg/ha N in the form of ammonium sulphate by surface application following planting, followed by sawdust laid 7 cm deep to control weeds during establishment. The sawdust had aged for about a year prior to purchase. Care was taken not to have the sawdust too deep at the base of each plant to avoid disease problems, and all stems or branches were laid above the sawdust. All planting, fertilising and mulching was completed on 24 Nov 2008.

△ ▽ △ ▽ △ ▽

Block 1	*Ophiopogon planiscapus*	*Juniperus procumbens* 'Nana'	*Pimelia prostrata* 'Anatoki'	*Ajuga reptans* 'Caitlin's Giant'	*Lithodora diffusa* 'Grace Ward'	*Veronica peduncularis* 'Oxford Blue'
	Grevillea lanigera 'Little Drummer Boy'	*Persicaria capitata*	*Acaena inermis* 'Purpurea'	*Sedum mexicanum* 'Acapulco Gold'	*Coprosma acerosa* 'Taiko'	*Muehlenbeckia axillaris*
Block 2	*Acaena inermis* 'Purpurea'	*Muehlenbeckia axillaris*	*Ajuga reptans* 'Caitlin's Giant'	*Ophiopogon planiscapus*	*Grevillea lanigera* 'Little Drummer Boy'	*Persicaria capitata*
	Pimelia prostrata 'Anatoki'	*Veronica peduncularis* 'Oxford Blue'	*Juniperus procumbens* 'Nana'	*Lithodora diffusa* 'Grace Ward'	*Sedum mexicanum* 'Acapulco Gold'	*Coprosma acerosa* 'Taiko'
Block 3	*Juniperus procumbens* 'Nana'	*Muehlenbeckia axillaris*	*Persicaria capitata*	*Ajuga reptans* 'Caitlin's Giant'	*Pimelia prostrata* 'Anatoki'	*Acaena inermis* 'Purpurea'
	Grevillea lanigera 'Little Drummer Boy'	*Lithodora diffusa* 'Grace Ward'	*Veronica peduncularis* 'Oxford Blue'	*Ophiopogon planiscapus*	*Coprosma acerosa* 'Taiko'	*Sedum mexicanum* 'Acapulco Gold'

Figure 3.14: Planting layout of the 12 species in a randomised complete block design. Triangles at the top indicating planting position for the column

3.4.2 Methods: Rate of establishment -- Measuring diameter and height

The rates of establishment were determined by making regular measurements of plant diameter and height. Each plant diameter was measured three times in planes approximately 45 degrees to each other to get a mean estimate, as some of the plants were irregularly shaped. Height was determined from the base of the plant to an approximate level of the ends of the majority of the shoots. This avoided taking the heights of singular "rogue" twigs. In addition to these physical dimensions, a visual estimate was also made of the percentage of each plot covered by the three plants. These measurements were taken every 2 months in 2009 (February, April, June, August, October, December); and then in May and November of 2010.

3.4.3 Methods: Visual estimate of plot coverage of ground cover plants

This measure was an estimate of the proportion of the 2 m by 2 m plot which was covered by the ground cover plants so that the underlying sawdust was not visible. In 2009, hand-weeding was carried out prior to recording observations so that the visual estimate was not confounded by the presence of other plants.

As the sample size is not large, the data could be skewed. Skewness measures the tendency of the deviations to be larger in one direction than in the other. The skewness value can be positive or negative; it measures the asymmetry of the data distribution. Observations which are normally distributed should have skewness near zero. Table 3.1 illustrates the improvements to minimise skewness after appropriate data transformation. If data transformation improved skewness, then the transformed data set was used in analysis.

Table3.1 Assessment of data set skewness to determine best transformation, if necessary, on plot coverage by ground cover plants prior to ANOVA.

Data period	**Untransformed data skew value**	**Optimal transformation**	
		Type	Improved skew value
Feb 09	1.77	Natural log	0.22
Apr 09	1.15	Natural log	-0.10
Jun 09	0.89	Natural log	-0.04
Aug 09	0.73	Square root	0.20
Oct 09	0.98	Natural log	-0.35
Dec 09	0.07	n.a.; none better	n.a.; raw data used
May 10	-0.25	n.a.; none better	n.a.; raw data used
Nov 10	-0.76	n.a.; none better	n.a.; raw data used

3.4.4 Methods: Light quality under the ground cover foliage

The light quality within the environment under the ground cover foliage canopy was of interest from the weed control perspective as it determined whether the conditions would be conducive for weed seed germination under the ground cover plants. This was carried out twice, in June and November 2010. Light measurements were recorded using a LI-1000 data logger, manufactured by the Li-Cor company with input from a pair of Skye Instruments SKP2155 light sensors. The data recorder and light sensor bases were mounted on a wooden platform, and placed in an open-top box measuring 40 cm by 60 cm. The light sensors were mounted on flexible metal arms extending 55 cm out of the box, with the actual light sensitive area being a circular pad 3 mm in diameter at the end of the flexible metal arms. These sensors were able to detect the quantity of light at the wavelengths of 660 nm (red light), 730 nm (far-red light), as well as compute the ratio of red light against far-red light at any given instant.

At each plot, ambient light conditions were measured by placing the light sensors on the ground facing up and not in any shade. The sensors were then placed on the ground at the edge of the plant base and gently pushed inward under the plant as far as the sensors allowed without resistance from plant stems, sometimes lifting the metal arms slightly to avoid stem disturbance. This was generally a distance of 5-15 cm from the edge of the plant base. As there was minimal disturbance to the plant stems, foliage cover was maintained at normal density. As the light sensors were mounted on paired metal arms taped together near the ends, accidentally flipping the sensors upside-down could be avoided by ensuring that the paired arms did not rotate when held. Once the sensors were in place, the light readings were recorded in quick succession. For each plant, this process was repeated three times.

3.4.5 Methods: Weed germination in plots with established ground cover plants

The ground cover plants were deemed to be established 18 months after they were planted, and hand weeding was performed for the last time on 17 May 2010. The intent was to clear the plot of weeds, and then observe subsequent weed invasion in each plot. This period lasted 24 weeks from 18 May to 2 Nov 2010.

At the end of this period, all the weeds were harvested from each plot. Within each plot, the weeds were cut at ground level and bagged according to whether they were found growing in the uncovered spaces between ground cover plants, or had germinated through the ground cover plant foliage. The weeds were then dried in an 80^{o}C oven for 5 days, and the dry weed mass weighed and collated according to whether or not the weeds were growing within or between ground cover plants.

To ensure that the dry weed mass collected across the different plots are easily comparable despite differences in plant diameter and ground coverage, the dry weed mass results are expressed below in grams per square metre of open area and of area covered in ground cover. The total area within the plot under ground cover foliage was estimated assuming that the plants approximate an elliptical shape, and the minimum and maximum plant diameter measurements used accordingly. The difference between these elliptical area estimates and the plot size of 4 m^2 was assumed to be the estimate of open space within the plot not under ground cover foliage. For plots where the ground cover plant reached the plot boundaries, the area of open space within the plot, if any, were visually estimated with approximate measurements, and ground cover foliage area was the difference between 4 m^2 plot size and estimated open space.

3.4.6 Methods: Data Analysis

Statistical analysis on the data was performed using SAS 9.2. Analysis of variance was used to determine which plant species were significantly different to each other for the characters measured. To improve the fit of data to assumptions for ANOVA, data transformation was necessary at times (see Table 3.1).

3.5 Results

3.5.1 Results: Diameter of the plants

The 12 plant species varied widely in their rates of growth over the 2 years as seen from Tables 3.2 and 3.3. *P. capitata* was the fastest to spread across the 2m by 2m plots, doing so in about 4 months. Although it appeared that *P. capitata* was a promising ground cover species to use for rapid cover with lower planting density due to its fast growth, it was found to be extremely frost tender. An early frost in mid-April inflicted considerable damage with leaves curling up and becoming discoloured after one night's exposure. By the onset of winter in June, the plant was completely defoliated. Two other plant species also managed to cover the entire plot, albeit after one full year of growth, these being the *A. inermis* and *M. axillaris*. In contrast, *O. planiscapus* grew steadily for about 3 months, and then exhibited little change in size over the subsequent months.

S. mexicanum was notable for growing to a comparable size amongst the group within 6 months, despite starting with an initial plant area less than half that of other ground covers.

L. diffusa was another smaller plant in the group. However, this may have been due to the soil and climate being wetter than what is optimal for the drought-tolerant species. Over the course of 2 years, five *L. diffusa* plants died or suffered from root rot.

Table 3.2 Mean diameter (cm) of ground cover plants at 2 weeks, 3 months, 5 months, 7months and 9 months after planting (MAP). Column means sharing the same letter are not significantly different at p>0.05.

Species	Dec 08 0.5 MAP		Feb 09 3 MAP		Apr 09 5 MAP		Jun 09 7 MAP		Aug 09 9 MAP	
A. inermis	16.5	d	52.6	efg	80.9	b	102.1	b	120.9	a
A. reptans	32.5	b	82.8	b	88.7	b	83.9	cd	77.7	bc
C. acerosa	33.9	b	58.1	def	62.3	c	64.8	e	64.3	def
G. lanigera	31.2	b	71.0	c	86.2	b	93.9	bc	85.0	b
J. procumbens	42.9	a	65.0	cd	59.4	cd	71.1	e	65.3	de
L. diffusa	23.1	c	41.6	h	50.3	de	53.0	f	53.5	f
M. axillaris	14.7	d	46.6	gh	55.6	cd	73.6	de	67.6	cd
O. planiscapus	26.0	c	42.0	h	41.1	ef	48.7	f	44.3	g
P. capitata	25.6	c	119.9	a	157.6	a	142.9	a	123.2	a
P. prostrata	22.4	c	50.8	fg	64.5	c	69.4	e	68.2	cd
S. mexicanum	8.4	e	31.1	i	41.1	f	46.7	f	58.3	ef
V. peduncularis	25.0	c	59.7	de	63.4	c	69.1	e	86.1	b

Table 3.3 Mean diameter (cm) of ground cover plants at 11 months; 13 months; 18 months; and 24 months after planting (MAP). Column means sharing the same letter are not significantly different at p>0.05.

Species	Oct 09 11 MAP		Dec 09 13 MAP		May 10 18 MAP		Nov 10 24 MAP	
A. inermis	148.8	a	merged	n.a.	merged	n.a.	merged	n.a.
A. reptans	87.2	b	103.9	a	119.0	a	147.2	a
C. acerosa	76.4	bc	80.6	c	124.0	a	129.7	ab
G. lanigera	87.0	b	88.6	bc	125.0	a	133.8	ab
J. procumbens	72.2	cd	82.5	c	115.3	a	127.7	ab
L. diffusa	52.3	e	64.5	d	67.3	bc	85.9	d
M. axillaris	76.9	bc	merged	n.a.	merged	n.a.	merged	n.a.
O. planiscapus	46.2	f	56.0	d	51.1	c	51.6	e
P. capitata	141.2	a	merged	n.a.	merged	n.a.	merged	n.a.
P. prostrata	71.4	cd	76.9	c	105.1	a	123.9	bc
S. mexicanum	64.7	de	61.9	d	73.6	b	98.6	d
V. peduncularis	86.7	b	94.5	ab	111.1	a	105.2	cd

"merged" means the individual plant boundaries could no longer be determined, so size of a single plant could not be measured.

3.5.2 Results: Visual estimate of plot coverage of ground cover plants

The visual estimate of plot coverage by ground cover plants, presented in Tables 3.5 and 3.6 was related to the diameter of the plants, but took into account any overlapping which occurred at the plant edges.

In November 2010, some plants died, possibly from root rot due to the wet climate in the Manawatu region. All plants in Block 3 of *Persicaria capitata and Lithodora diffusa* suffered damage*;* two plants of *Grevillea lanigera in block 3;* one plant of *L. diffusa,* and two more plants of *G. langinera* in Block 2; and two more *G. lanigera* plants in Block 1. Block 3 was generally the wettest block in the trial area, with an area just outside of Block 3 subject to occasional ponding during wet weather. ANOVA was re-run on the November data after adjusting mean plot coverage to account for plant death by scaling up coverage of incomplete blocks and introducing missing values for blocks where all plants were dead in the plot. These adjustments are presented in Table 3.4 and 3.5.

P. capitata offered good coverage of 80% in 3 months after planting even at the planting distance 1 m apart (Table 3.4). It continued to build up to 90% plot coverage in 5 months before succumbing to defoliation due to frost tenderness in June, with a drastic drop to 36.7% coverage though some dead leaves still lingered. By August, it was just leaf-less stems which covered little more than 10% of the ground. *P. capitata* did not recover well from the frost shock. Plot coverage in Dec 2009 was only 40% and only improved to 60% by November 2010. The other two ground covers which achieved a good spread after one year, *A. inermis* and *M. axillaris* expectedly also showed good plot coverage. Of the two, *A. inermis* appeared to achieve a denser spread more rapidly than *M. axillaris.*

The smallest sized species, *O. planiscapus*, clearly set itself apart from the rest of the ground covers. It consistently covered the least ground for the duration of the trial (Tables 3.4 and 3.5). As it was the slowest growing, the species may be more suited for study over a longer time frame than afforded in this trial. The rest of the ground cover species chosen for this study proved to be mostly evergreen and did not vary much across the seasons.

Table 3.4 Plot coverage (%) by all ground cover plants within the plot at 3 months; 5 months; 7 months; 9 months; and 11 months after planting (MAP). Column means sharing the same letter are not significantly different at p>0.05.

Species	Feb 09 3 MAP		Apr 09 5 MAP		Jun 09 7 MAP		Aug 09 9 MAP		Oct 09 11 MAP	
A. inermis	35.0	bc	56.7	ab	60.0	a	81.7	a	89.6	a
A. reptans	46.7	b	51.7	bc	53.3	a	53.3	bc	55.2	b
C. acerosa	26.7	cdef	25.0	de	25.0	efg	31.7	de	38.1	bc
G. lanigera	33.3	bcd	45.0	bc	43.3	abc	45.0	bcd	39.4	bc
J. procumbens	25.0	cdef	23.3	de	21.7	fg	36.7	de	28.2	c
L. diffusa	23.3	def	21.7	e	20.0	g	31.7	de	31.5	c
M. axillaris	26.7	cde	33.3	cd	31.7	cde	43.3	bcd	56.5	b
O. planiscapus	18.3	f	20.0	e	20.0	fg	16.7	f	13.1	d
P. capitata	80.0	a	90.0	a	36.7	bcd	13.3	ef	28.2	c
P. prostrata	35.0	bc	35.0	cd	46.7	ab	45.0	bcd	41.6	bc
S. mexicanum	21.7	ef	21.7	e	28.3	def	38.3	cde	31.1	c
V. peduncularis	35.0	bc	43.3	bc	33.3	bcde	55.0	b	43.8	bc

Table 3.5 Plot coverage (%) by all ground cover plants within the plot at 13 months; 18 months; and 24 months after planting (MAP). Column means sharing the same letter are not significantly different at p>0.05.

Species	Dec 09 13 MAP		May 10 18 MAP		Nov 10 24 MAP		Nov 10 24 MAP adjusted	
A. inermis	95.0	a	99.7	a	99.7	a	99.7	a
A. reptans	78.3	abc	76.7	b	85.0	ab	85.0	ab
C. acerosa	58.3	bcde	76.7	b	76.7	abc	76.7	bc
G. lanigera	56.7	cde	70.0	bc	58.3	cd	88.0	ab
J. procumbens	35.0	de	66.7	bcd	71.7	bc	71.7	bc
L. diffusa	36.7	de	65.0	bcd	42.5	de	47.5	d
M. axillaris	88.3	ab	99.7	a	98.3	a	98.3	a
O. planiscapus	30.0	e	25.0	f	21.7	e	21.7	e
P. capitata	41.7	de	53.3	de	45.0	de	60.0	cd
P. prostrata	51.7	cde	63.3	bcde	63.3	bcd	63.3	cd
S. mexicanum	50.0	cde	50.0	e	67.5	bcd	67.5	c
V. peduncularis	65.0	abcd	60.0	cde	73.3	bc	73.3	bc

3.5.3 Results: Height of the plants

ANOVA for plant heights was performed on data transformed using the natural log to minimise data skewness, except for the Oct 09 data which were transformed using the square root function.

In general, the taller ground cover plants tended to be woody. Tables 3.6 and 3.7 show *C. acerosa, G. lanigera,* and even the conifer, *J. procumbens,* commonly thought to be more prostrate, to be taller.

Table 3.6 Mean height (cm) of ground cover plants at 3 months; 5 months; 7 months; and 9 months after planting (MAP). Column means sharing the same letter are not significantly different at p>0.05.

Species	Feb 09 3 MAP		Apr 09 5 MAP		Jun 09 7 MAP		Aug 09 9 MAP	
A. inermis	11.6	cde	9.8	cde	4.1	g	4.2	g
A. reptans	23.4	a	23.2	a	18.0	a	14.3	bc
C. acerosa	12.0	cde	9.9	cd	11.2	b	12.4	bc
G. lanigera	18.3	b	16.0	b	17.0	a	16.4	ab
J. procumbens	11.0	de	10.6	c	10.1	bc	12.2	bc
L. diffusa	11.2	cde	10.5	c	8.6	cd	9.2	de
M. axillaris	9.7	ef	8.3	def	6.8	ef	5.9	f
O. planiscapus	13.9	c	10.2	cd	6.7	ef	7.1	ef
P. capitata	10.3	def	5.0	g	6.2	ef	6.4	f
P. prostrata	10.9	de	7.9	f	5.7	f	6.8	f
S. mexicanum	9.1	f	8.4	ef	10.0	bcd	13.6	cd
V. peduncularis	12.1	cd	9.1	cdef	8.0	de	20.3	a

Ajuga reptans 'Caitlin's Giant' started as a rather tall, upright plant. However, as the plant established, the leaves grew steadily larger and weighed down the overall height of the plant.

Some species showed seasonal variation in height, being shorter in the cool season and taller when it got warm. These species were the *L. diffusa, V. peduncularis, O. planiscapus,* and *P. capitata.* With the *L. diffusa* and *V. peduncularis,* the taller stature in summer was associated with the more pronounced flowering stems. For *Persicaria capitata to* display seasonal height variation was not surprising, given its deciduous behaviour. The *Ophiopogon planiscapus* was very much a squat-statured plant, neither spreading far nor growing much taller once established.

Table 3.7 Mean height (cm) of ground cover plants at 11 months; 13 months; 18 months; and 24 months after planting (MAP). Column means sharing the same letter are not significantly different at p>0.05.

Species	Oct 09 11 MAP		Dec 09 13 MAP		May 10 18 MAP		Nov 10 24 MAP	
A. inermis	3.1	i	7.0	d	7.6	g	7.1	f
A. reptans	15.1	bc	16.9	a	15.8	cde	11.7	de
C. acerosa	11.3	de	20.9	a	26.0	b	29.0	a
G. lanigera	14.7	bcd	17.9	a	37.0	a	27.2	a
J. procumbens	11.9	cde	12.3	c	18.1	c	16.6	bc
L. diffusa	10.6	ef	13.8	bc	15.5	cde	19.2	b
M. axillaris	5.0	hi	6.9	d	10.7	f	12.8	de
O. planiscapus	7.3	fg	15.7	ab	12.3	ef	12.7	de
P. capitata	5.4	gh	7.6	d	13.7	def	11.2	e
P. prostrata	5.2	gh	9.0	d	14.3	cde	14.1	cd
S. mexicanum	18.1	ab	11.9	c	18.0	cd	18.2	b
V. peduncularis	20.4	a	17.3	a	13.8	def	20.6	b

Pimelea prostrata established well horizontally, and achieved a good spread as seen in Tables 3.2 and 3.3, but remained extremely prostrate in the first year. Although it grew taller in the second year, it remained a shorter plant in this group (Table 3.7).

Rabbits (*Oryctolagus cuniculus*) and pūkeko (*Porphyrio porphyria*), a native bird, caused some disturbance in the plots with their burrowing and pecking actions respectively. To discourage the animals, rabbit bait was placed near the plots, and low electrical fencing was installed around the experimental area. The pūkeko and rabbits were also shot from time to time. Despite these measures, the fauna caused sporadic damage, notably to S*edum mexicanum* due to its relatively soft and brittle stems. The plant heights for *Sedum mexicanum* therefore varied widely between damaged and undamaged plants. Its single best specimen height was of 28 cm, recorded in May 2010.

Apart from *P. capitata* which has already been described in this section, *A. inermis* and *M. axillaris* were the other two species which also carpeted the entire plots. In the first year after transplanting, both species settled down from an initial clumped height to a more prostrate habit. In the second year, the height of *A. inermis* remained stable, while *M. axillaris* grew taller than *A. inermis.*

3.5.4 Results: Visual estimate of canopy foliage density of ground cover plants

The visual estimate of foliage density was a subjective measurement but any errors arising due to subjectivity were lessened by there being only one assessor throughout. It was useful for estimating how much light may have got through to the ground.

Two of the species, *A. inermis* and *M. axillaris,* opened up slightly during winter of the first year (Table 3.8). This effect was particularly pronounced for *M. axillaris*. This was not observed in the second year. The remaining carpet-forming species, *P. capitata*, was badly damaged during the first frost after planting in the field, and did not recover well the rest of the year during the summer 12 months after planting (MAP). However, foliage density improved at 24 MAP.

For some of the species with showy flowering displays, such as *Sedum mexicanum, Veronica peduncularis,* and *Lithodora diffusa*, the flowering activity also gave the plants a more open foliage canopy, as space was formed to allow the flowering stems to position the flowers prominently in October and December (Table 3.9).

Table 3.8 Mean estimated foliage density (%) of individual ground cover plants at 3 months; 5 months; 7 months; and 9 months after planting (MAP). Column means sharing the same letter are not significantly different at p>0.05.

Height (cm) /Species	Feb 09 3 MAP		Apr 09 5 MAP		Jun 09 7 MAP		Aug 09 9 MAP	
A. inermis	98.3	ab	90.0	ab	77.8	cd	85.6	a
A. reptans	100.0	a	100.0	a	96.1	a	93.3	a
C. acerosa	77.8	d	76.7	cde	68.3	de	73.3	cd
G. lanigera	91.1	bc	83.3	bcd	91.1	ab	84.4	ab
J. procumbens	66.7	e	46.7	f	45.0	f	53.3	f
L. diffusa	76.1	d	72.5	de	65.6	de	66.1	de
M. axillaris	93.9	abc	90.0	ab	43.9	fg	67.2	de
O. planiscapus	75.6	d	67.2	e	60.0	e	62.8	ef
P. capitata	100.0	a	88.3	b	31.7	g	26.7	g
P. prostrata	95.0	abc	85.0	bc	82.8	bc	74.4	bcd
S. mexicanum	90.0	c	78.9	bcd	87.8	abc	86.7	a
V. peduncularis	90.6	bc	90.0	ab	87.8	abc	83.3	abc

The two woody species without showy flowers, *C. acerosa* and *J. procumbens,* had relatively sparse foliage density in the first year (Table 3.8). With more branches as it became established in the following year, *C. acerosa* and *J. procumbens* closed up their foliage canopy (Table 3.9).

Table 3.9 Mean estimated foliage density (%)of individual ground cover plants at 11 months; 13 months; 18 months; and 24 months after planting (MAP). Column means sharing the same letter are not significantly different at p>0.05.

Height (cm) /Species	**Oct 09; 11 MAP**		**Dec 09; 13 MAP**		**May 10; 18 MAP**		**Nov 10; 24 MAP**	
A. inermis	90.0	ab	100.0	a	98.3	a	100.0	a
A. reptans	95.0	a	100.0	a	100.0	a	98.3	a
C. acerosa	92.2	ab	91.1	abc	96.7	a	100.0	a
G. lanigera	91.1	ab	95.0	ab	93.3	a	82.5	b
J. procumbens	90.6	ab	88.3	bc	88.3	ab	96.7	a
L. diffusa	86.3	bc	68.0	ef	90.0	ab	80.0	bc
M. axillaris	87.2	bc	90.0	abc	98.3	a	98.3	a
O. planiscapus	67.8	e	62.8	f	90.6	ab	81.7	bc
P. capitata	16.7	f	38.9	g	38.3	c	95.0	a
P. prostrata	81.7	cd	81.1	cd	78.3	b	95.7	a
S. mexicanum	85.6	bc	75.6	de	97.8	a	81.7	bc
V. peduncularis	78.3	d	86.7	bc	91.1	ab	76.7	c

Another species which displayed seasonal variation in canopy foliage density was the *P. prostrata*. This plant had a visibly sparser canopy in the cool seasons (Table 3.8), but developed more leaves when it got warmer (Table 3.9).

The rosette-forming *O. planiscapus* did not form a very dense foliage canopy when it was smaller (Table 3.8). The monocot plant had long lanceolate leaves cascading down the edges from a central stem. When the plant was young, the leaf tips tended to splay at the edge of the canopy and appeared open from the sides. As the plant matured in the second year (Table 3.9) and runners established plantlets around the mother plant, the interlocking foliage projected a denser appearance of the foliage canopy.

Two species which maintained a dense foliage canopy throughout were *A. reptans* and *G. lanigera* (Tables 3.8 and 3.9). The large elliptic leaves of *A. reptans* overlapped in layers, with little visible break in cover. *G. lanigera* possessed tightly interlocking leaves on numerous branching stems. Only the slight gaps at the terminal stem portions of *G. lanigera* lowered the score compared to *A. reptans*.

3.5.5 Results: Light quality under ground cover foliage

The presence of ground cover plants drastically reduced the amount of ambient sunshine that reached the ground where they were planted.

During early winter, the leaves of the deciduous *P. capitata* had begun to turn brown or got shed which explained the lowest light blockage at 71.1% of visible light (400-700 nm) (Table 3.10). The darkest under-foliage environment was found under *J. procumbens* canopy where more than 98% of visible light was blocked. The other plant species blocked out light to varying degrees between these two extremes.

When it came to blocking red light (660 nm) however, nearly all plants performed equally well. More than 96% of red light was blocked from passing through the foliage canopy of all species except for *P. capitata* which only managed to block 78% of red light, because its leaves were starting to die back. The larger woody plant species of *C. acerosa, G. lanigera,* and *J. procumbens* was most effective in blocking out far-red light, with over 96% reduction (Table 3.10).

Table 3.10 Mean reduction (%) of red, far-red and total light through foliage canopy in June 2010, and the mean ratio of red to far-red light (R:FR) . Column means sharing the same letter are not significantly different at p>0.05.

Species	Visible light reduction (%) (400-700nm)		Red light (R) reduction (%) (660nm)		Far-red light (FR) reduction (%) (730nm)		R:FR	
A. inermis	79.2	de	97.7	a	93.7	ab	0.287	de
A. reptans	88.7	abcd	99.4	a	89.5	abc	0.089	f
C. acerosa	96.5	ab	99.2	a	96.4	ab	0.137	ef
G. lanigera	96.3	ab	99.2	a	97.9	a	0.328	d
J. procumbens	98.2	a	99.9	a	97.9	a	0.223	def
L. diffusa	96.1	ab	96.8	a	93.9	ab	0.868	b
M. axillaris	81.8	cde	97.5	a	86.5	bc	0.199	def
O. planiscapus	80.2	de	98.4	a	82.7	cd	0.182	def
P. capitata	71.1	e	78.1	b	75.3	d	1.268	a
P. prostrata	92.9	abc	96.6	a	92.0	abc	0.586	c
S. mexicanum	93.2	abc	98.8	a	94.8	ab	0.065	f
V. peduncularis	86.0	bcd	97.9	a	88.2	abc	0.265	de
Mean ambient light (μmol $m^{-2}s^{-1}$)	3.70		2.60		9.52		1.74	

Overall, ground cover plants significantly reduced the red to far-red light ratio (R:FR) from an average of 1.735 in the ambient light. Even *P. capitata* which produced the least changed R:FR of 1.268 had a significantly reduced result. The R: FR ANOVA groups in Tables 3.10 and 3.11 were derived from square root transformed data.

During summer, the light blocking ability of some species had changed. Table 3.11 shows that *P. capitata* managed to block out more than 83% of visible light from under its canopy now that some leaves had grown, compared to 71% in winter. In contrast *O. planiscapus* allowed more light to reach the ground in summer, with only a 79% reduction in visible light. All other species blocked out more than 91% of visible light.

Despite the variability in blocking visible light, all ground cover species studied reduced red light by more than 92%. The deciduous *P. capitata* was again the worst red light blocker, but the ground cover species *A. inermis* and *M. axillaris* both blocked out virtually all (above 99%) red light, as did the larger *A. reptans, C. acerosa,* and *J. procumbens* (Table 3.11). Far-red light was also blocked out by ground cover plants in summer, with a minimum reduction of more than 82%. The greatest reductions of over 98% were achieved by the species *A. inermis* and *M. axillaris*, together with *J. procumbens* and *L. diffusa*.

Table 3.11 Mean reduction (%) of red, far-red and total light through foliage canopy in Nov 2010, and the mean ratio of red to far-red light (R:FR). Column means sharing the same letter are not significantly different at p>0.05.

Species	Visible light reduction (%) (400-700nm)		Red light (R) reduction (%) (660nm)		Far-red light (FR) reduction (%) (730nm)		R:FR	
A. inermis	96.7	ab	99.9	a	99.1	a	0.164	f
A. reptans	92.6	ab	99.5	a	82.2	d	0.117	f
C. acerosa	96.8	ab	99.5	a	96.5	ab	0.184	ef
G. lanigera	92.8	ab	97.3	abc	95.3	ab	0.970	a
J. procumbens	99.0	a	99.9	a	99.7	a	0.128	f
L. diffusa	98.8	a	98.9	ab	98.4	a	0.679	bc
M. axillaris	97.9	ab	99.8	a	99.1	a	0.122	f
O. planiscapus	79.1	c	97.4	abc	86.3	cd	0.212	ef
P. capitata	83.7	c	92.4	d	82.3	d	0.504	cd
P. prostrata	91.3	b	95.0	cd	93.5	abc	0.469	cd
S. mexicanum	93.4	ab	95.4	bcd	89.0	bcd	0.779	ab
V. peduncularis	92.2	ab	97.3	abc	94.4	ab	0.384	de
Mean ambient light (µmol $m^{-2}s^{-1}$)	88.5		45.5		32.6		1.5	

At the other end of the scale, less far-red light was blocked by *A. reptans, O. planiscapus, P. capitata,* and *S. mexicanum*. In general, the various species blocked out far-red light to varying extent, but far-red light was less well blocked out than red light.

For four of the ground cover species, the R:FR in November (Table 3.11) was significantly different from June (Table 3.10) as determined by a paired t-test at p = 0.05. These are *G. lanigera* (higher in Nov)*, P. capitata* (lower in Nov)*, S. mexicanum* (higher in Nov)*,* and *V. peduncularis* (higher in Nov). *P. capitata* had lower R:FR in Nov because it was deciduous and shed most of its leaves in winter (Jun). The other three species had higher R:FR in Nov because they were flowering and the canopy had spaces occupied by flowers instead of leaves.

3.5.6 Results: Mean dry mass of weeds growing within each plot and under ground cover foliage

In most cases, more weeds were found growing in the space not occupied by ground cover plants than growing through the foliage canopy of ground cover plants (Table 3.12). However, with *O. planiscapus* (Table 3.12), there was more weed mass found growing through the foliage than in spaces between plants. A closer examination of the weed species collected from *O. planiscapus* plots revealed that a vast majority of the weed mass was from the perennial weed *Oxalis corniculata*. This weed was persistently found in *O. planiscapus* plots throughout the trial despite efforts at handweeding.

The presence of the perennial weed was mostly an artefact from nursery conditions, as no other plots were infected with *Oxalis corniculata.* Fortunately, one plot was not affected and the dry weed mass collected was 1.541 g m^{-2} which ranks its weed deterrence performance in the middle of the group. This figure is not used in the ANOVA as there were no valid replicates.

Four ground cover species resisted weed invasion through its growing space very well, allowing less than 0.05 g m^{-2} of weed growth. They were: *A. inermis, C. acerosa, M. axillaris,* and *S. mexicanum.* A fifth species, *A. reptans* was next best with only 0.3 g m^{-2} of dry weed mass within its canopy (Table 3.12).

The amount of weeds collected from open ground spaces within the plots indicated that the trial plots experienced high weed pressure from surrounding bush. The vast difference between weeds found within the ground cover canopy and on open space hints at the weed quantity which had been avoided by planting the ground cover species (Table 3.12). The weed species present are listed in Table 3.13. Many had wind-blown seeds, which germinated on top of the mulch. In some areas, the mulch had also thinned out due to weathering or animal disturbance. Plots of the sprawling species *A. inermis,* had lower dry weed mass in open spaces due to the small spaces in those plots without any ground cover. For *M. axillaris*, plot coverage was virtually complete and trimming was necessary to prevent invasion of neighbouring plots. With *P. capitata*, the locations of the weeds were amongst the stem network and were considered to be within space occupied by the plant even though there was little foliage.

Table 3.12 Mean dry mass of weeds growing from 18 May – 2 Nov 2010 both within and out of ground cover canopy and mean R: FR in June and November, by species. Column means sharing the same letter are not significantly different at p>0.05.

Species	Mean weed mass (g m^{-2})			
	Under foliage		Open ground	
A. inermis	0.026	b	5.5	b
A. reptans	0.303	ab	65.3	ab
C. acerosa	0.041	b	16.5	b
G. lanigera	2.519	ab	9.1	ab
J. procumbens	3.145	ab	93.9	ab
L. diffusa	4.154	ab	75.0	ab
M. axillaris	0.017	b	n.a.	n.a.
O. planiscapus	*43.13**	n.a.	*9.11*	ab
P. capitata	8.198	a	n.a.	n.a.
P. prostrata	2.662	ab	45.1	ab
S. mexicanum	0.000	b	45.0	ab
V. peduncularis	2.578	ab	292.1	a
Overall	2.1		67.5	

*Not included in ANOVA.

The weeds which were found within the ground cover foliage are shown in Table 3.13 in order from most common to least. The most common weeds have wind-blown seeds. *Conium maculatum* and *Trifolium repens* do not have wind-blown seeds, however, these plants were common nearby.

Table 3.13 Weeds found growing within the ground cover plant canopy in November 2010, with the most common listed first.

Botanical name	***Common name***	***Count***
Holcus lanatus	Yorkshire fog	15
Crepis capillaris	Hawksbeard	12
Ehrharta erecta	Veld grass	5
Sonchus asper	Prickly sow thistle	3
Sonchus oleraceus	Sow thistle	3
Oxalis corniculata	Horned oxalis	3
Conium maculatum	Hemlock	2
Trifolium repens	White clover	1
Taraxacum officinale	Dandelion	1

3.6 Discussion

In general, the presence of ground cover plants greatly reduced weed invasion as opposed to leaving the soil bare. Although ground cover plants are not totally guaranteed to prevent weeds establishing, average figures in Table 3.12 across all plots showed that leaving the soil bare resulted in over 30 times more weeds than when ground cover plants were present.

The five best performing species of ground cover plants which resisted weed invasion best were *A. inermis, C. acerosa, M. axillaris, S. mexicanum*, and *A. reptans*. These species varied widely in terms of spread and height, suggesting that the physical dimensions of the ground cover species used were of no great importance in determining resistance to weed establishment.

Due to the presence of thick sawdust mulch, the weed species which germinated amongst the ground cover foliage were mainly species with wind-blown seeds which landed on top of the mulch. Weed seeds in the soil bank would have been prevented from germinating by the mulch. Most of these weed species have also been documented as being sensitive to light for germination (*Conium maculatum* (Baskin & Baskin 1990); *Crepis sp.* (Darwent & McKenzie 1978); *Holcus lanatus* (Williams 1983); *Sonchus asper, Sonchus oleraceus* and *Taraxacum officinale* (Milberg et al. 2000)) except for *Trifolium repens* which germinates in any light conditions; and *Oxalis corniculata* which has very low light requirements for germination (Holt 1987). However, as *Trifolium repens* is less likely to be disseminated by seed carried in the wind, there was only one incidence of *T. repens*.

As discussed in the literature review, response to light conditions for seed germination is mediated by the ratio of red to far-red light (R: FR). It may be expected that the R:FR for the five best performing species to be relatively low, so as to inhibit weed seeds with a light requirement for germination. A comparison of R: FR in November with the mean weed mass collected in the plots for the species *A. inermis, A. reptans, C. acerosa, and M. axillaris* in Table 3.14 shows that indeed to be the case. However, for *S. mexicanum*, the R:FR in November was the second highest in the list. This suggests that the R:FR in November was not necessarily a good predictor for weed suppression. This is because the weeds collected in November would have germinated in preceding weeks or months.

To explain the relative success of those five species of ground covers in weed suppression, one needs to examine the R:FR of an earlier time frame, such as that in June. Table 3.14 shows that the R:FR in June for three of the better weed suppressing ground cover species in the trial, namely *A. reptans, C. acerosa and S. mexicanum,* were amongst the lowest in the trial group. This suggests that ground cover species which maintained a dense canopy of live foliage in winter performed best in suppressing weeds in spring.

Table 3.14 Comparison between mean weed mass and recorded R:FR.

Species	Mean weed mass (g m^{-2})				Ratio of red to far red light (R:FR) under canopy			
	Under foliage		Open ground		Jun 10 Mean		Nov 10 Mean	
A. inermis	0.026	b	5.5	b	0.287	de	0.164	f
A. reptans	0.303	ab	65.3	ab	0.089	f	0.117	f
C. acerosa	0.041	b	16.5	b	0.137	ef	0.184	ef
G. lanigera	2.519	ab	9.1	ab	0.328	d	0.970*	a
J. procumbens	3.145	ab	93.9	ab	0.223	def	0.128	f
L. diffusa	4.154	ab	75.0	ab	0.868	b	0.679	bc
M. axillaris	0.017	b	n.a.	n.a.	0.199	def	0.122	f
O. planiscapus	1.541	ab	27.3	ab	0.182	def	0.212	ef
P. capitata	8.198	a	n.a.	n.a.	1.268	a	0.504*	cd
P. prostrata	2.662	ab	45.1	ab	0.586	c	0.469	cd
S. mexicanum	0.000	b	45.0	ab	0.065	f	0.779*	ab
V. peduncularis	2.578	ab	292.1	a	0.265	de	0.384*	de

*Means are significantly different from June 2010 readings using paired t-test at 5% critical level.

An exception to the above statement is for *A. inermis* and *M. axillaris*, which had a higher R: FR in June but yet managed to resist weed invasion admirably. *A. inermis* and *M. axillaris* both had an R: FR level in June similar to that of *G. lanigera*, *J. procumbens, O. planiscapus* and *V. peduncularis*, which had a mean weed mass of about 1.5-3.1 g m^{-2}. A possible reason for the better than expected weed resistance by *A. inermis* and *M. axillaris* is that blocking of light was not the sole factor which resulted in resilience against weed. The extensively sprawling growth habit for these two species, which root regularly at stem nodes, may represent considerable competition against weed seedlings that do germinate for growth resources found underground. As pointed out in the literature review, multiple resources under strong competition results in synergistic effects for the more aggressive species (Donald 1958).

A sprawling network of rooting stems is not sufficient to compensate for poor R: FR reduction in resisting weeds. *P. capitata* has a similar habit and spread across the allowed space within the plot in a matter of 3-4 months. However, it had the worst weed suppressing performance, allowing 8.2 g m^{-2} of mean weed dry mass. This amount of weed mass was similar to the weeds collected in the open space of some plots. The dismal performance of *P. capitata* in preventing weed invasion can be attributed to the loss of foliage during cooler months, which meant that red light could not be blocked by the leaves, allowing seed dormancy to be broken. Given the variable amounts of weed invasion in open ground conditions, ground cover plants with a deciduous habit can be considered to produce a level of weediness akin to no ground cover planting during the period after defoliation.

Deciduous habits are not the only seasonal trait which can affect light blocking and R: FR variations under the ground cover foliage canopy. The summer-time flowering of *G. lanigera, S. mexicanum,* and *V. peduncularis* caused significant rises in the R: FR in November from June. The transmission of red light through *S. mexicanum* canopy nearly quadrupled from 1.2% in June to 4.6% in November, and may be expected to increase further later into the summer season. This was due to the plant producing flowering stems with less or smaller leaves, thus reducing the available surface area with red-light absorbing pigments (see Figures 3.15 - 3.17). Red light has a stimulatory effect in seeds with light requirements for germination. Despite *S. mexicanum* showing good weed suppression in results collected in November, this performance is unlikely to be repeated in late summer as the high R: FR in November suggests that weed seed germination will not be inhibited in the weeks through summer. Similarly, in the case of *G. lanigera* and *V. peduncularis*, the flowering period led to more red light penetration through its canopy. This may be due to overall reduction in red-light absorbing surface area as the plant positions its flowers in a conspicuous manner which may cause gaps in the foliage canopy. This leads to higher R:FR, and Table 3.14 shows that

G. lanigera had a 0.97 R:FR in November compared to 0.328 in June; similarly for *V. peduncularis*, the R:FR increased from 0.265 in June to 0.384 in November .

Figure 3.15 (left) Top view of *Sedum mexicanum* in vegetative state
Figure 3.16 (middle) Top view of *Sedum mexicanum* in flowering state
Figure 3.17 (right) Sample flowering stem on left side, placed next to sample vegetative stem on right side. Note the tighter whorled foliage on the vegetative stem on right side

Some plant species become relatively dormant during the cooler months. This seemed to be the case for *P. prostrata* and *L. diffusa*, where the overall visible light penetration was greater in June than in November. With *P. prostrata*, the foliage was visibly reduced during the cooler months as noted in Tables 3.9 and 3.10. Visual ratings for foliage density of *L. diffusa* may have been less consistent as this drought tolerant species struggled with root rot or excessive moisture during the trial. This opening up of the canopy would have contributed to the higher R: FR in June 2010 than November 2010.

There was some difficulty encountered when assessing the mean weed mass for the *J. procumbens* plots. Despite consistently high readings of light blockage and one of the lower R: FR measured, there was still considerable weed mass collected from *J. procumbens* plots. This is attributed to the irregular shape and plant margins of the species, which made assessment of which weeds constituted “open space” or “under foliage” positions difficult. The weeds considered to be found “under foliage” were mostly near the plant margins and may have germinated in relatively unshaded conditions.

Overall, weed suppression by ground cover plants appeared to be dependent on maintaining a dense foliage canopy capable of greatly reducing red light penetration to achieve low R:FR conditions which inhibit germination from species with a light requirement for germination. The ideal ground cover plant should therefore be an evergreen perennial with dense foliage not given to seasonal variation for dormant growth periods or reproductive phases. Where a dense foliage canopy cannot be maintained, additional competitive traits for growth resources other than light, such as having an extensive rooting system just below the soil surface, will be an advantage.

Chapter 4 Comparing canopy covers of established ground cover species

4.1 Introduction

The previous chapter described observations of young ground cover plants establishing in field plots over a period of two years. It might be expected that the vigour of established plants may add slight advantage to the performance of these ground cover plants. This chapter identifies 14 ground cover populations well established in their respective sites at the time of this project and follows them over a period of one year to determine if ground cover afforded by these mature plants can be maintained throughout the year.

4.2 Objectives

The objective was to determine if well-maintained mature ground cover plants could provide dense cover throughout the year in Palmerston North, and if species differences produced varying effects in this regard.

4.3 Sites monitored and species introduction

Established populations of ground cover plants were identified around Massey University at ten sites and four sites around Palmerston North city were also included.

The ground cover populations selected at sites around Massey University were:

1. Dwarf variety of *Agapanthus x hybrid*; at Bernard Chambers car park, planting beds next to Lots 32, 45, 60.
2. *Ajuga reptans*; at corner of Computer Services Building facing main bus terminal;
3. *Cotyledon orbiculata* var. *oblonga*; at corner of Sir Geoffrey Peren Building facing Business Studies Central Building;
4. *Gazania rigens*; at plant bed between Totara Hall and Halls Communal Building, quadrats placed near three pillars.
5. *Hebe chathamica*; at plant bed next to main entrance of Sir Geoffrey Peren building near HR building.
6. *Hedera helix*; along the stretch of University Avenue between lanes leading to Green Bike hub and the Veterinary Farm and Equine Centre.
7. *Juniperus chinensis*; at the side of the Oval lawn just outside Tiritea House (former VC residence).

8. *Pimelea prostrata*; *o*utside the Landcare Research Building, around the signboard and planting bed next to car park lots at the entrance.
9. *Plectranthus ciliatus*; under the large fir tree in the sunken gardens along footpath leading to HR buildings.
10. *Viola sororia*; around the Wharerata lawn, near footpath leading to Fern Walk.

The ground cover populations selected in Palmerston North City were:

1. *Coprosma kirkii*; at Palmerston North Convention Centre car park lot dividers.
2. *Grevillea lanigera*; at location as above.
3. *Muehlenbeckia axillaris*; at plant bed along the fence of 67 Malden Street.
4. *Juniperus procumbens*; at plant bed along the fence of 84 Armstrong Street.

Agapanthus sp. is a monotypic genus in the family Agapanthaceae. It is a herbaceous monocotyledonous plant which was formerly allied to the Liliaceae in the Cronquist system; and also the Alliaceae in the Dahlgren system. The most common species in New Zealand is the South African native *Agapanthus x hybrid* but the species has been declared a noxious weed in the Auckland region in 2006, and banned from sale and trade, though its dwarf cultivars are not affected. Biosecurity New Zealand has been lobbying for it to be included in the National Plant Pest Accord since 2006 to ban sale and trade of all forms and cultivars (Thompson 2006; Williams & Thompson 2006) but the plant is currently still on a restricted list under surveillance. The plant is tolerant of a wide range of growing conditions, and also seeds prolifically in addition to rhizomatous spread. It therefore poses a risk to indigenous species by forming pure stands quickly and overwhelming the habitat with its presence. The population monitored here is an evergreen dwarf hybrid with variegated foliage and blue flowers of unknown variety name, and will be referred to as *Agapanthus x hybrid* (Figure 4.1). The strappy leaves are about 30 cm long and grow in a clump, arching over the ground. Flowers are formed in rounded umbelliferous inflorescences.

Ajuga reptans is a rhizomatous and stoloniferous herbaceous plant which was previously introduced in Chapter 3. The population monitored here is the regular-sized species with purple-tinged obovate leaves about 8cm long by 5 cm wide growing in a clump. Woodchip mulch was also present in the bed.

Cotyledon orbiculata var. *oblonga* (Figure 4.2) is another South African native which is a herbaceous succulent plant from the Crassulaceae family. The variety *oblonga* differs from the species in having long finger-shaped leaves rather than the round-leaved form commonly known as ‘Pig’s ears’. Indeed, a popular cultivar of *Cotyledon orbiculata* var. *oblonga* is known as ‘Grey Fingers’

(Rowley 2007). It also has various medicinal properties ascribed to it, among them the ability to cure boils, toothaches, warts and corns, flu, and diarrhoea (Arnold & Killick 2002; Calabria et al. 2008; Aremu et al. 2010). The monitored population had a decumbent to suberect form of inversely-lanceolate leaves about 12-15 cm long, 15-25 mm wide, and 6-8 mm thick, densely packed in a clump. The soil surface was filled with leaf litter.

The *Coprosma* genus was introduced in the previous chapter; the species being monitored here is the semi-woody *Coprosma kirkii* (Figure 4.3). This species is a low-growing shrub about 0.75m tall with good horizontal spread of up to 2m. It grows best in sandy soil and tolerates salt spray if grown on the coast. It has small narrowly obovate to lanceolate leaves about 15-20 mm long and 5 mm wide. Woodchip mulch was also present at the site. Leaves may also be variegated with white margins (Kirsten 2001).

Figures 4.1, 4.2, 4.3 (L-R) Agapanthus x hybrid; Cotyledon orbiculata var oblonga; Coprosma kirkii

Gazania rigens (Figure 4.4) is also originally from southern Africa and is a member of the Asteraceae. There are approximately 16 species and many more hybrids. *Gazania rigens* var *leucolaena* is a herbaceous plant with a trailing habit with greyish lanceolate basal leaves and bright yellow flowers which is used as a ground cover plant (Tenenbaum et al. 2001). The population monitored was of mixed hybrids in various flower colours with woodchip mulch applied in the bed. Leaf size was about 7-8 cm long and 1 cm wide.

The semi-woody shrub *Grevillea lanigera* was introduced in Chapter 3 and will not be repeated here. The plants had narrowly oblong leaves with margins slightly rolled under, about 10 mm long and 3 mm wide.

Hebe chathamica (Figure 4.5) is a small herbaceous New Zealand native that scrambles across the ground. The genus *Hebe* had been subsumed under genus *Veronica* for nearly two centuries despite the first described species *H. magellanica* in 1789 by Jussieu (Bayly & Kellow 2006). It was not until 1926 that the Royal Society of New Zealand recognised *Hebe* to be distinct from *Veronica.* In 1985, the genus *Hebe* was officially recognised in the UK with the setting up of the Hebe Society in London. *Hebe* differs from *Veronica* in being evergreen shrubs (as opposed to deciduous and herbaceous *Veronica* species), have seed pods which split horizontally and have a higher chromosome count than Veronica (Chalk 1988).

The founding of the Hebe Society honoured the diversity and beauty of New Zealand's largest genus of flowering plants, containing more than 100 species (Metcalf 2006). The genus *Hebe* is distributed across the New Zealand region, including its offshore islands. *H. chathamica* is one of three *Hebe* species which are endemic to the Chatham Islands. Only three *Hebe* species are not found in New Zealand; and some species in Australia and Papua New Guinea have now been renamed the *Derwentia*, *Parahebe* and *Detzneria* genera (Metcalf 2006).

Hebe chathamica is a low evergreen herbaceous shrub up to 0.25 m tall with a prostrate and mat-like habit measuring up to 1.2 m across. It is native to the coastal cliffs of Chatham Islands and surrounding islets. It flowers from early summer, forming racemes with petals which are initially violet but fading to white during senescence (Chalk 1988; Metcalf 2006). The ovate-oblong leaves in the monitored population were about 20-30 mm long and 8 mm wide, and there was woodchip mulch at the site.

Hedera helix (Figure 4.6) is a well-known ornamental vine common in many English gardens and also widely used in New Zealand. It is most familiar in its vegetative juvenile form when the leaves possess 3 to 5 lobes. When mature, leaves are ovate to rhombic in shape. Unfortunately, the species is invasive in many areas due to its stoloniferous ability to form a thick mat which hinders seed germination and climb up trees and smother tree canopies (Harrison 2006; Ingham 2009).

Figures 4.4, 4.5, 4.6 (L-R) Gazania rigens hybrids; Hebe chathamica; Hedera helix

As a result, hundreds of cultivars have been developed in an attempt to curb its vigorous growth while retaining its evergreen ornamental properties. It is unclear if the plant monitored at Massey University was one such cultivar. Fish (1970) lists more than 50 known forms. The population at Massey University had 3-lobed leaves with entire margins, measuring 9-10 cm in both length and width. The ground beneath the plants was always filled with leaf litter.

Juniperus sp. differs from the other ground cover species discussed so far in being a slower-growing woody shrub. As a relatively slow growing woody plant, junipers lend a sense of permanence and stability to the landscape as its effect is not easily accomplished within months as with annual plants. This sense of permanence lends it a stature which is compatible next to stone or pavers to aesthetically soften the look. Most require well-drained soil in full sun (Cox & Machin 2008). There are several species of *Juniperus* which have a prostrate form and a horizontally spreading growth habit suitable for use as ground covers. Examples include *J. communis,* which has silvery undersides; *J. conferta* which grows in sandy soil and is salt tolerant; *J. horizontalis* which is very flat (rarely more than 15 cm tall) with blue grey foliage tolerates heavy to sandy soils; *J. procumbens; J. sabina,* is actually a small shrubby tree usually about 2-3 m tall; *J. squamata* which is bluish-green and slow growing, and sometimes develops an irregular conical crown despite its prostrate habit; and *J. chinensis* which can grow up to 0.5 m tall (Michener & Sinton 2002). The population monitored at Massey University was *J. chinensis* (Figure 4.7); and the one in town area was *J. procumbens*. The *J. chinensis* monitored at Massey University had leaves arranged in 3 or 4 ranks with the final rank of needles measuring about 7 cm long by 3 cm wide. The soil beneath the plants was filled with leaf litter.

J. procumbens, Muehlenbeckia axillaris and *Pimelea prostrata* were introduced in Chapter 3 and will not be repeated here. The needles of the *J. procumbens* in the city were sharply pointed in groups of three measuring 20-30 mm long and 5 mm wide each. Bark mulch was present onsite. The *M. axillaris* had broadly ovate to rounded leaves measuring 5-6 mm in both length and width; with bark mulch and gravel beneath the plants. The *P. prostrata* had elliptic leaves about 5-6 mm long and about 1.5 mm wide; and the area around the plants was mulched with woodchip.

The *Plectranthus* genus is a major member of the Lamiaceae family, consisting of about 300 species spanning across most tropical regions in Africa, Australia and Asia. Like other members of the Lamiaceae family, it is also odoriferous (Lukhoba et al. 2006). The *Plectranthus* genus is widely used in the landscape for its striking foliage which may combine green, purple, and white in variegated patterns or show up on underside of leaves and leaf ribs (Armitage 2004). *Plectranthus ciliatus* (Figure 4.8) is a herbaceous perennial plant that usually grows to about 30 cm high, and does well in semi-shade conditions. The leaves are obovate about 9 cm by 5 cm. The undersides of the foliage are an attractive deep maroon, and the stems also root easily when in contact with soil, though stem cuttings are another option for propagation. It prefers rich soil which is slightly acid, and will flower in autumn giving a white and lilac display (Kirsten 2003). It is also listed as an unwanted organism established in New Zealand in the National Plant Pest Accord, because it can get weedy in native bush areas. The monitored plants had ovate leaves with toothed margins measuring about 12 cm long and 8 cm across; and the ground beneath was filled with leaf litter.

Figures 4.7, 4.8, 4.9 (L-R) Juniperus chinensis; **Plectranthus ciliatus**; **Viola sororia**

The *Viola* genus is one of the most popular ornamental plants for the garden found throughout the world. The genus is large with about 500 species and many more cultivars. The plants are herbaceous and its members include both annuals and perennials. Their popularity lies in the colourful petals, sometimes prized for their intricate and interesting markings. In addition, they are not too difficult to grow provided moist and well-drained soil is available. *V. sororia* (Figure 4.9) is a rhizomatous mat-forming low-growing perennial plant about 15 cm tall, which flowers in spring. It is able to grow in full sun and semi-shaded areas. Numerous cultivars have been developed with flower colours ranging from blue- or red-hued violets to white, and specks or vein markings may be prominent on the petals (Grey-Wilson 2009). The cordate leaves of the monitored population ranged from 6-8 cm in length and width.

4.4 Methods

At each site a quadrat enclosing 0.1 m^2 was applied on three positions suitable for the placement and reach of light sensors and data logger. The quadrats were positioned so that reasonably dense foliage filled up the entire area of the quadrat. The positions of these quadrats were marked so that return visits were monitored at the same three spots at each site.

The observations taken monthly at each quadrat position were the percentage ground coverage of the plant within the quadrat as estimated visually; height of the ground cover plant in centimetres; the number of weeds found within the area of the quadrat; the identification of the weed; and the light quality under the ground cover foliage at three random spots within the quadrat. The light quality observations comprised the amount of visible light within the wavelength range of 400-700 nm; red light of 660 nm wavelength; and far-red light of 730 nm wavelength. The quantum of these light readings was in units of $\mu molm^{-2}s^{-1}$. The transmission of visible light, red light and far red light were expressed as a percentage of the ambient levels of the respective light readings.

The sensor also recorded the ratio of red to far-red light (R:FR). If weeds were observed within the quadrat, the same light quality measurements were also recorded at the spot where the weed was growing. Weeds observed were removed after the current observation visit, so that only new weeds would be observed in the following visit.

The observation visits took place within the last 5 days of each month. This ensured that the observations took place at about the same time after the scheduled maintenance, which tended to occur in the first half of the month at the sites in town.

4.5 Results

4.5.1 Result data by species over one year

In the following pages data collected from each individual species is presented. Tables are presented which contain data on the visually estimated percentage ground coverage; estimated plant height; the percentage transmission of visible light; transmission of red light; and transmission of far-red light. Light quality as measured by R:FR are presented as a line graph, and any weeds found are listed separately in a table, and the R:FR associated with the weed's location have been plotted on the same graph.

4.5.1a Data from *Agapanthus x hybrid* population

The *Agapanthus x hybrid* is an evergreen which maintained its dense foliage throughout the year (Table 4.1). The slight reduction in height at year end was due to the thinning out of foliage by gardeners. The spike in light transmission in Table 4.1 in January and June was due to higher cloud cover causing a more diffuse ambient light environment. Cloud cover seemingly created multiple sources of weaker sunlight, enabling the diffuse light to reach areas which may have been otherwise shielded from direct overhead sunlight. It is noteworthy that red light transmission was only about a third or less of visible light, which attests to the strong absorbance by chlorophyll and carotenoid pigments by the plant. On the other hand, far-red light was much less strongly absorbed by the foliage. The R:FR was also kept below 0.25 for most parts of the year (Figure 4.10), and few weeds were detected within the quadrat areas sampled. Weeds were found in spots where the R:FR was above 0.3, higher than what was normally found under the foliage canopy. This made seed germination possible, but it was hard to determine if the seeds were from the soil bank or wind-blown, which may have been possible for the species identified (Table 4.2).

Table 4.1 Estimated ground coverage; plant height; mean visible light (400-700 nm) transmission; mean red light (660 nm) transmission; and mean far-red light (730 nm) transmission; in *Agapanthus x hybrid* over one year.

Month	Jan	Feb	Mar	Apr	May	Jun
Estimated ground coverage (%)	95	95	100	100	100	100
Estimated height (cm)	30.0	30.3	30.0	28.7	30.7	34.0
Mean visible light transmission (%) with standard error	14.0 ±5.0	2.98 ±2.34	3.22 ±1.80	1.17 ±0.38	0.80 ±0.40	6.50 ±3.22
Mean red light transmission (%) with standard error	4.17 ±1.63	0.0146 ±0.0052	0.136 ±0.056	0.121 ±0.035	0.0652 ±0.0233	1.81 ±0.76
Mean far-red light transmission (%) with standard error	22.5 ±11.3	0.42 ±0.28	1.94 ±0.80	1.25 ±0.40	0.65 ±0.25	20.5 ±10.1
Month	Jul	Aug	Sep	Oct	Nov	Dec
Estimated ground coverage	100	100	100	100	95	95
Estimated height (cm)	31.0	32.3	33.7	35.3	27.7	25.3
Mean visible light transmission (%) with standard error	4.14 ±1.66	1.96 ±0.60	1.33 ±0.57	1.33 ±0.72	1.51 ±0.39	1.05 ±0.42
Mean red light transmission (%) with standard error	0.875 ±0.541	0.351 ±0.118	0.0913 ±0.0271	0.124 ±0.064	0.0963 ±0.0285	0.103 ±0.043
Mean far-red light transmission (%) with standard error	6.30 ±2.78	3.30 ±1.24	1.46 ±0.60	1.52 ±0.85	0.67 ±0.15	0.99 ±0.59

Table 4.2 Weeds found within *Agapanthus x hybrid*, in ascending order of R:FR value for the month listed.

Month	**Weed ID**
February	*Euphorbia peplus* (milkweed)
December	*Leontodon taraxacoides* (hawkbit); *Sonchus oleraceus* (sow thistle)

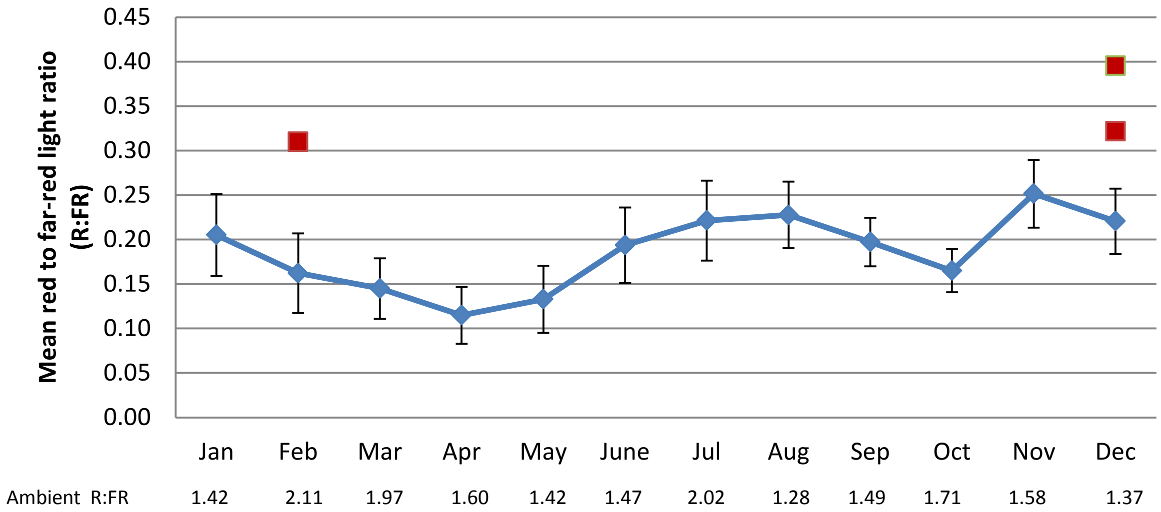


Figure 4.10 Mean R:FR of *Agapanthus x hybrid* population over one year; with lines showing standard errors; and squares not on line representing conditions where weeds were found.

4.5.1b Data from *Ajuga reptans* population

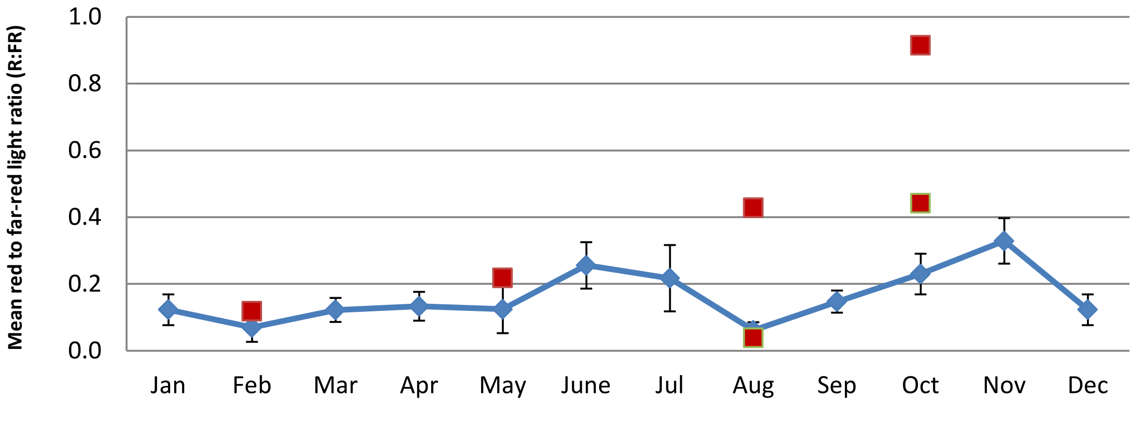
The *Ajuga reptans* population was not particularly dense, in part due to the spacings between plants, and the plants never grew well enough at the site. Gardeners replanted the *A. reptans* in February, but the plants grew smaller once cooler weather set in during April, and declined all through winter until the onset of spring in September (Table 4.3). Once the hot summer season arrived in November, the plants declined again in December and January. This was most probably due to water competition as transpiration rates increased at a time with less rain, and the close proximity of small trees and tall shrubs next to the *Ajuga reptans* bed.

The presence of taller plants and a building next to the Ajuga bed meant that light transmissibility was greatly affected by external conditions. Red light transmissibility through foliage was once again shown to be less than a third of other visible light. Far red light transmissibility was higher than red light.

Weeds tended to be found in spots with high R:FR of 0.4 and above where seed germination was possible (Figure 4.11). One instance of *Galium aparine* was found at a spot with very low R:FR, but the creeping nature of the weed made precise determination of the germination location difficult (Table 4.4).

Table 4.3 Estimated ground coverage; plant height; mean visible light (400-700 nm) transmission; mean red light (660 nm) transmission; and mean far-red light (730 nm) transmission; in *Ajuga reptans* over one year.

Month	Jan	Feb	Mar	Apr	May	Jun
Estimated ground coverage (%)	50	90	90	80	75	63
Estimated height (cm)	10.0	16.0	14.0	15.0	12.0	8.7
Mean visible light transmission (%) with standard error	11.2 ±3.0	14.1 ±3.6	2.50 ±0.41	3.75 ±0.92	30.1 ±4.7	16.9 ±7.5
Mean red light transmission (%) with standard error	1.70 ±0.87	0.597 ±0.266	0.419 ±0.166	0.396 ±0.153	0.797 ±0.341	4.76 ±3.01
Mean far-red light transmission (%) with standard error	13.7 ±3.8	14.9 ±2.9	3.73 ±0.80	4.33 ±1.04	20.4 ±5.0	13.2 ±3.9
Month	Jul	Aug	Sep	Oct	Nov	Dec
Estimated ground coverage (%)	65	65	70	70	80	50
Estimated height (cm)	11.0	15.7	13.3	11.3	10.0	10.0
Mean visible light transmission (%) with standard error	4.69 ±1.23	9.41 ±2.13	20.7 ±5.7	24.2 ±7.3	29.3 ±2.0	11.3 ±3.0
Mean red light transmission (%) with standard error	4.82 ±3.35	1.50 ±0.76	4.18 ±1.05	4.57 ±1.35	13.1 ±3.4	1.70 ±0.87
Mean far-red light transmission (%) with standard error	18.1 ±5.6	9.82 ±2.26	17.7 ±2.7	19.0 ±3.0	48.5 ±9.6	13.6 ±3.8



Ambient R:FR	1.37	0.73	1.38	1.30	1.61	1.21	1.48	0.94	1.01	1.07	1.47	1.37

Figure 4.11 Mean R:FR of *Ajuga reptans* population over one year; with lines showing standard errors; and squares not on line representing conditions where weeds were found.

Table 4.4 Weeds found within *Ajuga reptans*, in ascending order of R:FR value for the month listed.

Month	Weed ID
February	*Myosotis sylvatica* (forget-me-not)
May	*Plantago major* (broad-leaf plantain)
August	*Galium aparine* (cleavers); *Oxalis exilis* (creeping oxalis)
October	*Euphorbia peplus* (milkweed) x3

4.5.1c Data from *Coprosma* population

The mature *Coprosma kirkii* population looked very dense throughout the year, regardless of whether it had been pruned (Table4.5). The R:FR was mostly maintained at about 0.4 during the year (Figure 4.12). The February spike in R:FR was due to exceptionally low far-red light transmission at the time. No weeds were found within the quadrats.

Table 4.5 Estimated ground coverage; plant height; mean visible light (400-700 nm) transmission; mean red light (660 nm) transmission; and mean far-red light (730 nm) transmission; in *Coprosma kirkii* over one year.

Month	Jan	Feb	Mar	Apr	May	Jun
Estimated ground coverage (%)	95	100	100	100	100	100
Estimated height (cm)	53.3	45.3	31.0	45.7	39.3	42.7
Mean visible light transmission (%) with standard error	15.0 ±4.4	1.80 ±1.04	0.0399 ±0.0032	8.26 ±1.77	3.94 ±1.40	2.49 ±0.87
Mean red light transmission (%) with standard error	7.54 ±3.29	1.09 ±0.68	0.00392 ±0.00039	1.77 ±0.64	12.1 ±6.5	3.14 ±1.97
Mean far-red light transmission (%) with standard error	26.7 ±5.9	1.62 ±0.84	0.0159 ±0.0011	6.44 ±1.78	7.35 ±1.43	3.66 ±1.55
Month	Jul	Aug	Sep	Oct	Nov	Dec
Estimated ground coverage (%)	100	100	100	100	100	95
Estimated height (cm)	40.3	45.0	46.7	48.3	51.7	42.7
Mean visible light transmission (%) with standard error	0.146 ±0.044	2.97 ±0.80	0.743 ±0.167	0.522 ±0.142	0.350 ±0.097	0.798 ±0.279
Mean red light transmission (%) with standard error	0.109 ±0.036	1.37 ±0.50	0.390 ±0.14	0.243 ±0.089	0.0199 ±0.0044	0.0461 ±0.0128

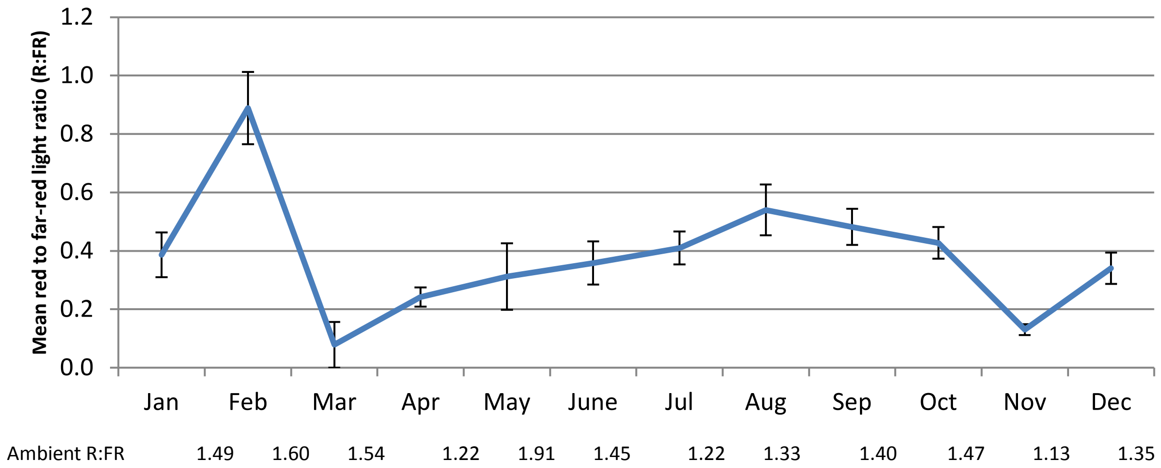


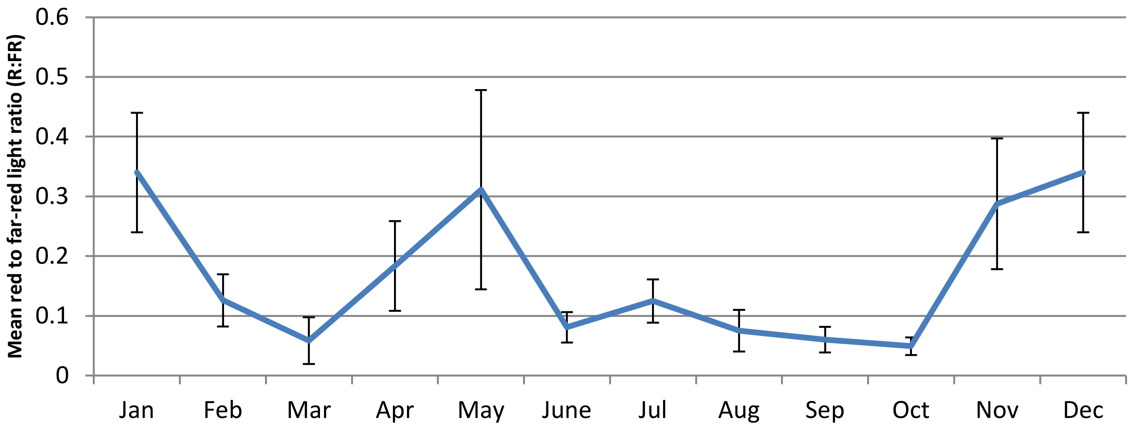
Figure 4.12 Mean monthly red to far-red light ratio under *Coprosma kirkii* canopy, over full year of 2010.

4.5.1d Data from *Cotyledon orbiculata* var *oblonga* population

The *Cotyledon orbiculata* var *oblonga* population was very dense throughout the year, the slightly less dense perception of the leaves in October was due to it sending out flowering stalks as it prepareed for an early summer bloom (Table 4.6). R:FR was kept largely below 0.3 (Figure 4.13), and no weeds were ever found growing between the thick succulent leaves.

Table 4.6 Estimated ground coverage; plant height; mean visible light (400-700 nm) transmission; mean red light (660 nm) transmission; and mean far-red light (730 nm) transmission; in *Cotyledon orbiculata* var *oblonga* over one year.

Month	Jan	Feb	Mar	Apr	May	Jun
Estimated ground coverage (%)	100	95	95	95	100	100
Estimated height (cm)	19.0	27.0	24.3	21.7	17.3	21.7
Mean visible light transmission (%) with standard error	0.205 ±0.079	1.26 ±0.69	0.238 ±0.081	2.46 ±1.01	2.54 ±1.20	1.64 ±0.56
Mean red light transmission (%) with standard error	0.105 ±0.061	0.124 ±0.075	0.00685 ±0.00383	1.81 ±1.43	0.526 ±0.32	0.0907 ±0.0644
Mean far-red light transmission (%) with standard error	0.508 ±0.213	1.80 ±0.63	0.153 ±0.054	3.88 ±2.01	1.56 ±0.95	1.40 ±0.69
Month	Jul	Aug	Sep	Oct	Nov	Dec
Estimated ground coverage (%)	100	100	95	90	100	100
Estimated height (cm)	22.3	22.0	21.3	21.7	20.7	19.0
Mean visible light transmission (%) with standard error	0.132 ±0.043	0.947 ±0.411	0.297 ±0.088	0.340 ±0.104	0.223 ±0.110	0.205 ±0.079
Mean red light transmission (%) with standard error	0.0509 ±0.0202	0.0429 ±0.0227	0.105 ±0.023	0.0188 ±0.0065	0.0130 ±0.0037	0.105 ±0.061
Mean far-red light transmission (%) with standard error	0.601 ±0.266	0.274 ±0.093	0.488 ±0.089	0.481 ±0.103	0.259 ±0.098	0.508 ±0.213



Ambient R:FR	1.71	1.69	1.47	0.94	1.02	1.63	1.35	1.50	1.39	1.27	1.35	1.71

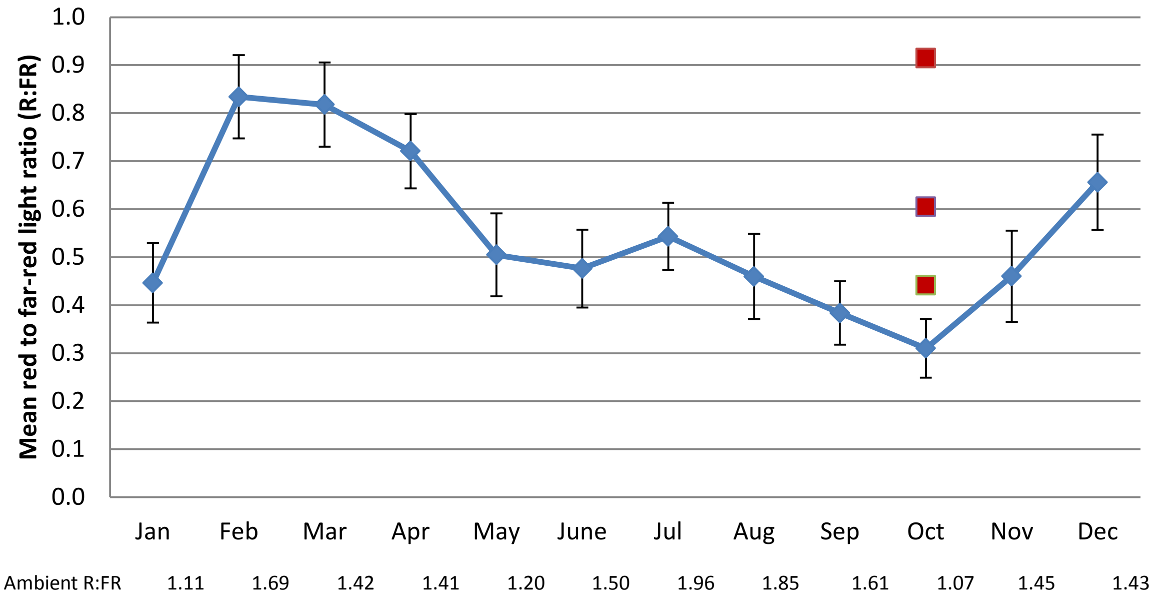
Figure 4.13 Mean red to far-red light ratio under canopy; with lines showing standard errors, over full year of 2010.

4.5.1e Data from *Gazania rigens* hybrids population

The *Gazania rigens* planting bed maintained a visually dense cover throughout the year. The plants were slightly taller during spring when a growth spurt produced new foliage (Table 4.7). The R:FR ratio was not always kept low as the plant grew in clumps, hence it was prone to opening up if one or more individual plants declined (Figure 4.14). However, the plant beds were kept weed-free most of the time, probably due to the thick bark mulch spread across the plant beds.

Table 4.7 Estimated ground coverage; plant height; mean visible light (400-700 nm) transmission; mean red light (660 nm) transmission; and mean far-red light (730 nm) transmission; in *Gazania rigens* hybrids over one year.

Month	Jan	Feb	Mar	Apr	May	Jun
Estimated ground coverage (%)	80	80	80	80	80	80
Estimated height (cm)	13.3	17.7	13.7	15.3	13.7	11.3
Mean visible light transmission (%) with standard error	0.222 ±0.076	8.00 ±2.00	3.72 ±1.38	3.33 ±1.32	6.56 ±1.86	19.0 ±4.2
Mean red light transmission (%) with standard error	0.175 ±0.46	8.47 ±2.35	2.62 ±0.84	1.83 ±0.82	3.45 ±1.50	4.18 ±1.23
Mean far-red light transmission (%) with standard error	0.412 ±0.131	12.2 ±3.8	3.00 ±0.92	2.82 ±1.15	6.63 ±2.36	17.9 ±4.5
Month	Jul	Aug	Sep	Oct	Nov	Dec
Estimated ground coverage (%)	80	80	85	90	80	80
Estimated height (cm)	13.0	20.3	20.0	19.0	13.0	15.0
Mean visible light transmission (%) with standard error	24.5 ±4.2	19.4 ±5.0	29.7 ±4.9	24.2 ±7.3	15.7 ±6.2	13.9 ±5.7
Mean red light transmission (%) with standard error	8.43 ±1.59	7.45 ±1.95	7.64 ±2.60	4.58 ±1.34	8.30 ±4.50	7.58 ±2.83
Mean far-red light transmission (%) with standard error	29.0 ±3.2	26.7 ±4.6	23.9 ±4.9	19.0 ±3.0	15.2 ±6.7	11.7 ±4.0



*Weeds found were all *Euphorbia peplus* (milkweed).

Figure 4.14 Mean R:FR of *Gazania rigens* population over one year; with lines showing standard errors; and square symbols not on line representing conditions where weeds* were found.

4.5.1f Data from *Grevillea lanigera* population

The *Grevillea lanigera* population received a pruning in April which made the plants appear more exposed as foliage nodes were cut and more woody branches were exposed (Table 4.8). This was also reflected in the high R:FR between April and Oct (Figure 4.15). Not many weeds were detected (Table 4.9), probably because the high visibility of the Conference Centre car park meant that maintenance was frequent. The few weeds found were all likely to have germinated from seed, and were growing in spots with R:FR greater than 0.4 (Figure 4.15).

Table 4.8 Estimated ground coverage; plant height; mean visible light (400-700 nm) transmission; mean red light (660 nm) transmission; and mean far-red light (730 nm) transmission; in *Grevillea lanigera* 'Little Drummer Boy' over one year.

Month	Jan	Feb	Mar	Apr	May	Jun
Estimated ground coverage (%)	95	95	90	90	87	85
Estimated height (cm)	30.0	32.7	36.7	25.3	25.3	27.3
Mean visible light transmission (%) with standard error	0.801 ±0.276	0.122 ±0.072	0.198 ±0.078	3.91 ±2.56	0.698 ±0.254	3.76 ±1.58
Mean red light transmission (%) with standard error	0.0243 ±0.0100	0.0740 ±0.0472	0.0682 ±0.0301	0.812 ±0.266	0.350 ±0.118	3.45 ±1.37
Mean far-red light transmission (%) with standard error	0.145 ±0.045	0.166 ±0.104	0.268 ±0.100	5.03 ±3.24	0.660 ±0.212	4.68 ±1.77
Month	Jul	Aug	Sep	Oct	Nov	Dec
Estimated ground coverage (%)	85	82	85	85	87	95
Estimated height (cm)	23.0	23.3	24.0	25.0	26.3	23.7
Mean visible light transmission (%) with standard error	3.45 ±1.47	5.28 ±3.01	10.5 ±7.2	10.9 ±7.9	0.239 ±0.079	0.804 ±0.421
Mean red light transmission (%) with standard error	0.941 ±0.250	2.03 ±0.69	1.10 ±0.34	0.996 ±0.404	0.0356 ±0.0121	0.725 ±0.357
Mean far-red light transmission (%) with standard error	1.65 ±0.44	2.86 ±0.83	3.35 ±1.66	3.36 ±1.79	0.243 ±0.076	1.18 ±0.59

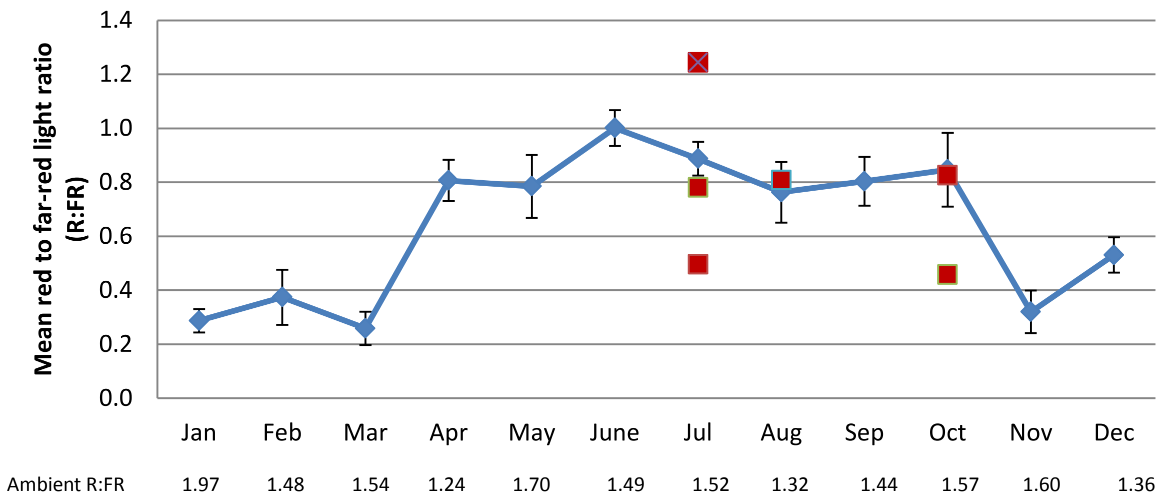


Figure 4.15 Mean R:FR of *Grevillea lanigera* population over one year; with lines showing standard errors; and square symbols not on line representing conditions where weeds were found.

Table 4.9 Weeds found within *Grevillea lanigera,* in ascending order of R:FR value for the month listed.

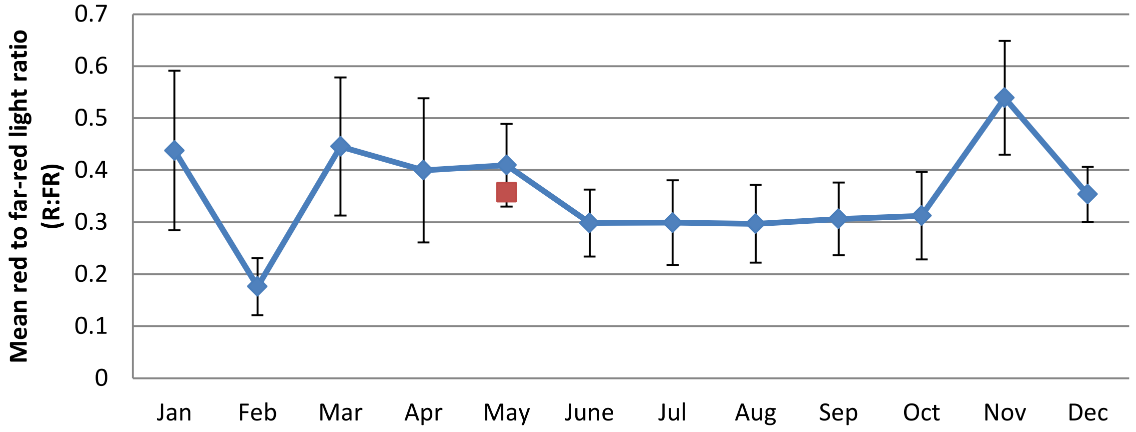
Month	**Weed ID**
Jul	*Conyza sumatrensis* (fleabane) x3
Aug	*Sonchus oleraceus* (*sow thistle*)
October	*Sonchus asper* (prickly sow thistle); *Senecio vulgaris* (groundsel)

4.5.1g Data from *Hebe chathamica* population

The *Hebe chathamica* is a very small semi-woody plant of about 8-12 cm tall and in most parts of the plant bed, there was little interlocking between plants. However, the planting bed was mulched with bark and this helped to keep out weeds. R:FR was higher from March to May as a result of pruning in March which exposed the plant bed. The plant recovered better from August onwards when it became warmer. A single incidence of weed (*Crepis capillaris*) (Table 4.10) occurred where R:FR measured 0.36 (Figure 4.16).

Table 4.10 Estimated ground coverage; plant height; mean visible light (400-700 nm) transmission; mean red light (660 nm) transmission; and mean far-red light (730 nm) transmission; in *Hebe chathamica* over one year.

Month	Jan	Feb	Mar	Apr	May	Jun
Estimated ground coverage (%)	65	70	50	60	53	60
Estimated height (cm)	8.0	8.0	11.7	9.3	12.3	8.0
Mean visible light transmission (%) with standard error	28.6 ±9.3	1.39 ±0.38	32.1 ±9.3	17.0 ±4.3	26.0 ±12.9	3.81 ±0.97
Mean red light transmission (%) with standard error	26.1 ±10.9	0.764 ±0.594	7.99 ±4.12	2.69 ±0.83	5.00 ±3.16	0.857 ±0.240
Mean far-red light transmission (%) with standard error	31.9 ±10.1	9.72 ±5.97	24.8 ±6.1	15.6 ±5.2	19.9 ±10.4	6.86 ±1.90
Month	Jul	Aug	Sep	Oct	Nov	Dec
Estimated ground coverage (%)	57	70	70	77	73	62
Estimated height (cm)	9.3	12.0	9.3	8.3	7.3	7.7
Mean visible light transmission (%) with standard error	20.2 ±7.2	13.7 ±4.9	7.92 ±3.15	14.4 ±4.9	9.54 ±3.04	14.1 ±5.2
Mean red light transmission (%) with standard error	4.60 ±1.98	3.65 ±1.70	2.25 ±1.06	4.21 ±2.72	3.24 ±1.17	1.92 ±0.92
Mean far-red light transmission (%) with standard error	15.2 ±5.3	12.4 ±4.2	7.11 ±1.62	11.8 ±3.8	8.59 ±2.35	9.59 ±4.23



Ambient R:FR	1.35	1.76	1.10	1.45	1.22	1.90	1.40	1.36	1.37	1.31	1.39	1.46

*Weed found was *Crepis capillaris* (hawksbeard)

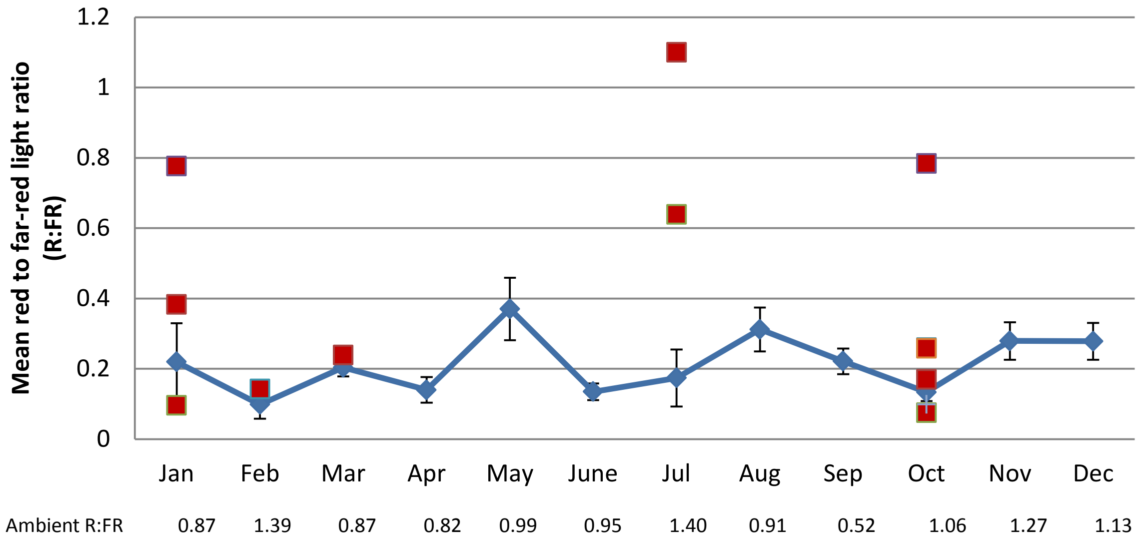
Figure 4.16 Mean R:FR of *Hebe chathamica* population over one year; with bars showing standard errors; and square symbols not on line representing conditions where weed* was found.

4.5.1h Data from *Hedera helix* population

The *Hedera helix* plants looked denser in the warmer months (Table 4.11). As the cooler season set in, the plants not only produced foliage sparsely, but also reduced its boundaries inward about 10cm. Height variations in the plant more closely represented whether or not the leaves were angled up or down rather than any real support by the vine. The foliage managed to block out most of the red light and R:FR was generally maintained at a low 0.3 (Figure 4.17). The ambient R:FR was also slightly lower than that found for other species in this chapter because the site was shaded by mature trees. All weeds found in the warmer months were *Ehrharta erecta.* From April to September there were no weeds because there was a thick layer of fallen leaves which collected near the bottom of the slope, where the *H. helix* plants were growing.

Table 4.11 Estimated ground coverage; plant height; mean visible light (400-700 nm) transmission; mean red light (660 nm) transmission; and mean far-red light (730 nm) transmission; in *Hedera helix* over one year.

Month	Jan	Feb	Mar	Apr	May	Jun
Estimated ground coverage (%)	90	100	100	95	85	85
Estimated height (cm)	10.7	9.3	12.7	15.7	15.0	15.0
Mean visible light transmission (%) with standard error	13.5 ±4.0	21.3 ±9.3	19.1 ±6.1	13.0 ±2.9	7.42 ±2.05	21.2 ±6.77.2
Mean red light transmission (%) with standard error	0.864 ±0.271	3.57 ±4.40	4.68 ±2.14	3.32 ±1.50	1.94 ±0.59	4.79 ±2.35
Mean far-red light transmission (%) with standard error	11.3 ±3.8	14.0 ±5.8	12.4 ±3.6	12.3 ±3.2	7.95 ±3.00	19.5 ±8.9
Month	Jul	Aug	Sep	Oct	Nov	Dec
Estimated ground coverage (%)	80	80	70	72	82	87
Estimated height (cm)	12.7	12.0	13.3	15.0	11.7	13.0
Mean visible light transmission (%) with standard error	20.2 ±10.6	26.6 ±14.1	39.8 ±4.0	12.1 ±0.92	3.20 ±0.92	7.83 ±3.18
Mean red light transmission (%) with standard error	4.60 ±1.98	10.2 ±4.4	41.8 ±10.7	1.77 ±0.79	0.331 ±0.153	2.22 ±0.92
Mean far-red light transmission (%) with standard error	15.2 ±5.3	21.7 ±5.2	27.0 ±16.3	14.2 ±5.9	1.18 ±0.38	8.68 ±3.01



*All weeds found at this site were *Ehrharta erecta* (veld grass).

Figure 4.17 Mean R:FR of *Hedera helix* population over one year; with bars showing standard errors; and square symbols not on line representing conditions where weeds* were found.

4.5.1i Data from *Juniperus procumbens* in Palmerston North City

There was no perceptible difference in the *Juniperus procumbens* foliage density throughout the year. The *Juniperus* needles were tightly interlocking in all seasons. Light transmissibility was also very low throughout the year with less than 1% light transmission at all times it was monitored (Table 4.12). The sudden spike in R:FR in the later part of the year was magnified due to the changes of very small magnitude in the far-red light detected (Figure 4.18). No weeds were found under the *Juniperus procumbens* foliage canopy at any time.

Table 4.12 Estimated ground coverage; plant height; mean visible light (400-700 nm) transmission; mean red light (660 nm) transmission; and mean far-red light (730 nm) transmission; in *Juniperus procumbens* over one year.

Month	Jan	Feb	Mar	Apr	May	Jun
Estimated ground coverage (%)	100	100	100	100	100	100
Estimated height (cm)	15.7	26.7	16.3	16.7	18.0	18.3
Mean visible light transmission (%) with standard error	0.0 ±0.0	0.733 ±0.365	0.0274 ±0.0221	0.0903 ±0.0540	0.0447 ±0.0234	0.0325 ±0.0294
Mean red light transmission (%) with standard error	0.0 ±0.0	0.0153 ±0.0101	0.00439 ±0.00044	0.0 ±0.0	0.0 ±0.0	0.447 ±0.445
Mean far-red light transmission (%) with standard error	0.0202 ±0.0020	1.13 ±0.55	0.0100 ±0.0091	0.0868 ±0.0607	0.143 ±0.109	0.840 ±0.833
Month	Jul	Aug	Sep	Oct	Nov	Dec
Estimated ground coverage (%)	100	100	100	100	100	100
Estimated height (cm)	27.0	23.7	24.0	24.7	22.3	17.3
Mean visible light transmission (%) with standard error	0.0154 ±0.0015	0.00121 ±0.00012	0.0153 ±0.0113	0.00717 ±0.00705	0.0462 ±0.0214	0.319 ±0.250
Mean red light transmission (%) with standard error	0.0403 ±0.0321	0.00171 ±0.00017	0.0618 ±0.0338	0.00895 ±0.00769	0.00138 ±0.00013	0.00617 ±0.00527
Mean far-red light transmission (%) with standard error	0.147 ±0.015	0.00597 ±0.00395	0.0456 ±0.0298	0.00330 ±0.00239	0.0100 ±0.0061	0.0244 ±0.0227

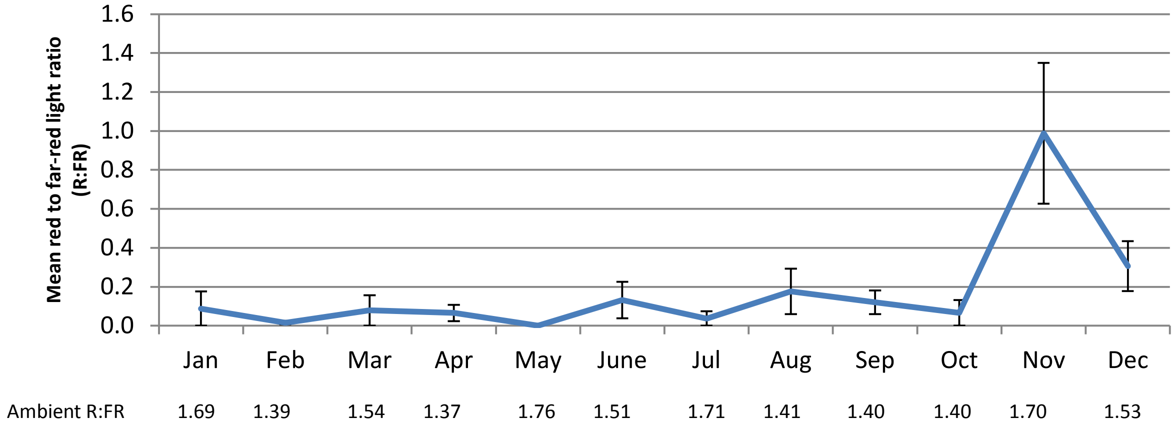


Figure 4.18 Mean R:FR of *Juniperus procumbens* population over one year; with bars showing standard errors.

4.5.1j Data from *Juniperus chinensis* at Massey University

Unlike the *Juniperus procumbens* population monitored, *Juniperus chinensis* appeared less dense (Table 4.13). The foliage canopy was also slightly lifted off the ground at some spots. Light transmission through the foliage canopy was generally not high, at levels below 15%. Even in situations which permitted higher light transmission, red light was generally well-absorbed by the foliage, usually with less than 10% transmission. Far-red light transmission was also very low at this location, accounting for higher R:FR values throughout (Figure 4.19). Weeds were regularly found at this location, and mostly included the perennial *Tradescantia fluminensis* and *Ehrharta erecta* with their stoloniferous and rhizomatous spread respectively, from outside the ground cover canopy. *Aphanes inexspectata* possibly germinated from seed in the high R:FR conditions, since this weed was not commonly encountered (Table 4.14).

Table 4.13 Estimated ground coverage; plant height; mean visible light (400-700 nm) transmission; mean red light (660 nm) transmission; and mean far-red light (730 nm) transmission; in *Juniperus chinensis*_ over one year.

Month	Jan	Feb	Mar	Apr	May	Jun
Estimated ground coverage (%)	95	97	95	95	93	90
Estimated height (cm)	30.0	32.7	40.0	37.3	38.3	38.3
Mean visible light transmission (%) with standard error	6.31 ±1.33	12.7 ±4.6	5.04 ±1.33	6.22 ±2.74	12.0 ±4.7	11.5 ±3.0
Mean red light transmission (%) with standard error	1.16 ±0.59	11.8 ±8.8	1.18 ±0.40	5.61 ±3.10	6.67 ±2.57	8.83 ±5.80
Mean far-red light transmission (%) with standard error	13.7 ±4.6	9.71 ±2.31	2.38 ±0.67	5.21 ±1.90	5.88 ±1.89	11.9 ±4.0
Month	Jul	Aug	Sep	Oct	Nov	Dec
Estimated ground coverage (%)	90	90	90	90	93	95
Estimated height (cm)	25.3	35.3	30.3	25.3	33.3	31.7
Mean visible light transmission (%) with standard error	28.3 ±8.4	9.47 ±4.38	7.09 ±1.50	7.35 ±1.65	8.45 ±3.95	7.84 ±2.93
Mean red light transmission (%) with standard error	9.13 ±2.64	10.0 ±4.9	2.35 ±0.70	2.08 ±0.75	2.99 ±1.55	2.19 ±0.98
Mean far-red light transmission (%) with standard error	16.6 ±4.7	10.3 ±4.2	5.66 ±1.67	5.23 ±1.45	5.43 ±2.06	4.34 ±1.64

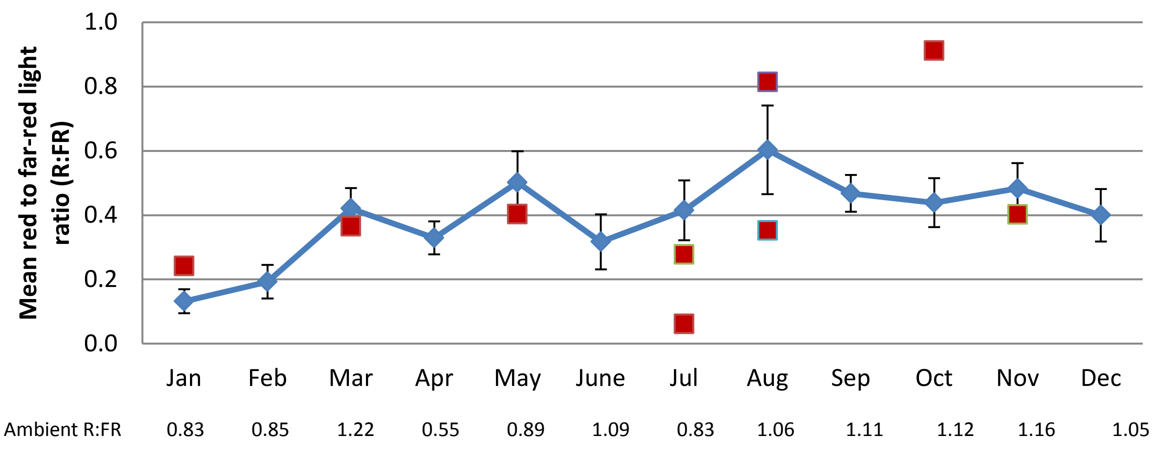


Figure 4.19 Mean R:FR of *Juniperus chinensis* population at Massey University over one year; with bars showing standard errors; and square square symbols not on line representing conditions where weeds were found.

Table 4.14 Weeds found within *Juniperus chinensis*, in ascending order of R:FR value for the month listed.

Month	Weed ID
January	*Ehrharta erecta* (veld grass)
March	*Tradescantia fluminensis* (wandering Jew)
May	*E. erecta*
July	*T. fluminensis*; *Ehrharta erecta*
August	*T. fluminensis* x2
October	*Aphanes inexspectata* (parsley piert)
November	*T. fluminensis*

4.5.1k Data from *Muehlenbeckia axillaris* population

The *Muehlenbeckia axillaris* population covered the plant bed well, but its foliage varied with the seasons, being sparser in winter and lusher in summer (Table 4.15). Visible light transmission was highly variable at times, but absorbance by leaf pigments ensured that red light transmissions remained low, being less than 1% most of the time. R:FR for this population did not always remain low due to less far red light detected under the foliage (Figure 4.20) when a flush of new foliage growth occurred in spring. However, no weeds were found, as there was gravel and wood mulch under the plants.

Table 4.15 Estimated ground coverage; plant height; mean visible light (400-700 nm) transmission; mean red light (660 nm) transmission; and mean far-red light (730 nm) transmission; in *Muehlenbeckia axillaris* over one year.

Month	Jan	Feb	Mar	Apr	May	Jun
Estimated ground coverage (%)	90	90	85	85	82	80
Estimated height (cm)	14.3	15.7	17.3	13.7	16.3	16.7
Mean visible light transmission (%) with standard error	14.1 ±5.6	5.15 ±1.40	6.58 ±5.39	4.02 ±1.38	1.33 ±0.65	2.03 ±0.75
Mean red light transmission (%) with standard error	0.806 ±0.548	0.564 ±0.181	0.418 ±0.231	0.912 ±0.333	0.613 ±0.342	0.572 ±0.239
Mean far-red light transmission (%) with standard error	11.1 ±5.8	7.85 ±4.02	1.17 ±0.61	3.23 ±1.10	1.29 ±0.64	1.40 ±0.58
Month	Jul	Aug	Sep	Oct	Nov	Dec
Estimated ground coverage (%)	80	85	90	98	100	100
Estimated height (cm)	13.3	12.7	14.0	16.0	21.0	13.7
Mean visible light transmission (%) with standard error	4.0 ±2.0	5.01 ±2.00	2.17 ±0.53	1.59 ±0.50	0.299 ±0.033	0.388 ±0.099
Mean red light transmission (%) with standard error	1.46 ±0.73	2.25 ±1.00	0.439 ±0.162	0.0679 ±0.0279	0.00227 ±0.00072	0.231 ±0.120
Mean far-red light transmission (%) with standard error	11.1 ±5.8	7.85 ±4.02	1.17 ±0.61	3.23 ±1.10	1.29 ±0.64	1.40 ±0.58

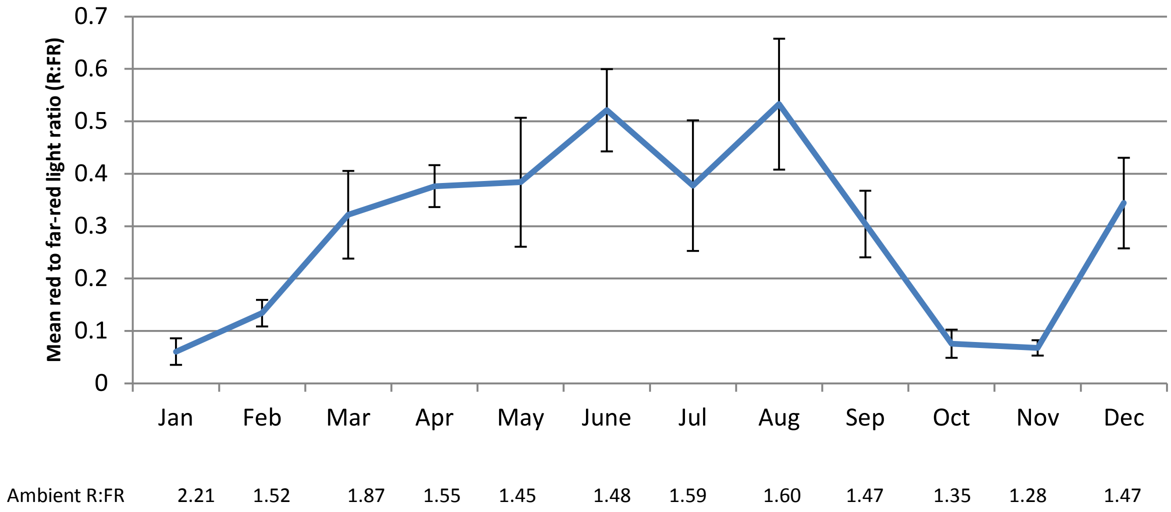


Figure 4.20 Mean R:FR of *Muehlenbeckia axillaris* population over one year; with bars showing standard errors.

4.5.11 Data from *Pimelea prostrata* population

The *Pimelea prostrata* varied in its foliage density, with the cooler seasons having slightly sparse foliage. The sites of 2 quadrats were right under the building signboard, leading to highly variable light transmission rates. R:FR was mostly around the 0.45 level, and there were numerous incidences of weeds found throughout the year. However, most of the weeds were perennial species with the ability of stoloniferous spread (Table 4.17). The weeds were likely to have established in areas outside the ground cover canopy or at the site before *P. prostrata* was planted, and continued to re-establish themselves from remnants left behind despite weeding maintenance. A check with the contracted maintenance staff revealed no herbicide use. The only annual weed species were *Stachys arvensis* and *Euphorbia peplus*; which could have germinated from seed since they were found at spots with higher R:FR (Table 4.17).

Table 4.16 Estimated ground coverage; plant height; mean visible light (400-700 nm) transmission; mean red light (660 nm) transmission; and mean far-red light (730 nm) transmission; in *Pimelea prostrata* over one year.

Month	Jan	Feb	Mar	Apr	May	Jun
Estimated ground coverage (%)	90	90	87	85	85	80
Estimated height (cm)	14.3	14.3	15.3	16.0	15.7	14.3
Mean visible light transmission (%) with standard error	14.0 ±6.6	13.4 ±3.3	0.922 ±0.424	0.844 ±0.257	3.33 ±2.09	3.73 ±1.02
Mean red light transmission (%) with standard error	1.17 ±0.94	10.9 ±7.7	0.659 ±0.338	0.789 ±0.489	8.58 ±7.48	4.28 ±1.94
Mean far-red light transmission (%) with standard error	2.16 ±1.41	15.7 ±5.9	1.63 ±0.93	1.95 ±1.35	2.70 ±2.04	6.42 ±2.68
Month	Jul	Aug	Sep	Oct	Nov	Dec
Estimated ground coverage (%)	75	82	90	92	95	87
Estimated height (cm)	14.3	14.0	13.7	13.7	12.7	13.3
Mean visible light transmission (%) with standard error	8.76 ±2.64	3.38 ±1.56	2.22 ±0.72	2.12 ±0.67	2.38 ±0.73	2.39 ±0.98
Mean red light transmission (%) with standard error	2.95 ±1.21	1.15 ±0.32	0.542 ±0.32	0.541 ±0.427	1.18 ±0.52	2.46 ±1.15
Mean far-red light transmission (%) with standard error	2.16 ±1.41	15.7 ±5.9	1.63 ±0.93	1.95 ±1.35	2.70 ±2.04	6.42 ±2.68

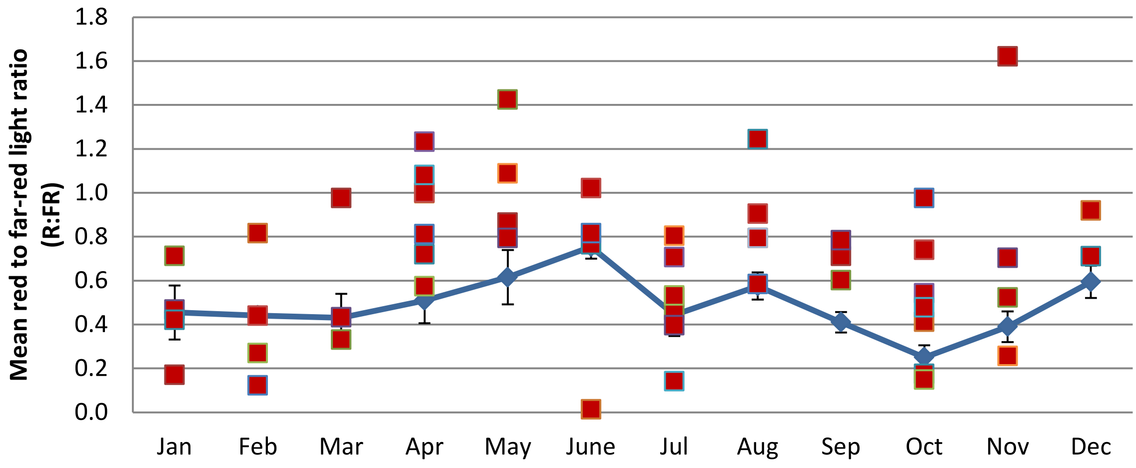


Figure 4.21 Mean R:FR of *Pimelea prostrata* population over one year; with bars showing standard errors; and square symbols not on line representing conditions where weeds were found.

Table 4.17 List of weeds found within *Pimelea prostrata*, in ascending order of R:FR value for the month listed.

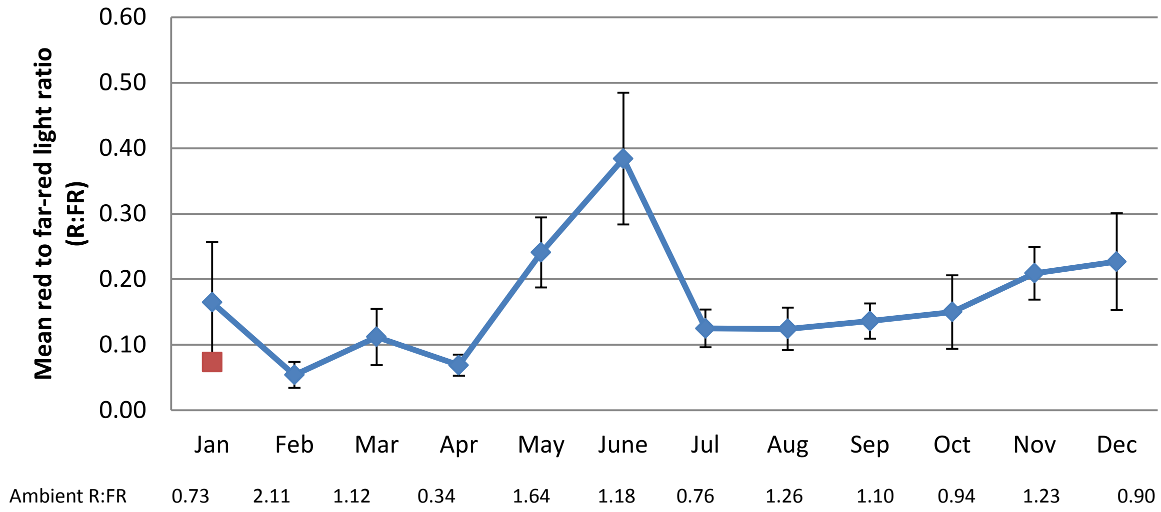
Month	Weed ID
January	*Ranunculus repens* (creeping buttercup); *Oxalis exilis* (creeping oxalis); *R. repens* x2;
February	*Elytrigia repens* (couch) x4
March	*Trifolium repens* (white clover); *O. exilis*; *E. repens*
April	*E. repens* x5; *T. repens* x2
May	*E. repens* x3; *T. repens*
June	*E. repens* x 4
July	*E. repens x 7*
August	*E. repens x 5*
September	*E. repens x 3*
October	*E. repens* x2; *Stachys arvensis* (staggerweed) x2; *T. repens* ; *E. repens* x2;
November	*T. repens; Veronica filiformis (creeping speedwell); O. exilis; Elytrigia repens* (couch) all numerous
December	*E. repens; Euphorbia peplus* (milkweed)

4.5.1m Data from *Plectranthus ciliatus* population

The *Plectranthus ciliatus* population was generally very dense throughout the year (Table 4.18). Light transmission through the tall and lush plants was low. R:FR was also maintained below 0.3 for much of the year, and there was only one incidence of weed growth at the beginning of the project in January (Figure 4.22) found near the boundary of the ground cover.

Table 4.18 Estimated ground coverage; plant height; mean visible light (400-700 nm) transmission; mean red light (660 nm) transmission; and mean far-red light (730 nm) transmission; in *Plectranthus ciliatus* over one year.

Month	Jan	Feb	Mar	Apr	May	Jun
Estimated ground coverage (%)	95	95	95	95	95	95
Estimated height (cm)	45.0	50.3	55.0	66.7	59.0	43.3
Mean visible light transmission (%) with standard error	3.56 ±0.96	1.25 ±0.74	3.42 ±1.22	14.9 ±3.8	7.73 ±2.36	2.91 ±1.07
Mean red light transmission (%) with standard error	0.213 ±0.106	0.0633 ±0.0409	0.846 ±0.415	3.20 ±0.88	2.01 ±0.72	2.92 ±1.41
Mean far-red light transmission (%) with standard error	3.43 ±1.19	1.36 ±0.96	6.16 ±2.02	13.7 ±3.5	5.67 ±1.48	6.31 ±1.96
Month	Jul	Aug	Sep	Oct	Nov	Dec
Estimated ground coverage (%)	95	100	95	95	92	95
Estimated height (cm)	53.3	50.3	50.0	34.3	31.3	36.7
Mean visible light transmission (%) with standard error	19.1 ±4.5	8.37 ±2.59	6.96 ±1.47	8.28 ±1.88	14.2 ±3.0	9.56 ±2.47
Mean red light transmission (%) with standard error	6.72 ±4.45	0.844 ±0.341	0.858 ±0.184	0.690 ±0.308	1.23 ±0.37	1.69 ±0.69
Mean far-red light transmission (%) with standard error	19.2 ±5.3	6.95 ±1.72	4.89 ±0.94	5.39 ±1.07	6.78 ±1.51	9.61 ±2.63



* Unidentified Liliaceae family species from previous ornamental planting.

Figure 4.22 Mean R:FR of *Plectranthus ciliatus* population over one year; with bars showing standard errors; and square symbol not on line representing conditions where weed* was found.

4.5.1n Data from *Viola sp.* population

The *Viola sp.* population grew better in the warmer season, with cool weather causing some defoliation from March to August (Table 4.19). This led to greater light transmission during those months as the foliage was mostly one layer thick. Despite this, the R:FR levels were relatively stable under the foliage, at less than 0.3 throughout the year (Figure 4.23). The generally sparse foliage also encouraged weediness to set in at the site throughout the year. However, the weeds were generally the perennial *Agrostis capillaris* and *Tradescantia fluminensis* which were commonly found outside the ground cover bed, and probably did not spread as new weed germinations (Table 4.20).

Table 4.19 Estimated ground coverage; plant height; mean visible light (400-700 nm) transmission; mean red light (660 nm) transmission; and mean far-red light (730 nm) transmission; in *Viola sororia* over one year.

Month	Jan	Feb	Mar	Apr	May	Jun
Estimated ground coverage (%)	65	60	50	35	40	40
Estimated height (cm)	16.0	16.0	13.7	9.8	8.0	7.7
Mean visible light transmission (%) with standard error	13.1 ±2.9	16.9 ±4.7	11.1 ±2.5	29.2 ±7.5	58.4 ±7.5	52.4 ±6.0
Mean red light transmission (%) with standard error	0.825 ±0.214	1.32 ±0.64	0.704 ±0.305	2.99 ±1.36	13.6 ±3.4	5.35 ±1.82
Mean far-red light transmission (%) with standard error	11.3 ±3.1	5.14 ±1.29	6.01 ±1.33	19.2 ±5.4	57.5 ±9.3	36.5 ±7.1
Month	Jul	Aug	Sep	Oct	Nov	Dec
Estimated ground coverage (%)	50	65	90	100	83	72
Estimated height (cm)	9.0	12.3	15.0	20.0	20.7	16.0
Mean visible light transmission (%) with standard error	36.3 ±6.3	0.410 ±0.178	8.28 ±2.37	9.95 ±3.30	15.1 ±4.0	19.6 ±4.3
Mean red light transmission (%) with standard error	5.40 ±1.36	0.0481 ±0.0296	2.67 ±2.21	3.06 ±2.81	0.833 ±0.357	6.50 ±3.50
Mean far-red light transmission (%) with standard error	37.1 ±4.7	0.411 ±0.139	7.47 ±2.73	7.27 ±2.95	12.9 ±5.3	20.0 ±5.1

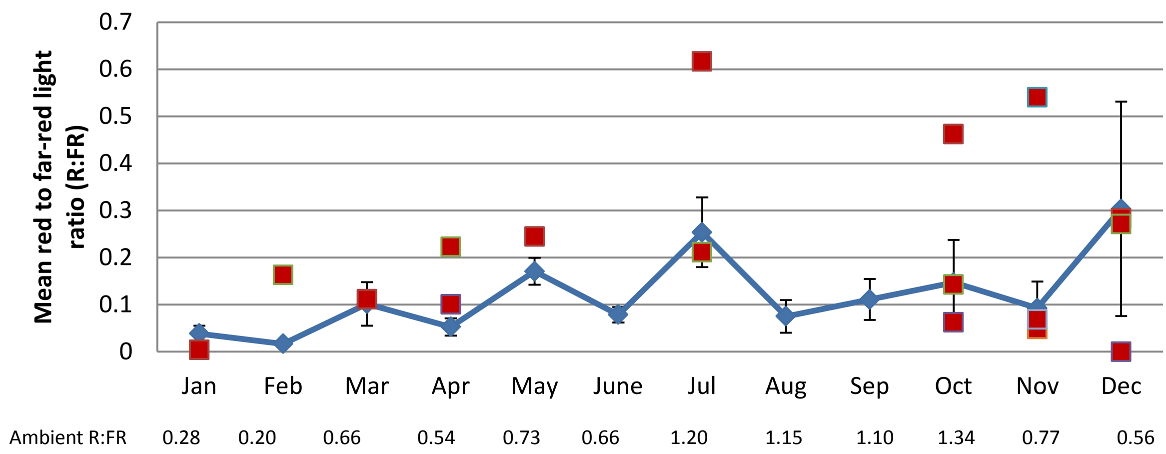


Figure 4.23 Mean R:FR of *Viola sororia* population over one year; with bars showing standard errors; and square symbols not on line representing conditions where weeds were found.

Table 4.20 Weeds found within *Viola sororia*, in ascending order of R:FR value for the month listed.

Month	Weed ID
January	*Agrostis capillaris* (browntop)
February	*A. capillaris*
March	*A. capillaris*
April	*A. capillaris* x2
May	*Tradescantia fluminensis* (Wandering Jew; fallen leaves present on ground)
July	*A. capillaris*; *T. fluminensis*
October	*A. capillaris* (numerous)
November	*A. capillaris* (numerous)
December	*A. capillaris* (numerous)

4.5.2 Light quality data across all populations by quarterly interval

Agapanthus x hybrid, Coprosma kirkii, Cotyledon orbiculata var *oblonga,* and *Juniperus procumbens* in town, blocked out much of the light consistently throughout the year (Table 4.21). *Muehlenbeckia axillaris* also performed better after January, perhaps after some growth. With the *Ajuga reptans* and *Gazania rigens*, light blocking ability was reduced after the cooler season set in. *Pimelea prostrata* opened up slightly during winter too, but light transmission was more pronounced in summer when it was flowering. Another plant which let in more light during flowering was *Grevillea lanigera.* A few plant species did not appear to block visible light very well, these being *Hebe chathamica*, *Hedera helix*, *Juniperus chinensis*, *Plectranthus ciliatus*, and *Viola sororia*.

Table 4.21 Mean visible Light transmission (% quality) in January, April, July and October 2010

Species	January 2010	April 2010	July 2010	October 2010
Agapanthus x hybrid	14.0	1.2	4.1	1.3
Ajuga reptans	11.3	3.8	4.7	24.2
Coprosma kirkii	15.0	8.3	0.1	0.5
Cotyledon orbiculata	0.2	2.5	0.1	0.3
Gazania rigens	0.2	3.3	24.5	0.4
Grevillea lanigera	0.8	3.9	3.4	10.9
Hebe chathamica	28.6	17.0	20.2	14.4
Hedera helix	13.5	13.0	13.3	12.1
Juniperus chinensis	6.3	6.2	28.3	7.4
Juniperus procumbens	0.0	0.1	0.02	0.01
Muehlenbeckia axillaris	14.1	4.0	4.0	1.6
Pimelea prostrata	14.0	0.8	8.8	2.1
Plectranthus ciliatus	3.6	15.0	19.1	8.3
Viola sororia	13.1	29.2	36.3	9.9
$LSD_{0.05}$	12.0	8.2	11.4	9.9

Red light was strongly absorbed by foliage and most plants had much lower red light transmission rates than visible light (Table 4.22). As the red light measured (660 nm) is a subset of the visible light data (400-700 nm), species behaviour was similar as above.

Far red light is generally better transmitted through foliage, at levels similar to visible light (Tables 4.23 and 4.21). This indicates that foliage pigments do not absorb far-red light well. *Hebe chathamica, Viola sororia*, and *Hedera helix* were the populations which had high far-red light content under the canopy. *Gazania rigens* let in more far-red during winter when the plant let in more light overall. *Cotyledon orbiculata, Grevillea lanigera, Juniperus procumbens*, *Muehlenbeckia axillaris*, and *Pimelea prostrata* were the populations which allowed less far-red light transmission through its foliage.

Table 4.22 Mean red light (660 nm) transmission (% quality) in January, April, July and October 2010

Species	January 2010	April 2010	July 2010	October 2010
Agapanthus x hybrid	4.2	0.1	0.9	0.1
Ajuga reptans	1.7	0.4	4.8	4.6
Coprosma kirkii	7.5	1.8	0.1	0.2
Cotyledon orbiculata	0.1	1.8	0.1	0.02
Gazania rigens	0.2	1.8	8.4	0.08
Grevillea lanigera	0.02	0.8	0.9	1.0
Hebe chathamica	26.1	2.7	4.6	4.2
Hedera helix	0.9	3.3	3.6	1.8
Juniperus chinensis	1.2	5.6	9.1	2.1
Juniperus procumbens	0.0	0.0	0.0	0.01
Muehlenbeckia axillaris	0.8	0.9	1.4	0.1
Pimelea prostrata	1.2	0.8	3.0	0.5
Plectranthus ciliatus	0.2	3.2	6.7	0.7
Viola sororia	0.8	3.0	5.4	3.1
$LSD_{0.05}$	8.2	3.2	5.3	3.2

Table 4.23 Mean far red light (730 nm) transmission (% quality) in January, April, July and October 2010

Species	January 2010	April 2010	July 2010	October 2010
Agapanthus x hybrid	22.5	1.3	6.3	1.5
Ajuga reptans	13.7	4.3	18.1	19.0
Coprosma kirkii	26.7	6.4	0.3	1.0
Cotyledon orbiculata	0.5	3.9	0.6	0.5
Gazania rigens	0.4	2.8	29.0	0.2
Grevillea lanigera	0.1	5.0	1.6	3.4
Hebe chathamica	31.9	15.6	15.2	11.8
Hedera helix	11.3	12.3	25.2	14.2
Juniperus chinensis	13.7	5.2	25.0	5.2
Juniperus procumbens	0.02	0.1	0.1	0.0
Muehlenbeckia axillaris	11.1	3.2	11.2	0.7
Pimelea prostrata	2.2	1.9	11.2	1.7
Plectranthus ciliatus	3.4	13.7	19.2	5.4
Viola sororia	11.3	19.2	37.1	7.3
$LSD_{0.05}$	14.6	7.7	14.3	6.5

From Table 4.24, the populations with lower R:FR through its canopies were *Agapanthus x hybrid, Ajuga reptans, Cotyledon orbiculata, Juniperus procumbens, Plectranthus ciliatus, and Viola sororia.* The populations with higher R:FR were *Gazania rigens, Grevillea lanigera, Hebe chathamica,* and *Pimelea prostrata.*

Table 4.24 Mean red to far red light ratios (R:FR) under the ground cover canopy in January, April, July and October 2010

Species	January 2010	April 2010	July 2010	October 2010
Agapanthus x hybrid	0.205	0.115	0.221	0.165
Ajuga reptans	0.123	0.133	0.217	0.230
Coprosma kirkii	0.387	0.242	0.410	0.427
Cotyledon orbiculata	0.340	0.183	0.125	0.049
Gazania rigens	0.446	0.721	0.543	0.310
Grevillea lanigera	0.287	0.807	0.887	0.847
Hebe chathamica	0.438	0.400	0.299	0.312
Hedera helix	0.220	0.140	0.174	0.133
Juniperus chinensis	0.132	0.329	0.415	0.439
Juniperus procumbens	0.088	0.065	0.037	0.066
Muehlenbeckia axillaris	0.060	0.376	0.377	0.075
Pimelea prostrata	0.455	0.510	0.443	0.250
Plectranthus ciliatus	0.165	0.069	0.125	0.150
Viola sororia	0.038	0.053	0.254	0.147
$LSD_{0.05}$	0.240	0.182	0.203	0.188

4.6 Discussion

Measurements of the various light qualities faced the challenge of non-uniform light distribution due to position of the sun and extent of cloudiness. Readings were necessarily taken over a period of about 4-5 hours to complete all the site visits. To reduce light reception irregularity by the sensors, this was performed from 10am to 3pm in a day, so as to ensure that the position of the sun was vertically overhead as much as possible. Unfortunately, ambient light changes due to cloudiness was beyond the control of a single person using a single set of equipment, as the readings were taken successively rather than concurrently across all sites. The amount of light that reached under the plant canopy may be affected by cloudiness. When sunlight is filtered through clouds, each gap in the cloud appears to act as a light source and sunlight reaches the surface at varying angles. This light diffusion may have allowed more light to reach under the ground cover canopy (Johnson & Smith 2006). However, the data were still useful for comparing the relative transmissibility against different light wavelengths of the same month. The ratio of red to far-red light also appeared to be subject to less variability, since its nature as a ratio allows for the comparison in a relative manner between the two wavelengths.

Agapanthus x hybrid population

Despite some irregularities causing a spike in readings for January and June, possibly due to cloud cover, the R:FR remained low throughout the year. Weeds which were found within this species were all annuals which could have germinated from seed, as they were all found at locations which had R:FR above 0.3, which seemed to be the critical value above which seed germination was possible for many species as found in Chapter 3.

Ajuga reptans population

The *Ajuga reptans* population was not particularly dense, in part due to the spacings between plants, and the plants never grew well enough at the site. Gardeners replanted the *A. reptans* in February, but the plants grew smaller once cooler weather set in during April, and declined all through winter until the onset of spring in September. Once the hot summer season arrived in November, the plants declined again in December and January. In contrast, the *Ajuga reptans* 'Caitlin's Giant' used in the trial in Chapter 3 did not show any signs of decline during the summer where it grew in relatively uncrowded plots, although there was also a reduction in size during winter. Hence, the decline in summer for this population was most probably due to water competition as transpiration rates increased at a time with less rain, and the close proximity of small trees and tall shrubs next to the Ajuga bed.

The presence of taller plants and a building next to the *Ajuga reptans* bed meant that light transmissibility was greatly affected by external conditions. Weeds were expected to be found in spots with high R:FR of 0.4 and above (from Chapter 3). One instance of *Galium aparine* was found at a spot with very low R:FR, but the creeping nature of the weed made precise determination of the germination location difficult. Other weeds were from wind-blown seed species. The large spaces between plants would have allowed for variation in light quality throughout the day. Even though spot readings may indicate some weeds at low R:FR locations, this would likely change over the period of a day and sufficient time at higher R:FR levels amenable for seed germination at this site was likely.

The presence of weeds in the *Ajuga reptans* populations was most likely due to the wide spacing during planting. A combination of site factors including accidental foot traffic when going round the corner and competition from larger trees and shrubs right next to the *Ajuga reptans,* contributed to the monitored population not growing dense enough to form a complete cover over the soil surface during the period of observation. This was in contrast to the *Ajuga reptans* 'Caitlin's Giant' used in the previous chapter, where the leaves proved very effective in blocking out light, and would have performed better in a scenario where planting density was more spaced out.

Coprosma kirkii population

The *Coprosma kirkii* shrubs appeared dense throughout the year and no weeds were found during the visits. However, R:FR levels under foliage were not consistent, and were relatively high at above 0.4 for about half the time. The lack of weeds found may be attributed to more regular maintenance by the City Council at a site of high visibility in town; and the presence of mulch may further discourage weed germination from the soil seed bank.

Cotyledon orbiculata var *oblonga* population

The succulent, stubby leaves of the *Cotyledon orbiculata* var *oblonga* were very crowded in this mature population, and this provided dense shading with the R:FR kept below 0.3 for most of the year; in addition to the physical competition for light and soil resources.

Gazania rigens hybrids population

The *Gazania rigens* hybrids were not tightly spaced, and interplant spaces were visible. However, the site was also covered in wood mulch about 5-6 cm thick. Foliage was better at blocking out light during the summer months. The low light transmissibility in January was due to an extremely intense ambient light reading at the time of reading. The plants appeared more dense during October as it produced new growth, and the thicker foliage absorbed red light more strongly resulting in lower R:FR. Despite the combination of ground cover and thick wood mulch, weed seeds which landed on top of the mulch still managed to germinate as evidenced by the October detection of three instances of *Euphorbia peplus.* Hence, the presence of wood mulch could only deter weed seed germination from existing soil seed bank, but the wood mulch itself could be used by opportunistic weed seeds as a feasible growing medium.

Grevillea lanigera population

The *Grevillea lanigera* appeared sparser by late winter and denser in summer. This was not due to defoliation, but due to the perception that the budding flowering inflorescence occupied substantial space on the branch, resulting in the foliage opening up and allowing more light through. During the late winter months, *Grevillea lanigera* prepared to flower. The R:FR under the foliage canopy was also lower during the summer months. A separate study might determine if there are any changes in the composition of foliage pigments which may account for this. Weeds were also generally found in spots with R:FR higher than 0.3. All the weeds were wind-blown species from the Asteraceae, which probably germinated from seed carried by wind, as a mulch layer was present which would have prevented germination from within the soil.

Hebe chathamica population

The *Hebe chathamica* is a very small semi-woody plant of about 8-12 cm tall and in most parts of the plant bed, there was little interlocking between plants. However, the planting bed was mulched with bark and this helped to keep out weeds. Only one instance of *Crepis capillaris* was found at a spot above 0.3 R:FR.

Hedera helix population

The *Hedera helix* vines were most dense by late summer, but the foliage thinned out as autumn got under way and the boundary of the area occupied by the vines in summer actually retreated in the winter by about 10-20 cm at the sites monitored. Light transmissibility was higher in late winter and early spring. However, where the foliage and vines remained, the areas under them remain well shaded from sunlight with R:FR usually at levels below 0.3 in at least some spots throughout the year. The site was on a slope below shrubs and trees and all the weed occurrences found were of *Ehrharta erecta* which is a perennial plant species capable of rhizomatous spread. This allowed the weed plants to overcome the competitive shading by ground covers which prevent edgermination, and accounted for the weeds found in regions with low R:FR. However, *Ehrharta erecta* is also a prolific seeder, and some of the smaller plants in poorly shaded spots may have germinated from seed.

Juniperus procumbens population in Palmerston North City

This was a mature population outside a commercial property in the industrial part of the city. The premises were vacated about 3 months after the start of the project and no further maintenance work would have been carried out. In any case, the foliage was consistently dense throughout the year, as evidenced by both visual observation and light sensor measurement. Visible light transmissibility was always maintained below 1% on average throughout the year. The spike in R:FR in November was due to a slight reduction in far-red light. Otherwise R:FR was typically below 0.2 throughout the year, which appeared to be low enough to dissuade weeds from germinating despite no on-going landscape maintenance on-site.

Juniperus chinensis population at Massey University

Unlike the *Juniperus procumbens* population monitored, *Juniperus chinensis* appeared less dense. The foliage canopy was also slightly lifted off the ground at some spots. This may have permit tedreflected light from entering, hence reducing the shading effect of the ground cover. In any case, the transmission of red light under the canopy seemed to be at a similar level as visible light. The R:FR levels of the *J. chinensis* was higher than that of the *J. procumbens* monitored. Incidences of weed occurrence was also higher, but *Ehrharta erecta* and *Tradescantia fluminensis* are capable of vegetative spread, so the sites where they were rooted may not have been directly influenced by the R:FR values. The *Aphanes inexspectata* found in October was the only instance of a weed germination, possibly from the soil seed bank as there was no mulch over the soil surface, and it established in a well-lit spot where R:FR was at 0.9.

Muehlenbeckia axillaris population

Despite the variation in foliage density throughout the year, which was similarly observed in the field experiment, the *M. axillaris* ground cover proved resilient against weed invasion. Once again, light blockage by the low-lying and very prostrate plant was not as high as other larger ground cover species which also resisted weeds well. This species differs from the other ground cover plant species monitored in being very freely rooting from stem nodes. The roots are also put down fairly deeply, as removal of this plant requires considerable effort. In Chapter 3, this species was found to produce good weed deterrence despite not being the best at blocking out light. The possibility mentioned in the previous chapter that competition for resources under the soil surface by the dense root network of the ground cover plant should be considered.

Pimelea prostrata population

The *Pimelea prostrata* population monitored was often weedy during the time it was monitored. This may have been due to the planting design on-site. For two of the sampling sites, the plants were used here more as planted edging surrounding the building signboard, being planted to a width of about 30-35 cm. The other sampling site was a parking lot divider about 1 m wide, also planted linearly (at a similar width of 30 cm) to frame taller plants in the centre of the divider. The linear and narrow planting arrangement resulted in a long boundary line with external contact with not much area covered by the *Pimelea prostrata.* This made it more likely for external weeds to encroach into its area. *Elytrigia repens,* a perennial grass species which could also spread by rhizomatous growth, had the likelihood of successful invasion into the *Pimelea prostrata* planting bed greatly increased by virtue of its natural characteristics; the planting design; and the habit of *Pimelea prostrata* to open up during winter. The opening up of the *P. prostrata* foliar canopy in winter was particularly untimely (also observed in field experiments in Chapter 3) as *Elytrigia repens* grows well in the cooler season (Karsten & Carlassare 2005). The *Elytrigia repens* could have been eradicated if the herbicide haloxyfop was used. Although it was not specifically tested to be safe on *Pimelea prostrata,* its mode of action usually only damages monocotyledonous plants such as grass weeds, leaving dicotyledonous plants unharmed.

The light transmission data for this site were erratic between visits. A possible contributory factor was the presence of the building signboard nearby. It was a metal panel which was reflective. This could have allowed additional diffused light to be picked up by the sensors, and exacerbated differences between cloudy and clear conditions. The narrow planting strip of the *Pimelea prostrata* meant that the signboard and plants were close by, which made reflective light interference likely. However, the R:FR data showed less variation, as the reflectance should have affected both red and far-red light similarly. Overall, the R:FR was observed at relatively high levels of above 0.4 for most parts of the year, which could have easily allowed weed seed germination, even if the *Elytrigia repens* was not present.

The annual weeds found were two of S*tachys arvensis* and one of *Euphorbia peplus.* One instance of *Stachys arvensis* was found growing at a spot, which had R:FR measured at a low 0.2 at the time. This was a one-off anomaly which could be explained by a gap in the ground cover which closed up at the time of measurement. The other S*tachys arvensis* was growing at a spot with 0.5 R:FR and the *Euphorbia peplus* at 0.9.

Plectranthus ciliatus population

The plants had compact and almost uniformly dense foliage throughout the year. The plants were grown under a grove of tall fir trees and received filtered light at this site. Generally, the quality of R:FR under the *Plectranthus ciliatus* was kept below 0.3, possibly because of the filtered ambient light, and perhaps in combination with the purple-hued foliage. There was only one incidence of a weed found at this site at the beginning of this project in January, and it was most likely a remnant from a previous ornamental planting, as it appeared to be a liliaceous bulb.

Viola sororia population

The *Viola sororia* population was growing around the base of a tree. The positioning of the quadrats around the base of the tree may have contributed variation to the light readings as one of the quadrats faced the setting sun while the other quadrats were usually subject to ambient filtered light under the mature tree. The *Viola'*s size and amount of foliage also varied with the seasons, being lusher in summer and having fewer leaves in winter. Weeds were also regularly found at this site, but they were all perennial species. The *Agrostis capillaris* found is likely a remnant from pre-existing lawn which continuously emerges from stolons; and the *Tradescantia fluminensis* is a perennial which also spreads vegetatively. Hence the low R:FR environment under the *Viola* foliage, even when it is at its most lush in summer, did not deter those weeds. Being sited under a tree, leaf litter covers the ground throughout the year and was most prominent during autumn. The leaf litter may have discouraged weeds from germinating from the soil bank.

4.7 Conclusion

This project sampled pre-existing ground cover populations to observe if ground cover canopy in mature populations can be well-maintained at all times so as to be effective against weeds. However, there were a myriad of differences in site conditions, such as presence of mulch; varying soil textures and types; landscape maintenance regime; site topography; proximity and types of companion planting; irregular times of day; and variances in cloud cover. As such, no direct comparisons could be made with regards to the effectiveness of these ground covers against weed invasion.

However, the sites monitored were all intended as an aesthetic installation; and this was mainly achieved by the planting of ornamental ground cover plants for visual enhancement; and to keep out unsightly weeds. The intention to keep weeds at bay was further reiterated by the fact that many of these sites had mulch applied (which prevents weed seed germination from the soil bank), and they all received regular hand weeding maintenance. This multi-pronged approach did keep weed numbers low at most sites. The weed numbers could have been kept down even more, if judicious spot-application of low-risk herbicides such as haloxyfop (only kills grasses, safe on most dicotyledons) or glyphosate (foliar action, no residual effects, and deactivated by soil) had been used at the right time. During the period of monitoring, no herbicides were applied.

Across the various ground cover species, some general observations can be made regarding effective weed deterrence by the plants. Ground cover plants rely mainly on a dense foliage canopy which shades out the soil surface, thereby preventing seeds from germination which is triggered by a high R:FR light conditions. Species such as *Cotyledon orbiculata*, *Juniperus procumbens,* and *Plectranthus ciliatus* maintained a dense, unbroken canopy at all times of the year and were unlikely to have weeds germinating from within their planting beds. This was in contrast to species like *Ajuga reptans, Pimelea prostrata* and *Viola sororia,* which opened up during winter, and *Grevillea lanigera* which permitted more light through when flowering.

The presence of a mulch layer effectively prevented seeds in the soil bank from germinating, but could not prevent seeds from external sources like the wind-blown Asteraceae family weed seeds or the seeds of *Euphorbia peplus* which is dispersed through explosive action, and subsequent animal or environmental carriers.

Weeds which were already well established at or near the site and possessed vegetative structures like rhizomes and stolons were also difficult to keep out with ground cover plants, mulch, and hand weeding alone. The observation with *Pimelea prostrata* also showed that a narrow and linear planting design exposed the ground cover area to greater risk of succumbing to invasive weeds, as there is more contact with the external environment.

Further investigative work could also be carried out on ground cover species with extensive stoloniferous or rhizomatous networks to determine if aggressive rooting outcompetes weeds for soil resources, despite poorer light blockage, as in the case of *Muehlenbeckia axillaris.*

Chapter 5 Herbicide trials for three ground cover species of different growth forms

5.1 Introduction

Ground cover plants can help reduce the labour requirement for weeding of planted sites, and also reduce use of herbicides needed for weed control. However, the establishment phase of ground covers is vulnerable to weed invasion when the ground cover plants are small and have been planted at appropriate spacings, which leaves large gaps in the planting bed between plants. Clearly, some form of weed control is necessary during the establishment phase of a ground cover planting before the ground cover plant can exert any competitive advantage over weeds.

To mitigate against the time- and labour-intensiveness of hand- and tool-based weeding, synthetic herbicides were developed and popularised for agricultural use from the 1930s onwards. However, due to their relatively high cost, herbicides are used mainly in the more developed economies. As urban populations seek higher quality-of-life, non-agricultural applications, such as for aesthetic and recreational purposes, and the maintenance of urban infrastructure such as railway tracks and motor vehicle highways, have also become widespread (Krech et al. 2004). Selective herbicides were used to assist with ground cover establishment in the project outlined below, and their effectiveness has been evaluated.

Before widespread use of ground cover plants can be adopted, it is necessary to determine the best method to establish them on a large scale for weed suppression. Possible methods include mulching, hand weeding, and the use of selective herbicides. However, before a comparison could be made between these methods, it was necessary to determine which herbicides were safe to use on each ground cover species. These findings were subsequently used when further trials were carried out to determine the best establishment method, so selective herbicide treatments could be compared.

5.1.1 Objective

Herbicide trials were carried out to determine which selective herbicides would be tolerated by the following three ground cover species: the single-stemmed, woody *Coprosma acerosa* 'Taiko', the scrambling *Persicaria capitata* which sets seed profusely and easily roots at stem nodes, and the succulent herbaceous *Sedum mexicanum* 'Acapulco Gold' which can regenerate from fragments and also roots easily from stem nodes. These species were introduced in Chapter 3. For each species, two herbicide trials were carried out.

Part of this chapter was published as: Foo, C. L., Harrington, K. C., & MacKay, M. B. (2010). Herbicide tolerance of three ornamental ground cover species: *Polygonum capitatum, Sedum mexicanum* and *Soleirolia soleirolii*. Proceedings of the 17th Australasian Weeds Conference, pp 303-306.

5.2 Herbicide trials

A total of 24 commercial herbicide products were used for the trials described in this chapter. While not all products were used in each trial, many of these products were used more than once. For convenience, all products used in this trial are listed in Table 5.1 for easy reference.

Table 5.1 Product list and description of herbicides used in trials for Chapter 5

No.	Active Ingredient	Product	Description
1	2,4-D/Dicamba	Banvine	Contains 200 g/litre 2,4-D plus 100 g/litre dicamba both as amine salts in the form of a soluble concentrate.
2	aminopyralid	Tordon Max	Contains 30 g/litre aminopyralid as the triisopropylamine salt in the form of a soluble concentrate.
3	amitrole	Amitrole 4L	Contains 400 g/litre amitrole plus 100 g/litre ammonium thiocyanate in the form of a soluble concentrate.
4	bentazone	Basagran	Contains 480 g/litre bentazone in the form of a soluble concentrate.
5	bromoxynil +ioxynil + mecoprop	Axall	Contains 75 g/litre bromoxynil, 75 g/litre ioxynil, both as octonoate and heptanoate esters and 345 g/litre mecoprop as the iso-octyl ester in the form of an emulsifiable concentrate.
6	clopyralid	Versatill	Contains 300 g/litre clopyralid as the amine salt in the form of a water soluble concentrate.
7	dicamba	Banvel	Contains 200 g/litre dicamba as the dimethylamine salt in the form of a soluble concentrate.
8	dicamba/ MCPA/ mecoprop/	Kiwicare Turfclean Ready Mix	Contains 1.68 g/L mecoprop, 0.42 g/L MCPA, 0.21 g/L dicamba as a liquid.
9	diflufenican	Quantum	Contains 500 g/litre diflufenican in the form of a suspension concentrate.
10	diuron	Karmex	Contains 800 g/kg diuron in the form of a water dispersible granule.
11	glufosinate	Buster	Contains 200 g/litre glufosinate-ammonium in the form of water soluble concentrates.
12	glyphosate	Transorb 540	Contains 540 g/litre glyphosate as the potassium salt in the form of a soluble concentrate.
13	haloxyfop	Gallant NF	Contains 100 g/litre haloxyfop [(R)-isomer] as the methyl ester in the form of an emulsifiable concentrate.
14	MCPA	DowElanco MCPA	Contains 375 g/litre MCPA as the potassium salt in the form of a soluble concentrate.
15	metsulfuron	Escort	Contains 600 g/kg metsulfuron-methyl ester in the form of a water dispersible granule (dry flowable).
16	oxadiazon	Foresite	Contains 380 g/litre oxadiazon in the form of a suspension concentrate.
17	oxyfluorfen	Goal	Contains 240 g/litre oxyfluorfen in the form of an emulsifiable concentrate.
18	paraquat/diquat	Preeglone 250	Contains 135 g/litre paraquat plus 115 g/litre diquat as the dichloride and dibromide salts respectively in the form of a soluble concentrate.
19	pendimethalin	Stomp 330E	Contains 330 g/litre pendimethalin in the form of an emulsifiable concentrate.
20	simazine	Gesatop 500FW	Contains 500 g/litre simazine in the form of a suspension concentrate.
21	tribenuron	Granstar	Contains 750 g/kg tribenuron-methyl in the form of water dispersible granules.
22	triclopyr / picloram	Tordon Brushkiller	Contains 100 g/litre picloram (amine salt) plus 300 g/litre triclopyr (butoxyethyl ester as an emulsifiable concentrate), and 410 g/litre diethylene glycol.

5.2.1 *Persicaria capitata* herbicide trials

5.2.1a *Persicaria capitata* herbicide trial: Materials and methods

P. capitata plants were propagated in PB 2 bags containing potting mix with 3-month slow release Osmocote and dolomite, using stem cuttings about 15 cm long. The cuttings were allowed to establish for 3 months. During this time, stems and leaves of the plants were pruned and arranged to ensure that they stayed within the confines of the planting bags.

For the first herbicide trial, there were 21 treatments (Table 5.2) each with five replicates. Each treatment was applied by a hand-held pump sprayer (Fig 5.1) at a distance of about 30 cm to ensure even coverage over the whole planting bag. This was intended to simulate spot–spraying by a gardener using hand-operated apparatus. 4.0 ml was applied to each plant, which was the minimum to ensure full coverage of the planting bag's surface area; and the planter bag diameter was 13 cm on average when fully packed. The water rate equated to 3013.6 L ha^{-1}, but for dose calculations, this was rounded to 3010 L ha^{-1}. Treatments were applied to each plant individually on a bench, before being transferred to assigned floor space in an unheated shade house. The plants were arranged randomly in rows of 20 plants, with care taken that no part of the plants were touching each other during placement. The automated overhead sprinkler irrigation was activated at 9 am daily for 10 minutes.

Figure 5.1 Hand held pump sprayer similar to the one used for herbicide application in trials

Every 2-3 weeks, the plants were scored on a scale of 1-10, with 1 being healthy and 10 being completely necrotic. The trial lasted 18 weeks from 20 June 2008 to 24 October 2008. The mean maximum and minimum temperatures 3 weeks following the herbicide application were 12.8^{o}C and 2.4^{o}C respectively. A visual sample of the scores used is illustrated in the Fig. 5.2.

Figure 5.2 Sample of scores in herbicide trial (from left): *P. capitata* plants with scores 1, 3, 6, 9

A second trial was set up with 22 treatments (Table 5.3) on 18 March 2009 following the same methodology as the first trial. This trial lasted 21 weeks, and ended on 14 August 2009. The mean maximum and minimum temperatures 3 weeks following the herbicide application were 19.0^{o}C and 8.0^{o}C respectively. The treatments chosen for the second trial were those which did not kill or seriously damage (scored above 8) the *P. capitata* in the first trial. These herbicides were re-tested in this trial using different rates to test the plant's tolerance, and to re-confirm the results of the last trial in warmer weather.

5.2.1b *Persicaria capitata* herbicide trial: Results

The results of the first herbicide trial for *P. capitata* are shown in Table 5.2. Herbicides which were very damaging (mean scores above 8) to *P. capitata* were: 2,4-D/dicamba (Banvine), amitrole, glufosinate, MCPA, MCPA/mecoprop/dicamba mix, mecoprop / ioxynil / bromoxynil mix (Axall), metsulfuron, oxyfluorfen, paraquat/diquat mix (Preeglone), and triclopyr/picloram mix (Tordon Brushkiller).

The herbicides which caused some damage but were tolerated and allowed the *P. capitata* to recover were clopyralid, dicamba, diflufenican, glyphosate, oxadiazon, and pendimethalin (Table 5.2). Some herbicides which appeared to be safe to use on *P. capitata* were bentazone, haloxyfop, simazine, and tribenuron (Table 5.2).

Table 5.2 Mean scores (1 = healthy, 10 = dead) of herbicide treatments on *Persicaria capitata* trial 1 at 1-18 weeks after treatment (WAT)

Active Ingredient	*Dose (kg ai ha^{-1})*	1 WAT	3 WAT	5 WAT	7 WAT	10 WAT	13 WAT	18 WAT
2,4-D/dicamba	1.2/0.602	*3.2	*5.2	*6.2	*9.8	*9.8	*10.0	*9.6
amitrole	1.2	2.2	3.2	4.4	5.6	*6.8	*8.4	*9.0
bentazone	1.44	2.2	3.0	3.4	4.0	3.8	2.6	1.8
clopyralid	0.909	2.2	4.2	*5.6	5.6	*5.4	*5.8	3.4
dicamba	0.401	*3.4	4.4	4.6	4.0	4.6	3.6	2.4
diflufenican	0.301	2.0	4.2	4.8	6.0	*6.0	3.8	2.2
glufosinate	1.2	*3.6	*7.2	*9.8	*10.0	*9.8	*9.6	*7.4
glyphosate	3.25	2.0	3.0	4.0	3.8	4.4	*5.4	3.4
haloxyfop	0.909	2.0	4.2	4.6	4.6	3.0	2.4	1.2
MCPA	1.13	*4.8	*7.4	*9.8	*10.0	*10.0	*10.0	*10.0
MCPA/mecoprop /dicamba	0.737/ 2.71/ 0.201	*3.6	4.4	*6.6	*8.8	*9.0	*9.8	*9.8
mecoprop/ioxynil /bromoxynil	0.226/ 0.226	2.6	4.4	*6.8	*8.2	*8.4	*7.8	*4.6
metsulfuron	0.0903	2.0	3.2	5.0	*7.0	*8.2	*9.2	*7.6
oxadiazon	0.763	*3.8	*4.6	*6.4	*7.0	*6.6	3.8	2.0
oxyfluorfen	1.2	*6.0	*8.0	*10.0	*10.0	*10.0	*7.6	*5.4
paraquat/diquat	1.22/1.04	*6.8	*9.8	*10.0	*10.0	*10.0	*8.4	*8.6
pendimethalin	1.49	2.2	3.2	4.6	5.0	5.0	4.2	2.0
simazine	1.51	2.2	3.6	4.0	4.0	3.2	2.4	1.6
tribenuron	0.0909	2.0	1.8	2.8	3.4	2.6	2.0	1.0
triclopyr / picloram	1.81/0.602	*3.4	*5.0	*6.6	*10.0	*10.0	*10.0	*9.2
untreated	n.a.	2.0	2.8	3.6	4.2	3.6	2.6	1.4
$LSD_{0.05}$		0.9	1.7	1.7	2.0	1.8	1.7	2.3

* indicates significant difference from the untreated control
$LSD_{0.05}$ = Least Significant Difference

In the second trial, herbicides which were very damaging to *P. capitata* were dicamba (both rates), and glyphosate (high) (Table 5.3). Less damaging herbicides which caused some visual effect to *P. capitata* which then subsequently recovered were clopyralid (all rates), diflufenican (both rates), glyphosate (low), and oxadiazon (both rates).

The herbicides which appeared to be safe on *P. capitata* with the rates tested in the second trial were bentazone (both rates), haloxyfop (both rates), pendimethalin (both rates), simazine (both rates), and tribenuron (both rates) (Table 5.3).

It appears that dicamba is an effective herbicide for the control of *P. capitata.* When dicamba was sprayed in combination with 2,4-D during the cooler conditions of the first trial, it severely damaged the plants within 7 weeks (Table 5.3). When dicamba was sprayed on its own during the warmer months, even the lower rate of dicamba, which was less than the 2,4-D/ dicamba mix, produced severely damaging results within 5 weeks after application.

Table 5.3 Mean scores (1 = healthy, 10 = dead) of herbicide treatments on *Persicaria capitata* trial 2 at 3-21 weeks after treatment (WAT)

Active Ingredient	*Dose (kg ai ha^{-1})*	*3 WAT*	*5 WAT*	*7 WAT*	*9 WAT*	*13 WAT*	*15 WAT*	*21 WAT*
bentazone (low)	1.44	1.8	2.4	3.6	2.6	2.6	2.0	1.6
bentazone (high)	2.89	1.6	2.4	3.4	2.6	1.8	1.8	1.6
clopyralid (low)	0.452	*3.6	3.0	4.6	2.0	2.2	2.0	1.0
clopyralid (medium)	0.903	*5.0	*5.2	*5.8	3.8	3.0	3.2	1.6
clopyralid (high)	1.81	*4.8	*4.6	*6.0	3.4	*4.6	2.6	1.6
dicamba (low)	0.421	*6.6	*8.6	*9.2	*8.8	*9.2	*8.2	*8.2
dicamba (high)	0.843	*7.4	*9.6	*9.6	*10.0	*10.0	*10.0	*10.0
diflufenican (low)	0.1	*3.4	3.4	4.4	2.2	1.2	1.8	1.2
diflufenican (high)	0.201	*3.6	*4.0	4.8	1.6	2.4	1.0	1.2
glyphosate (low)	1.08	*3.6	2.8	3.2	*4.4	3.2	*4.6	1.2
glyphosate (high)	2.17	*3.4	3.4	4.4	*7.4	*9.8	*9.8	*9.8
haloxyfop (low)	0.903	2.0	2.4	3.2	2.4	2.2	1.8	1.4
haloxyfop (high)	1.81	1.6	1.8	3.0	2.6	2.2	1.8	1.4
oxadiazon (low)	0.742	*4.4	2.6	3.4	1.4	1.6	1.2	1.2
oxadiazon (high)	1.48	*4.8	2.8	4.0	1.2	1.4	1.4	2.4
pendimethalin (low)	1.49	1.6	1.4	2.2	2.2	2.2	1.8	1.2
pendimethalin (high)	2.98	2.4	2.6	3.2	2.6	2.6	2.4	1.6
simazine (low)	1.51	1.8	2.0	3.0	1.8	2.0	1.8	1.2
simazine (high)	3.01	1.8	1.6	2.4	2.6	2.6	2.6	1.6
tribenuron (low)	0.0903	2.0	3.0	4.0	2.2	1.8	1.4	1.6
tribenuron (high)	0.181	2.2	2.2	2.8	1.8	1.0	1.2	2.6
control	n.a.	1.8	2.4	3.6	2.6	2.6	2.0	1.6
LSD0.05		1.4	1.4	1.6	1.7	1.3	1.5	1.4

* indicates significant difference from the untreated control
$LSD_{0.05}$ = Least Significant Difference

More severe damage caused by application during a warmer time of the year was not limited to dicamba. The effects of glyphosate were also seemingly tolerated by *P. capitata* when applied during the cooler period of the first trial (Table 5.2). During the warmer month of application for the second trial, even a lowered rate of 2.17 kg ai ha^{-1} produced severe damage to the plants; although further lowering to 1.08 kg ai ha^{-1} was tolerated (Table 5.3).

On the other hand, the slightly damaging effects of pendimethalin in the first trial appeared to be due to environmental causes, as it occurred only when the control plants were stressed. The damage did not occur when the treatment was repeated during the warmer application period of the second trial; nor did increased rates of pendimethalin produce any significant damage in the second trial.

5.2.1c *Persicaria capitata* herbicide trials: Discussion

With three residual herbicides (oxadiazon, pendimethalin and simazine) well tolerated by *P. capitata*, many options exist for extending the weed-free period after transplanting the ground cover species to assist in early establishment. As the plants get more established, grass weeds can easily be controlled with haloxyfop. Should broad-leaved weeds be more problematic, the use of clopyralid, diflufenican, bentazone and tribenuron, which control a wide range of species between them, would prove useful. If both monocotylenous and dicotyledonous weeds are present, haloxyfop can be added to the herbicides which control broad-leaved weeds.

5.2.2 *Sedum mexicanum* herbicide trials

5.2.2a *Sedum mexicanum* herbicide trials: Materials and methods

S. mexicanum plants were propagated in PB ¾ bags containing potting mix with 3-month slow release Osmocote and dolomite, using stem cuttings about 10 cm long. The cuttings were allowed to establish for 3 months. During this time, stems and leaves of the plants were pruned and arranged to ensure that they stayed within the confines of the planting bags.

In the first herbicide trial, there were 20 treatments (Table 5.4) each with five replicates. Each treatment was applied by a hand-held pump sprayer at a distance of about 30 cm to ensure even coverage over the whole planting bag. 2.0 ml was applied to each plant, and the diameter of the fully packed PB ¾ bag was 9 cm. The water rate equated to 3143.9 L ha^{-1}, which was rounded to 3140 L ha^{-1} for dosage rate calculations. Treatments were applied to each plant individually on a bench, before being transferred to assigned floor space in a shade house. The plants were arranged in a completely randomised manner in rows of 20 plants, with care taken that no part of the plants were touching each other during placement. The shade house was equipped with overhead sprinkler irrigation activated once daily at 9 am for 10 minutes.

Every 2-3 weeks, the plants were scored on a scale of 1-10, with 1 being healthy and 10 being completely necrotic (Fig 5.3). The trial lasted 18 weeks from 20 June 2008 to 24 October 2008. The mean maximum and minimum temperatures three weeks following the herbicide application were 12.8^{o}C and 2.4^{o}C respectively.

Figure 5.3 Sample of scores in herbicide trial (from left): *S. mexicanum* plants with scores 1, 3, 6, 9

A second trial was conducted for *S. mexicanum* with the same herbicides but applied during a warmer time of the year. The trial was conducted from 24 March 2009 to 14 August 2009. The mean maximum and minimum temperatures 3 weeks following the herbicide application were 18.9^{o}C and 7.3^{o}C respectively. For three treatments, the dose used was changed. The rate for glyphosate was reduced, a different rate was used for the MCPA / mecoprop / dicamba treatment, and the diflufenican dose was lowered. The rates for the other treatments remained the same, to test the effects of warm weather application on the herbicide treatments.

5.2.2b *Sedum mexicanum* herbicide trial: Results

In the first trial, herbicides which were very damaging to *S. mexicanum* were diflufenican, and the paraquat/ diquat mix (Table 5.4).

Table 5.4 Mean scores (1 = healthy, 10 = dead) of treatments on *S. mexicanum* Trial 1 at 1-18 weeks after treatment (WAT)

Active Ingredient	*Dose (kg ai ha^{-1})*	*1 WAT*	*3 WAT*	*5 WAT*	*7 WAT*	*10 WAT*	*13 WAT*	*18 WAT*
2,4-d/dicamba	1.26/0.628	2.6	*3.0	*2.4	*2.4	2.2	1.2	1.0
amitrole	1.26	1.6	1.6	1.8	1.0	1.4	1.4	1.0
bentazone	1.51	1.8	2.0	1.0	1.2	1.4	1.6	1.0
clopyralid	0.942	2.2	1.4	1.8	1.4	1.6	1.8	1.0
dicamba	0.44	1.8	1.8	1.2	1.0	1.2	1.0	1.0
diflufenican	0.314	*3.2	*3.6	*3.4	*3.2	*6.8	*8.4	*9.0
glufosinate	1.26	2.0	2.6	*6.6	*5.0	*5.2	*3.2	*2.8
glyphosate	3.39	2.0	1.0	1.0	1.0	1.2	1.0	1.0
haloxyfop	0.942	2.0	1.6	1.0	1.0	1.2	1.4	1.0
mcpa	1.18	2.6	*3.2	*5.2	*4.2	*4.0	1.6	1.0
mcpa/ mecoprop/ dicamba	0.769/2.83/0.209	2.4	1.8	1.6	1.2	1.4	1.2	1.0
mecoprop/ ioxynil/ bromoxynil	1.08/0.236/0.236	2.2	*3.4	*3.6	2.0	1.4	1.0	1.0
metsulfuron	0.0942	1.8	1.0	1.0	1.0	1.2	1.4	1.0
oxadiazon	0.795	*3.4	*6.2	*6.4	*5.8	*4.2	2.2	1.0
paraquat/ diquat	1.27/1.08	*6.0	*10.0	*10.0	*10.0	*10.0	*10.0	*10.0
pendimethalin	1.55	2.0	1.0	1.0	1.0	1.0	1.4	1.0
simazine	1.57	2.0	1.4	1.2	1.0	1.0	1.6	1.0
tribenuron	0.0942	2.2	1.0	1.2	1.0	1.6	1.0	1.0
triclopyr / picloram	1.88/0.628	2.2	*3.4	*5.6	*5.6	*6.6	*6.0	*5.2
untreated	n.a.	2.2	2.0	1.0	1.0	1.2	1.2	1.0
$LSD_{0.05}$		0.7	0.9	1.3	1.2	1.6	1.4	1.6

* indicates significant difference from the untreated control

$LSD_{0.05}$ = Least Significant Difference

Those herbicides which caused some damage to *S. mexicanum* but where the plants subsequently recovered were 2,4-D/dicamba, glufosinate, MCPA, oxadiazon, and the mixtures mecoprop/ ioxynil/ bromoxynil (Axall), and triclopyr / picloram. Herbicides which appeared to be safe on *S. mexicanum* with little observable visual damage when used at the rates tested in this trial were amitrole, bentazone, clopyralid, dicamba, haloxyfop, MCPA/ mecoprop/ dicamba, metsulfuron, pendimethalin, simazine, and tribenuron.

In the second trial, herbicides which were very damaging to *S. mexicanum* were: paraquat/diquat mix (high), diflufenican (both rates), and triclopyr / picloram mix (both rates) (Table 5.5).

Table 5.5 Mean scores (1 = healthy, 10 = dead) of herbicide treatments on *Sedum mexicanum* trial 2 at 3-20 weeks after treatment (WAT)

Active Ingredient	*Dose (kg ai ha^{-1})*	*3 WAT*	*5 WAT*	*7 WAT*	*9 WAT*	*11 WAT*	*13 WAT*	*15 WAT*	*20 WAT*
2,4-D/dicamba	1.26/0.628	*3.4	2.6	2.8	*3.4	2.2	2.4	2.0	1.0
amitrole	0.209	1.4	2.2	2.4	*2.8	2.6	2.8	2.4	1.2
bentazone	1.51	1.8	2.0	2.0	2.2	2.2	2.4	3.0	1.2
clopyralid	0.942	1.6	1.6	2.0	2.0	1.4	1.8	2.8	1.0
dicamba	0.44	*5.2	*4.8	*4.6	*4.8	*4.6	*3.6	2.4	1.0
diflufenican (low)	0.105	*3.2	*4.0	*6.2	*7.8	*8.8	*9.2	*9.6	*10.0
diflufenican (high)	0.209	*4.8	*5.4	*5.4	*7.6	*8.6	*9.4	*9.4	*10.0
glufosinate	0.628	2.2	2.2	2.2	2.4	1.2	1.6	1.0	1.0
glyphosate	2.26	1.8	1.6	1.8	*2.8	3.2	3.0	*4.8	1.2
haloxyfop	0.942	1.4	1.4	1.8	2.2	1.4	1.8	1.8	1.2
MCPA	1.18	*6.6	*6.8	*6.8	*6.8	*5.4	*4.2	2.8	1.0
MCPA/ mecoprop/ dicamba	1.32/5.28/0.659	*5.0	*4.8	*6.2	*5.4	*4.0	2.8	2.6	2.2
mecoprop/ioxynil/bromoxynil	1.08/0.236/0.236	*4.8	1.6	1.6	2.2	1.6	1.8	1.6	1.0
metsulfuron	0.0942	1.6	1.6	1.4	1.8	2.6	2.4	3.2	1.2
oxadiazon	0.795	*5.8	*6.4	*5.2	*3.6	2.6	*4.0	*3.8	1.0
paraquat/diquat (low)	0.628/0.544	*6.4	*4.6	*4.6	*3.8	2.8	*4.6	*4.8	*4.6
paraquat/diquat (high)	1.27/1.08	*8.6	*6.4	*9.6	*8.4	*9.0	*9.6	*8.4	*8.2
pendimethalin	1.55	*2.4	2.0	2.4	2.6	2.2	2.4	3.0	1.4
simazine	1.57	1.2	1.0	1.4	1.4	1.4	1.2	2.0	1.0
tribenuron	0.0942	1.2	1.2	1.8	1.2	1.8	2.0	2.4	1.2
triclopyr / picloram (low)	1.88/0.628	*5.6	*7.8	*8.0	*8.2	*8.2	*7.4	*7.0	*6.8
triclopyr / picloram (high)	3.77/1.26	*6.8	*7.8	*9.4	*9.4	*9.4	*8.4	*6.0	*4.6
untreated	n.a.	1.2	1.0	1.2	1.0	1.4	1.2	1.6	1.0
$LSD_{0.05}$		1.2	1.9	1.7	1.8	1.9	2.0	2.0	2.3

* indicates significant difference from the untreated control
$LSD_{0.05}$ = Least Significant Difference

The following herbicides caused some damage to *S. mexicanum* in the second trial but the plants subsequently recovered: 2,4-D/dicamba (Banvine), dicamba, MCPA, MCPA/ mecoprop/ dicamba mix, mecoprop / ioxynil / bromoxynil (Axall), oxadiazon, pendimethalin, and paraquat/diquat (low). Finally, some herbicides appeared to be safe on *S. mexicanum* with the rates tested in this trial: amitrole, bentazone, clopyralid, glufosinate, glyphosate, haloxyfop, metsulfuron, simazine, and tribenuron (Table 5.5).

The most damaging herbicide appeared to be diflufenican, which caused discolouration even when rates were twice lowered in the second trial. However, the higher temperatures during the period after application might have played a role. Temperature clearly affected the results of the picloram/ triclopyr mixture when the plants seemingly tolerated this treatment in the colder temperatures of the first trial, but significant damage was observed in the warmer second trial, including at the lower rate.

On the other hand, the paraquat and diquat mixture at the higher rate caused significant damage during both trials, suggesting that temperature differences did not matter. The lower rate appears to be tolerated by *S. mexicanum* with the noted recovery in the second trial, though some damage was observed at three weeks after treatment.

The *Sedum mexicanum* plants also seemed to tolerate glufosinate at sufficiently low doses which still prove useful for weed control. Some burn effects were observed in the first trial, but no significant effects were observed in the second trial with a lowered dose, even at the warmer temperatures at time of application.

The dicamba/ MCPA/ mecoprop mixture used in the first trial was a custom blend using individual products containing single active ingredients. This was well tolerated by *S. mexicanum*. However, when a commercial product with a higher dose was applied on the plants, damage was observed.

5.2.2c *Sedum mexicanum* herbicide trials: Discussion

Simazine and pendimethalin are residual herbicides that can be used to prevent weeds establishing between *Sedum mexicanum* plants. Subsequently, grass weeds can be controlled with haloxyfop. Translocated knock-down herbicides suitable for broad-leaved weeds include amitrole, clopyralid, metsulfuron and tribenuron. Smaller weeds like annuals may be effectively controlled by bentazone. If weeds are not controlled by any of these herbicides, then glyphosate and glufosinate are further options.

Sedum species are capable of being weedy due to the strong regenerative properties of the plant, even from short stem fragments. An example is *Sedum acre* which is weedy in the UK (Chatto & Wooster 2000) and USA (Buchanan 2000). Therefore being able to control this species effectively using herbicides with various modes of action is worthwhile. For medium to long term control, the residual herbicide diflufenican may be used. The knock-down herbicide containing the mixture picloram/ triclopyr may be used if spot control is desired. For fast-acting non-selective control including *Sedum mexicanum*, the diquat/ paraquat mixture can be recommended.

5.2.3 *Coprosma acerosa* 'Taiko' herbicide trials

5.2.3a *Coprosma acerosa* 'Taiko' herbicide trial 1: Materials and methods

For the *Coprosma acerosa 'Taiko'* trial, eighty 2-year-old plants were purchased from the nursery. The first trial involved 18 treatments each with four replicates. The healthiest-looking plants were chosen and then randomly assigned to treatments. The plants were in PB 5 bags with an average diameter of 16 cm when fully packed. Each plant was sprayed individually with 6 ml of the treatment solution, equivalent to 2984.2 L ha^{-1}. An approximate water rate of 2980 L ha^{-1} was used to calculate the dosage rate. The sprayed plants were then placed within the same shade-house used for the earlier herbicide trials, in rows of 10 plants each. The plants were positioned in a completely randomised block. Every 2-3 weeks, the plants were scored on a scale of 1-10, with 1 being healthy and 10 being completely necrotic (Fig 5.4). The first trial was monitored for 26 weeks from 23 September 2009 to 28 March 2010. The mean maximum and minimum temperatures 3 weeks following the herbicide application were 14.2^{o}C and 6.2^{o}C respectively.

Figure 5.4 Sample of scores in herbicide trial (from left): *C. acerosa* plants with scores 1, 3, 6, 9

For the second trial, some of the more commonly used herbicides for landscape management were selected (Table 5.7) and tested at higher rates, with some tested at the same rates to verify the previous results. Tolerance at higher rates would increase the range of weeds controlled. This trial lasted 20 weeks from 4 October 2010 to 21 February 2011. The mean maximum and minimum temperatures 3 weeks following the herbicide application were 15.7^{o}C and 7.9^{o}C respectively.

5.2.3b *Coprosma acerosa* 'Taiko' herbicide trial: Results

Results for the first *Coprosma acerosa* herbicide trial 3-15 weeks after treatment are shown in Table 5.6. Although the trial lasted 26 weeks, results up to 15 weeks only are shown, as the plants did not show any evidence of damage beyond 11 weeks after treatment. Almost all the treatments did not seem to harm *C. acerosa* 'Taiko'. Two treatments appeared to cause slight stress to the plants. These were amitrole and the paraquat / diquat mix.

Table 5.6 Mean scores (1 = healthy, 10 = dead) of herbicide treatments on *Persicaria capitata* trial 1 at 3-15 weeks after treatment (WAT)

Active Ingredient	*Dose (kg ai ha^{-1})*	*3 WAT*	*5 WAT*	*7 WAT*	*9 WAT*	*11 WAT*	*13 WAT*	*15 WAT*
aminopyralid	0.0447	1.5	1.0	1.5	1.3	1.5	2.0	2.0
amitrole	1.19	*2.8	*2.8	2.5	*2.3	1.8	2.5	2.5
bromoxynil +ioxynil + mecoprop	0.224/0.224/1.03	1.0	1.0	*1.8	1.5	1.5	1.5	1.8
clopyralid	0.298	1.0	1.0	1.9	1.3	1.0	1.5	2.0
dicamba	0.149	1.0	1.0	1.5	1.8	1.3	1.8	2.0
diflufenican	0.0993	1.3	1.3	1.5	1.3	1.0	1.8	2.3
diuron	2.38	1.3	1.0	1.5	1.8	1.0	2.3	1.5
glufosinate	0.993	1.5	1.0	*1.8	1.5	1.3	1.8	2.5
glyphosate	0.815	1.3	1.0	1.0	1.0	1.0	2.3	2.0
haloxyfop	0.149	1.0	1.0	1.3	1.0	1.0	1.5	1.8
MCPA	1.49	1.3	1.3	1.3	1.3	1.3	1.5	2.0
oxadiazon	1.51	1.0	1.0	1.3	1.0	1.0	1.5	2.3
oxyfluorfen	1.43	1.3	1.0	1.5	1.3	1.0	1.5	1.5
paraquat+diquat	0.745	*3.0	*3.0	*3.0	*3.0	*3.3	2.5	2.5
pendimethalin	1.81	1.0	1.3	1.5	1.0	1.3	1.8	2.0
simazine	2.48	1.3	1.3	1.3	1.0	1.5	2.0	2.3
tribenuron	0.0224	1.0	1.0	1.5	1.0	1.0	1.5	1.5
untreated	n.a.	1.0	1.0	1.0	1.3	1.3	2.3	1.8
$LSD_{0.05}$		0.59	0.54	0.75	0.63	0.55	0.91	0.95

* indicates significant difference from the untreated control
$LSD_{0.05}$ = Least Significant Difference

Results for the second herbicide trial 2-20 weeks after treatment are shown in Table 5.7. None of these treatments were very damaging (score >8) nor killed any of the *C. acerosa* 'Taiko' plants. With the herbicides which caused some damage to *C. acerosa* 'Taiko', the plants subsequently recovered. These herbicides were amitrole (both rates), glufosinate (high), metsulfuron (high), and paraquat / diquat mix (both rates). Some herbicides appeared to be safe on *C. acerosa* 'Taiko' with no visible damage at the rates tested in this trial, these being: aminopyralid (both rates), clopyralid (both rates), glufosinate (low), glyphosate (both rates), MCPA (both rates), metsulfuron (low), and simazine (both rates).

Table 5.7 Mean scores (1 = healthy, 10 = dead) of herbicide treatments on *Coprosma acerosa* trial 1 at 2-20 weeks after treatment (WAT)

Active Ingredient	*Dose (kg ai ha^{-1})*	*2 WAT*	*3 WAT*	*5 WAT*	*7 WAT*	*9 WAT*	*12 WAT*	*16 WAT*	*20 WAT*
aminopyralid (low)	0.0596	2.3	2.0	1.3	1.8	1.0	1.3	1.0	1.3
aminopyralid (high)	0.119	1.8	1.5	2.3	1.8	2.0	1.8	1.3	1.3
amitrole (low)	1.19	2.5	*2.8	*3.0	*4.0	2.5	1.5	*3.5	1.0
amitrole (high)	2.38	2.8	2.5	*2.8	*3.5	2.0	1.0	*3.5	1.0
clopyralid (low)	0.298	1.8	1.0	1.3	2.0	1.0	1.0	3.0	*3.0
clopyralid (high)	0.596	1.5	1.0	1.0	1.0	1.5	1.0	1.0	1.3
glufosinate (low)	1.99	3.0	1.5	1.3	1.5	1.0	1.0	1.0	1.0
glufosinate (high)	2.98	*7.3	*7.8	*7.8	*7.0	*4.0	*2.8	1.0	1.0
glyphosate (low)	1.63	2.3	2.0	1.5	1.3	1.3	1.3	1.0	1.0
glyphosate (high)	3.8	2.3	1.8	1.8	1.3	1.0	1.0	2.0	1.0
MCPA (low)	2.24	2.8	1.5	1.3	1.3	1.0	1.3	1.8	1.0
MCPA (high)	4.47	2.5	2.0	1.5	1.5	1.3	1.3	1.0	1.3
metsulfuron (low)	0.0298	1.5	1.3	1.5	1.5	1.5	1.5	1.0	1.0
metsulfuron (high)	0.119	3.0	*3.0	*5.8	*5.8	*5.8	*7.5	1.5	1.0
paraquat+diquat (low)	0.745	*5.0	*3.3	*3.3	*3.0	*3.0	*3.0	1.5	2.0
paraquat+diquat (high)	1.49	*7.3	*7.0	*5.0	*5.3	*4.5	*3.8	*3.5	*3.0
simazine (low)	2.48	2.0	1.5	1.0	2.0	1.8	1.0	1.0	1.3
simazine (high)	4.97	1.5	1.3	1.0	1.0	1.0	1.0	1.0	1.0
untreated	n.a.	1.8	1.5	1.0	1.0	1.3	1.0	1.0	1.0
$LSD_{0.05}$		1.36	1.11	1.26	1.67	1.35	0.95	2.37	1.30

* indicates significant difference from the untreated control

$LSD_{0.05}$ = Least Significant Difference

5.2.3c *Coprosma acerosa* 'Taiko' herbicide trial: Discussion

The *Coprosma acerosa* 'Taiko' proved to be tolerant of all the herbicide treatments used in the trial, being able to recover from all ill-effects even though the trials were carried out during the warm season, and higher rates were also tested.

The wide range of herbicides tolerated by *Coprosma acerosa* allows for numerous options in weed control during establishment. Simazine can be applied for its residual weed control action to stop new weeds establishing between plants. Other residual herbicides which may also be suitable include diuron, oxadiazon, oxyfluorfen, and pendimethalin. Knock-down herbicides for broad-leaf weed control are aminopyralid, clopyralid, dicamba, metsulfuron, MCPA, tribenuron, glyphosate and glufosinate.

The species was found to be resistant to aminopyralid, clopyralid, glyphosate, MCPA, and simazine even when rates higher than recommended were applied. Amitrole caused some temporary damage, but the higher rate applied in this trial did not seem to cause worse damage, so the *Coprosma* is fairly tolerant of amitrole too. Glufosinate, metsulfuron and paraquat/diquat mix can produce damage to the plants, so high rates should be avoided.

5.3 Conclusion

The three species all showed fairly good tolerance to herbicides of different modes of action. This suggested if they were planted as ground cover plants, herbicide options would be available to assist not only during the establishment phase when the plants are fairly small, with open spaces between them, but also when the plants are mature through use of spot treatment of weeds which invade the planted area. The range of herbicides tolerated by each species means that most types of weeds can be controlled selectively.

At the same time, information was also found on which herbicides will kill the ground cover species. This gives grounds managers the reassurance that should the planted ground cover escape beyond intended areas, herbicides would be available to control their spread.

As there is relative lack of information on herbicide tolerance of species used within ornamental horticulture, this work should contribute to plant management in amenity landscapes.

Chapter 6 Comparison of establishment methods for ground cover plants of three different growth forms

6.1 Introduction

Once results from Chapter 5 had been obtained, the information could be used in the field to determine the best establishment method for ground cover plants. However, as the herbicide trials in Chapter 5 were run concurrently to the trials in this chapter, some herbicide decisions had to be made without full knowledge of the results for the herbicide trials. The use of herbicides to which each ground cover species had shown resistance or tolerance should allow competition from weeds for growth resources during establishment to be reduced.

In many less developed regions and organic themed properties, hand weeding is the most widely used method to facilitate establishment of new plants. Hand weeding was reported to be the most widely used method by organic growers in Australia; and included chipping, using forks for deep-rooted weed species, using hand or wheeled hoes, and manual pulling. This was reported to give satisfactory results, and is a vital operation (Kristiansen et al. 2001). However, the downside of hand weeding is that it is very costly and time consuming. Also, hand weeding efficiency differs greatly between individuals (Melander & Rasmussen 2001). In less developed economies where labour cost is lower, manual weeding methods using simple tools such as the garden hoe can increase efficiency and decrease worker fatigue (Chatizwa 1997). However, even in more developed nations, hand weeding is still commonly used as it is the most effective way to remove weeds growing in elaborate designs where many different species grow in close proximity. Hand weeding was one of the methods used as a comparison for the trial reported below.

Other than the use of chemicals, landscape maintenance also relies on creating a physical barrier which resists seedling emergence. As discussed in Chapter 2, wood-based mulches of varying particle sizes from sawdust to bark pieces have been used for their aesthetic appearance, weed suppressing abilities, and benefits to soil moisture relations and reducing soil temperature fluctuations. In addition to wood-based mulches, the trial discussed in the current chapter also looked at man-made barriers such as the plastic weed mat and EcoCover paper mulch.

EcoCover (www.ecocover.com) is a mulch mat made from recycled paper shreds developed in New Zealand. This can be used as mulch with all the benefits listed for mulches within Chapter 2. In addition, it is touted as a biodegradable product that will naturally decay over a period of 6-12 months when the plants are better established and can better discourage weed invasion themselves.

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The commercial product is also available in a fertiliser enriched form, but this trial used the plain paper form aimed at testing its weed suppression ability.

6.2 Objective

The objective of this trial was to investigate how best to establish ground cover species so that weeds are adequately controlled during the initial growth stage. The three species used in the trial were: the woody *Coprosma acerosa* 'Taiko', the scrambling *Persicaria capitata,* and the succulent herbaceous *Sedum mexicanum* 'Acapulco Gold'. These species were introduced in Chapter 3 and were also studied in Chapter 5.

A range of mulch options were compared with selective herbicides and hand-weeding for these three ground cover species of different forms. Effects of mulch on soil temperature and moisture were also monitored to determine whether different mulch treatments affect soil temperature and water availability (infiltration and evaporation rates) for growth.

6.3. Mulch and cover materials

As stated above, the three species used in this trial were *Coprosma acerosa* 'Taiko', *Persicaria capitata,* and *Sedum mexicanum* 'Acapulco Gold'. Each species was planted in plots receiving the following treatments:

1. Hand-weeding of bare soil every 2 months.
2. Selective herbicides to control weeds establishing on bare soil five times over a year.
3. Sawdust mulch – Particle size between 2-4 mm: about 50% by weight of the sawdust could be sieved through a 2 mm mesh; and 71% through a 4 mm mesh. This was the same sawdust as used in Chapter 3.
4. Woodchip mulch – Particle size between 8-16 mm: 58% by weight of woodchips could be sieved through an 8 mm mesh; and 89% through a 16 mm mesh.
5. Bark nugget mulch – Particle size between 22.4 - 31.5mm: 62% by weight of the bark nuggets could be sieved through a 22.4 mm mesh and 94% through a 31.5 mm mesh.
6. Paper mulch (EcoCover) – shredded paper compressed between recycled unbleached paper.
7. Black plastic weed mat – regular black polythene weed mat from the garden centre.
8. Weedmat with woodchip mulch on top.

6.4. Methods: Establishment trial

Plots of cultivated Manawatu fine sandy loam soil 2 m by 2 m were each planted with three plants of either *P. capitata* or *S. mexicanum*, or two plants of *C. acerosa*, all at 1.0 m from each other within the plot (Fig 6.1). The eight weed control strategies listed above were compared for each of the three species. The bark nuggets, wood chips and sawdust were laid to a minimum depth of 7 cm, and the treatment of wood chips on black weed mat had wood chips laid to a depth of 3-4 cm. The hand-weeded treatment was aided by a hand hoe every 6-8 weeks to remove weeds, and also a treatment in which selective herbicides were used as required. The black weed mat and paper mulch were laid in a single layer. The herbicides used varied depending on the weed species present (Table 5.1), and were applied using a back pack sprayer.

The trial was established in late November 2008. Plots treated with bark nuggets and wood chips had 100 kg N/ha (as sulphate of ammonia) applied prior to laying of the mulch to allow for nitrogen immobilisation, and sawdust plots received 200 kg N/ha. All combinations of ground cover species and weed control strategies were replicated three times using a randomised block design (Fig 6.2). At planting, the average diameter of ground cover plants was 8.5 cm, 25.6 cm and 33.9 cm for *S. mexicanum*, *P. capitata* and *C. acerosa* respectively. Every 2 months the diameter of each cover plant was measured, then estimates were made of the percentage ground cover in each plot once the plants grew into each other (as in the case of the *P. capitata*). The number of weeds per plot was counted every 2 months from February to October 2009 and in January 2010, and then they were removed manually after each counting or sprayed and left to die in the case of the herbicide treatment. The EcoCover mulch broke down after 6 months, so herbicides were applied in these plots in November 2009 and February 2010.

Figure 6.1 The establishment trial four months after setup

	1	2	3	4	5	6	7	8	9
1	*Sedum mexicanum* Weed mat	*Persicaria capitata* Bark nuggets	*Sedum mexicanum* Sawdust	*Coprosma* 'Taiko' Sawdust	*Persicaria capitata* Weed mat	*Sedum mexicanum* Hand weed	*Sedum mexicanum* Sawdust w/ weed mat	*Coprosma* 'Taiko' Hand weed	*Sedum mexicanum* Bark nuggets
2	*Persicaria capitata* Hand weed	*Coprosma* 'Taiko' Weed mat	*Sedum mexicanum* Wood chips	*Persicaria capitata* Paper	*Persicaria capitata* Herbicide	*Persicaria capitatum* Sawdust w/ weed mat	*Persicaria capitata* Sawdust	*Sedum mexicanum* Herbicide	*Persicaria capitata* Wood chips
3	*Coprosma* 'Taiko' Herbicide	*Coprosma* 'Taiko' Paper	*Coprosma* 'Taiko' Bark nuggets	*Sedum mexicanum* Paper	*Coprosma* 'Taiko' Sawdust w/ weed mat	*Coprosma* 'Taiko' Wood chips	*Persicaria capitata* Paper	*Persicaria capitata* Sawdust	*Coprosma* 'Taiko' Sawdust
4	*Sedum mexicanum* Paper	*Coprosma* 'Taiko' Hand weed	*Persicaria capitata* Wood chips	*Persicaria capitata* Bark nuggets	*Persicaria capitata* Herbicide	*Coprosma* 'Taiko' Herbicide	*Sedum mexicanum* Weed mat	*Coprosma* 'Taiko' Bark nuggets	*Sedum mexicanum* Bark nuggets
5	*Persicaria capitata* Weed mat	*Coprosma* 'Taiko' Sawdust w/ weed mat	*Coprosma* 'Taiko' Wood chips	*Persicaria capitata* Hand weed	*Coprosma* 'Taiko' Weed mat	*Persicaria capitata* Sawdust w/ weed mat	*Sedum mexicanum* Sawdust w/ weed mat	*Sedum mexicanum* Sawdust	*Sedum mexicanum* Wood chips
6	*Sedum mexicanum* Hand weed	*Sedum mexicanum* Herbicide	*Coprosma* 'Taiko' Paper	*Sedum mexicanum* Herbicide	*Sedum mexicanum* Bark nuggets	*Coprosma* 'Taiko' Weed mat	*Persicaria capitata* Paper	*Sedum mexicanum* Weed mat	*Sedum mexicanum* Sawdust
7	*Sedum mexicanum* Hand weed	*Sedum mexicanum* Paper	*Persicaria capitata* Sawdust	*Coprosma* 'Taiko' Sawdust	*Persicaria capitata* Weed mat	*Persicaria capitata* Wood chips	*Coprosma* 'Taiko' Wood chips	*Coprosma* 'Taiko' Bark nuggets	*Coprosma* 'Taiko' Sawdust w/ weed mat
8	*Persicaria capitata* Bark nuggets	*Sedum mexicanum* Sawdust w/ weed mat	*Persicaria capitata* Hand weed	*Persicaria capitata* Herbicide	*Coprosma* 'Taiko' Paper	*Coprosma* 'Taiko' Herbicide	*Coprosma* 'Taiko' Hand weed	*Persicaria capitata* Sawdust w/ weed mat	*Sedum mexicanum* Wood chips

Colour Key Block 1 Block 2 Block 3

North

Figure 6.2 Plot layout of combinations of ground cover species and eight establishment treatments

Herbicides were applied on the herbicide treatment plots as needed, and the herbicides were selected based on the weeds present and herbicide tolerance as determined in Chapter 5. Herbicides were applied in February, March, and April 2009, then again in November 2009 and February 2010. The herbicides were applied at a water rate equivalent to 1500 L ha^{-1}, but only at the spots where the weeds were located, using a backpack sprayer. The herbicides applied are listed in Table 6.1.

Table 6.1 Herbicides applied for herbicide treatment plots

Herbicide application date: 9 February 2009	
Ground cover species	Herbicide & rate (kg ai ha^{-1})
Coprosma acerosa	clopyralid (0.45 kg ai ha^{-1}) and haloxyfop (0.45 kg ai ha^{-1})
Persicaria capitata	clopyralid (0.45 kg ai ha^{-1}) and haloxyfop (0.45 kg ai ha^{-1})
Sedum mexicanum	clopyralid (0.45 kg ai ha^{-1}) and haloxyfop (0.45 kg ai ha^{-1})
Herbicide application date: 5 March 2009	
Ground cover species	Herbicide
Coprosma acerosa	clopyralid (0.45 kg ai ha^{-1}) and haloxyfop (0.45 kg ai ha^{-1})
Persicaria capitata	clopyralid (0.45 kg ai ha^{-1}) and haloxyfop (0.45 kg ai ha^{-1})
Sedum mexicanum	metsulfuron (45 g ai ha^{-1}) and simazine (2.25 kg ai ha^{-1})
Herbicide application date: 2 April 2009	
Ground cover species	Herbicide
Coprosma acerosa	clopyralid (0.45 kg ai ha^{-1}) and haloxyfop (0.45 kg ai ha^{-1})
Persicaria capitata	metsulfuron (18 g ai ha^{-1}) and haloxyfop (0.45kg ai ha^{-1})
Sedum mexicanum	metsulfuron (45 g ai ha^{-1})
Herbicide application date: 16 November 2009	
Ground cover species	Herbicide
Coprosma acerosa	glyphosate (0.81 kg ai ha^{-1}) and simazine (1.5 kg ai ha^{-1})
Persicaria capitata	tribenuron (1.1 kg ai ha^{-1}) and haloxyfop (0.25kg ai ha^{-1})
Sedum mexicanum	glufosinate (1.2 kg ai ha^{-1}) and simazine (1.5kg ai ha^{-1})
Herbicide application date: 19 February 2010	
Ground cover species	Herbicide
Coprosma acerosa	glyphosate (0.81 kg ai ha^{-1}) and simazine (1.5 kg ai ha^{-1})
Persicaria capitata	glyphosate (1.08 kg ai ha^{-1}) and simazine (1.5kg ai ha^{-1})
Sedum mexicanum	tribenuron (18.7 g ai ha^{-1}) [reduced water rate 1000L ha^{-1}]

To determine whether different mulch treatments affected soil temperature and water availability (infiltration and evaporation rates) which are important growth factors, soil temperature and moisture were also measured. After 13 months, soil temperature was measured at a depth of 5 cm under each mulch type (including some freshly laid paper mulch in an area beside the plots) using four Hortplus temperature micro-loggers per treatment type (excluding handweeded bare soil, since it duplicated herbicide treated bare soil) every 10 minutes during 11 - 25 December 2009, and compared with the temperature at 5 cm depth for plots with bare soil. Winter temperature was also measured for 2 weeks during 10-23 August 2010; however, only three replicates were used for five treatment types as fewer sensors were available for this period. The winter treatments were sawdust, weedmat, bare soil (with comparison between soil exposed under sun and soil under the shade of a *Coprosma* plant separately measured), bark nuggets and re-laid paper mulch. The wood chip treatment was not included in the winter measurements due to resource constraints. The warmest and coolest temperature of each day was noted.

Likewise, soil water measurements were made using time-domain reflectrometry (TDR) probes under each mulch type and under bare soil plots. Weekly readings were taken at four positions each time for a 5 week period from December 2009 to January 2010. This was repeated for a longer period of 11 weeks from 4 Nov 2010 to 17 Jan 2011. From the second measurement, a 5 week period with more rainfall (22 Nov – 30 Dec 2010) was selected to better test the drying and wetting behaviour of the mulch treatments.

By June 2010, the ground covers were established for more than one and a half years. Hand weeding and herbicide application was stopped for 4 months from 25 June to 18 October 2010, to test the weed suppression ability of the ground covers that had established. All weed remnants were removed from all plots on 24 June 2010. At the end of this period, weeds were collected from each plot, dried in an 80^{o}C oven for 5 days and weighed. The weeds collected were separated into those found growing within the space not covered by ground covers, and those weeds found growing from within the ground cover plant canopy. The dry weed mass per unit area found within and outside the ground cover plant canopy was estimated using data from the visual estimates of percentage ground coverage of each plot, where each plot was known to be 4 m^2.

All data collected were subjected to an analysis of variance using SAS 9.2, and least significant differences were calculated at P = 0.05 when significant differences between means were detected.

6.5 Rates of growth

To assess the rates of growth, the parameters of plant diameter and height, as well as a visual estimate of the percentage ground coverage within the 4 m^2 plot, were assessed. The analysed results from these measurements are presented in Tables 6.2 – 6.10 for each species over a one year establishment period. The means in Tables 6.2 – 6.10 within a column sharing the same letter were not significantly different at p = 0.05. The dates of observation were 22 February, 17 April, 24 June, 22 August, 28 October 2009 and 22 January 2010.

6.5.1 Results: Rates of growth -- *Coprosma acerosa* 'Taiko'

The weed mat only treatment produced the largest diameters, tallest, and best spreading *Coprosma acerosa* 'Taiko' plants (Tables 6.2-6.4). The paper mulch treatment also allowed the plants to spread rapidly (Table 6.4). The bare soil treatments also produced taller plants overall (Table 6.3).

The herbicide treatment, on the other hand, produced the smallest plants which were short and did not spread well. Handweeded plots also produced smaller plants with poorer spread.

Table 6.2 The change in mean plant diameter of *Coprosma acerosa* cv Taiko for different establishment techniques. Column means sharing the same letter are not significantly different at p>0.05.

Treatment	Feb 2009		Apr 2009		Jun 2009		Aug 2009		Oct 2009		Jan 2010	
Bark nugget	54.1	bc	55.7	b	64.5	cd	59.7	d	68.9	cd	88.6	bc
Hand weed	55.0	bc	57.9	ab	72.2	abc	63.2	cd	72.2	bcd	77.0	cd
Herbicide	61.7	ab	54.7	b	66.9	bcd	65.5	bcd	56.2	e	63.8	d
Paper	64.7	a	68.0	a	78.4	a	75.1	ab	80.8	ab	88.7	bc
Sawdust	53.7	c	54.2	b	57.7	d	58.8	d	63.6	de	83.7	bc
Weed mat	57.6	abc	63.2	ab	75.8	ab	82.8	a	88.7	a	111.1	a
Wood chip	54.3	bc	57.7	ab	65.2	cd	65.2	bcd	68.2	cd	93.6	b
Wood chip + weed mat	56.8	bc	57.8	ab	69.1	abc	71.0	cd	79.1	abc	96.4	b

Table 6.3 The change in mean plant height of *Coprosma acerosa* cv Taiko for different establishment techniques. Column means sharing the same letter are not significantly different at p>0.05.

Treatment	Feb 2009		Apr 2009		Jun 2009		Aug 2009		Oct 2009		Jan 2010	
Bark nugget	8.8	c	7.3	d	9.7	b	9.6	b	9.7	b	6.7	c
Hand weed	13.8	ab	11.5	a	13.0	a	12.3	a	12.7	ab	11.5	ab
Herbicide	11.2	bc	9.5	bc	12.2	a	10.2	ab	11.3	ab	13.8	a
Paper	10.3	c	9.2	bcd	10.8	ab	9.3	b	10.3	b	11.0	ab
Sawdust	9.7	c	8.5	cd	11.0	ab	11.0	ab	12.2	ab	13.8	a
Weed mat	14.2	a	10.8	ab	12.7	a	12.2	a	13.8	a	13.3	a
Wood chip	9.5	c	9.0	bcd	10.8	ab	11.0	ab	10.4	b	7.8	bc
Wood chip + weed mat	9.5	c	9.7	abc	11.2	ab	11.3	ab	10.6	b	12.2	ab

Table 6.4 The change in mean estimated ground coverage (%) of *Coprosma acerosa* cv Taiko for different establishment techniques. Column means sharing the same letter are not significantly different at p>0.05.

Treatment	Feb 2009		Apr 2009		Jun 2009		Aug 2009		Oct 2009		Jan 2010	
Bark nugget	7.7	a	11.7	a	16.7	bc	18.3	a	25.0	b	28.3	bc
Hand weed	8.7	a	11.7	a	18.3	abc	18.3	a	30.0	ab	35.0	ab
Herbicide	9.3	a	13.3	a	15.0	bc	18.3	a	23.3	b	21.7	c
Paper	10.0	a	14.0	a	23.3	a	21.7	a	31.7	ab	30.0	abc
Sawdust	8.3	a	13.3	a	13.3	c	18.3	a	25.0	b	26.7	bc
Weed mat	11.0	a	11.7	a	16.7	bc	25.0	a	36.7	a	40.0	a
Wood chip	13.0	a	15.0	a	20.0	ab	18.3	a	25.0	b	26.7	bc
Wood chip + weed mat	12.0	a	15.0	a	20.0	ab	20.0	a	30.0	ab	35.0	ab

6.5.2 Results: Rates of growth -- *Persicaria capitata*

Bare soil treatments (hand weeding and herbicide) produced larger plants (Table 6.5), which also tended to be taller (Table 6.6) and well spread-out (Table 6.7). *Persicaria capitata* plants grown on weed mat also spread out well. Paper mulch tended to produce taller plants. However, *P. capitata* plants were extremely frost sensitive. An early frost in mid-April caused the foliage to shrivel up and fall off, which accounted for the decline in ground coverage in April (Table 6.7). The black weed mat allowed the foliage to be less affected, whereas bark nuggets covering the soil produced the most rapid loss of ground coverage as winter approached. Overall, wood chip and bark nugget treatments produced smaller and shorter plants which did not spread well in this trial.

Table 6.5 The change in mean plant diameter of *Persicaria capitata* for different establishment techniques. Column means sharing the same letter are not significantly different at p>0.05.

Treatment	Feb 2009		Apr 2009		Jun 2009		Aug 2009		Oct 2009		Jan 2010	
Bark nugget	71.9	b	111.4	c	106.0	d	105.9	bc	104.9	c	96.1	b
Hand weed	79.3	ab	140.9	a	146.9	a	115.9	abc	118.4	ab	138.3	a
Herbicide	86.4	a	138.3	ab	132.5	b	125.7	a	126.7	a	138.1	a
Paper	74.9	b	115.6	c	118.8	cd	106.8	bc	102.4	c	136.3	a
Sawdust	74.7	b	119.6	c	116.3	c	113.4	abc	102.1	c	99.7	b
Weed mat	80.1	ab	125.9	abc	131.2	bc	119.3	ab	112.0	bc	148.8	a
Wood chip	74.3	b	116.9	c	108.9	d	105.2	c	105.6	c	103.7	b
Wood chip + weed mat	73.9	b	123.2	bc	115.3	d	109.6	bc	109.9	bc	96.4	b

Table 6.6 The change in mean plant height of *Persicaria capitata* for different establishment techniques. Column means sharing the same letter are not significantly different at p>0.05.

Treatment	Feb 2009		Apr 2009		Jun 2009		Aug 2009		Oct 2009		Jan 2010	
Bark nugget	8.0	a	4.3	c	5.4	b	4.2	b	3.9	b	4.9	d
Hand weed	8.0	a	5.9	a	6.9	a	5.1	ab	4.7	ab	12.1	ab
Herbicide	8.4	a	5.4	ab	6.9	a	4.2	b	4.6	ab	12.6	ab
Paper	8.4	a	6.1	a	6.2	ab	4.9	ab	5.1	a	13.3	a
Sawdust	7.8	a	4.4	c	6.2	ab	5.0	ab	4.5	ab	10.2	bc
Weed mat	7.4	a	5.6	ab	4.9	b	4.9	ab	4.1	ab	11.9	ab
Wood chip	8.0	a	4.1	c	5.1	b	4.3	b	3.9	b	8.1	c
Wood chip + weed mat	8.2	a	4.9	bc	6.9	a	5.9	a	4.9	ab	7.6	cd

Table 6.7 The change in mean estimated ground coverage (%) of *Persicaria capitata* for different establishment techniques. Column means sharing the same letter are not significantly different at p>0.05.

Treatment	Feb 2009		Apr 2009		Jun 2009		Aug 2009		Oct 2009		Jan 2010	
Bark nugget	100.0	a	68.3	b	53.3	c	70.0	a	10.0	d	11.7	b
Hand weed	100.0	a	75.0	ab	71.7	a	70.0	a	40.0	a	75.0	a
Herbicide	100.0	a	76.7	ab	73.3	a	73.3	a	28.3	ab	70.0	a
Paper	100.0	a	73.3	ab	56.7	bc	66.7	a	23.3	bc	60.0	a
Sawdust	100.0	a	73.3	ab	60.0	bc	61.7	a	11.7	cd	26.7	b
Weed mat	100.0	a	78.3	a	76.7	a	66.7	a	18.3	bcd	55.0	a
Wood chip	100.0	a	73.3	ab	60.0	bc	61.7	a	10.0	d	15.0	b
Wood chip + weed mat	100.0	a	75.0	ab	61.7	b	70.0	a	10.0	d	18.3	b

6.5.3 Results: Rates of growth -- *Sedum mexicanum* 'Acapulco Gold'

For *Sedum mexicanum*, the treatments that allowed better establishment appeared to be those with sawdust and weed mat (Tables 6.8-6.10). Plants in these plots were larger, taller, and were generally well spread out.

Treatments which were less effective for *Sedum mexicanum* were the bare soil treatments (hand weeding and herbicide applied), and wood chip treatment.

Table 6.8 The change in mean plant diameter of *Sedum mexicanum* cv Acapulco Gold for different establishment techniques. Column means sharing the same letter are not significantly different at p>0.05.

Treatment	Feb 2009		Apr 2009		Jun 2009		Aug 2009		Oct 2009		Jan 2010	
Bark nugget	31.0	ab	43.6	ab	52.4	ab	60.2	a	69.8	bcd	60.9	bc
Hand weed	22.1	cd	32.0	cd	39.7	c	56.7	a	60.4	de	52.6	cde
Herbicide	19.5	d	28.0	d	34.4	c	50.9	a	53.8	e	48.7	de
Paper	27.0	bc	40.5	ab	50.2	ab	65.6	a	73.4	bc	61.0	bc
Sawdust	28.0	bc	43.5	ab	53.2	a	70.8	a	87.9	a	80.0	a
Weed mat	35.0	a	48.1	a	57.4	a	69.7	a	81.4	ab	71.7	ab
Wood chip	30.4	ab	38.4	bc	43.0	bc	63.5	a	54.4	e	45.7	e
Wood chip + weed mat	32.9	ab	44.6	ab	51.7	ab	59.4	a	68.1	cd	59.4	cd

Table 6.9 The change in mean plant height of *Sedum mexicanum* cv Acapulco Gold for different establishment techniques. Column means sharing the same letter are not significantly different at p>0.05.

Treatment	Feb 2009		Apr 2009		Jun 2009		Aug 2009		Oct 2009		Jan 2010	
Bark nugget	8.3	ab	8.2	bc	8.4	cd	10.5	bcd	15.7	bc	8.4	abc
Hand weed	6.7	c	7.3	c	9.8	bc	13.9	a	17.4	abc	9.3	ab
Herbicide	6.9	bc	8.2	bc	9.1	bc	9.3	cd	14.7	bcd	6.7	c
Paper	8.0	abc	9.0	abc	11.1	ab	12.5	abc	18.4	abc	8.0	abc
Sawdust	8.3	ab	10.1	ab	10.3	abc	14.1	a	21.9	a	7.6	bc
Weed mat	8.9	a	11.0	a	12.9	a	12.8	ab	19.2	ab	9.7	a
Wood chip	8.8	a	7.6	c	6.0	d	5.6	e	10.0	d	8.1	abc
Wood chip + weed mat	7.9	abc	8.8	bc	9.4	bc	8.9	d	13.8	cd	8.6	abc

Table 6.10 The change in mean estimated ground coverage (%) of *Sedum mexicanum* cv Acapulco Gold for different establishment techniques. Column means sharing the same letter are not significantly different at p>0.05.

Treatment	Feb 2009		Apr 2009		Jun 2009		Aug 2009		Oct 2009		Jan 2010	
Bark nugget	15.0	ab	18.3	abc	23.3	bcd	33.3	abc	53.3	ab	31.7	ab
Hand weed	6.7	b	10.0	c	18.3	cd	28.3	bc	38.3	bc	18.3	b
Herbicide	6.7	b	10.0	c	16.7	d	23.3	c	30.0	c	18.3	b
Paper	15.0	ab	18.3	abc	31.7	ab	41.7	abc	51.7	ab	31.7	ab
Sawdust	11.7	ab	13.3	bc	26.7	abc	45.0	ab	60.0	a	43.3	a
Weed mat	18.3	a	23.3	a	35.0	a	50.0	a	63.3	a	45.0	a
Wood chip	11.7	ab	16.7	abc	21.7	cd	23.3	c	30.0	c	18.3	b
Wood chip + weed mat	15.0	ab	20.0	ab	26.7	abc	35.0	abc	50.0	abc	21.7	b

6.5.4 Discussion: Rates of growth in various treatments

Weed mat which covered the entire plot surface seemed to be suitable for all plants in this trial. This may be because this treatment persistently prevented seeds within the soil bank from germinating. For *Coprosma acerosa* 'Taiko', this was the single best treatment. In contrast, the other two species also performed well when grown in other treatments. The *Persicaria capitata* also did very well in treatments which did not cover the soil surface, namely the hand weeded and herbicide assisted treatments, and also performed well in the paper mulch treatment after it had degraded. These treatments allowed numerous rooting nodes of the *P. capitata* to draw more nutrients from the soil, but the same treatments produced poorer results for the single-stemmed *C. acerosa*. The *Sedum mexicanum* did well in the sawdust treatment. This may be due to the friable nature of the material which facilitated the penetration of the thicker roots from stem nodes into the sawdust medium. This would have also assisted stem fragments to regenerate since covered roots were less prone to drying out.

6.6 Soil moisture and temperature

6.6.1 Results: Soil moisture and temperature

Table 6.11 consolidates all the results from the two sets of TDR measurements with the mean high and low temperatures in summer and winter. Means within a column sharing the same letter are not significantly different at p = 0.05.

From Table 6.11, wood chip and weed mat combined retained moisture or resisted evaporative loss best. Weed mat alone, and the bark nugget treatment also retained moisture well. Bare soil had the poorest moisture retentive properties, followed closely by the sawdust treatment.

Table 6.11 Soil moisture content sampled over two summers and the mean maximum and minimum temperatures in summer and winter of soil under various treatments. Column means sharing the same letter are not significantly different at p>0.05.

Treatment	Soil moisture 1* (%)		Soil moisture 2** (%)		Summer low (°C)		Summer high (°C)		Winter low (°C)		Winter high (°C)	
bark nuggets	33.7	ab	31.5	abc	17.1	c	19.2	f	9.4	a	10.7	d
paper	32.4	bc	30.1	bc	16.8	d	22.8	c	8.8	b	12.4	c
sawdust	30.7	cd	29.8	d	17.8	a	20.9	e	8.1	c	13.0	b
weed mat	33.4	abc	31.7	ab	15.6	e	27.7	a	8.0	c	14.7	a
wood chip	35.9	a	31.1	bc	17.4	b	21.8	d	n.m		n.m	
wood chip + weed mat	33.9	ab	34.1	a	17.6	ab	22.8	c	n.m		n.m	
bare soil (exposed)	28.2	d	28.8	cd	15.2	f	26.7	b	8.1	c	12.9	b
bare soil (shaded)	n.a.		n.a.		n.a.		n.a.		7.9	c	12.3	c

*Soil moisture 1: 15 Dec 2009 – 12 Jan 2010 **Soil moisture 2: 22 Nov 2010 – 30 Dec 2010
n.m. : not measured

Soil under bark nuggets also heated up the least, in both summer and winter months, and retained heat best during the winter. Exposed black weed mat heated up the most in both summer and winter, but also lost the heat quickly at night.

6.6.2 Discussion: Soil moisture and temperature

The temperatures measured for bark nuggets and black weed mat related well to the earlier observation of frost sensitivity in *P. capitata* plots. It confirmed that soil under bark nuggets absorbed less heat during the day, and that heat was absorbed well under black weed mat which also released most of the absorbed heat during the night. Therefore, frost tender *P. capitata* plants lost foliage most quickly when grown with bark nugget mulch and resisted frost damage better with black weed mat under them. When the weed mat was covered by wood chips, it gained less heat during the day but also lost less warmth at night. During summer months, sawdust retained heat gained during summer well at night, but this ability was not evident in winter. Bare soil which was shaded gained less heat in the day than bare soil exposed to the sun, and lost all of it at night to achieve comparable night time temperature to bare soil exposed to the sun.

Soil under bark nuggets had high moisture in both years monitored, possibly because it heated up less and did not encourage evaporative loss, despite ample gaps in the medium. The two treatments with weed mat also had high moisture in the soil underneath, but probably for different reasons than bark nuggets. Despite heating up more during the day in summer, the impervious nature of the polyethylene sheet resisted moisture loss. The exposed bare soil had low soil moisture, simply due to the lack of resistance to evaporation. Sawdust mulch also had relatively dry soil under it. The sawdust layer was observed to be caked, with a dry outer surface, but when broken up, the inner surface was moist. This was probably due to the sawdust retaining the moisture and not allowing it to percolate through.

6.7 Assessment of weeds found in plots

6.7.1 Results: Mean weed numbers found in plots

The mean number of weeds found within the plot boundaries for various establishment treatments of each ground cover species are shown in Tables 6.12 - 6.14. Means within a column sharing the same letter are not significantly different at p > 0.05.

Table 6.12 Mean weed numbers per plot found within *Coprosma acerosa* cv Taiko plot boundaries that had established since removal following the previous assessment. Column means sharing the same letter are not significantly different at p>0.05.

Treatment	Feb 2009		Apr 2009		Jun 2009		Aug 2009		Oct 2009		Jan 2010	
Bark nugget	0.7	b	0.3	d	0.7	b	1.3	b	0.0	b	0.3	b
Hand weed	22.0	a	100.6	a	41.0	a	83.3	a	33.7	a	23.0	a
Herbicide	17.0	a	46.3	b	31.3	ab	92.0	a	35.0	a	24.3	a
Paper	1.3	b	5.3	cd	6.7	ab	7.7	b	6.7	b	17.3	a
Sawdust	0.3	b	0.3	d	8.0	ab	4.7	b	2.0	b	0.3	b
Weed mat	0.3	b	0.7	d	1.0	b	0.0	b	0.0	b	0.0	b
Wood chip	0.7	b	8.7	c	1.7	b	3.3	b	0.3	b	5.3	b
Wood chip + weed mat	0.0	b	3.7	cd	1.7	b	4.7	b	0.7	b	0.7	b

Table 6.13 Mean weed numbers per plot found within *Persicaria capitata* plot boundaries, built up after weed removal from previous observations. Column means sharing the same letter are not significantly different at p>0.05.

Treatment	Feb 2009		Apr 2009		Jun 2009		Aug 2009		Oct 2009		Jan 2010	
Bark nugget	0.7	b	0.0	b	3.3	b	3.7	b	0.0	b	1.0	b
Hand weed	18.7	a	56.7	a	56.7	a	53.7	a	16.0	a	26.0	a
Herbicide	6.3	b	11.0	b	21.0	b	42.3	a	12.3	a	29.3	a
Paper	0.0	b	0.0	b	0.3	b	1.0	b	3.3	b	23.0	a
Sawdust	0.3	b	0.3	b	0.3	b	0.3	b	0.0	b	2.3	b
Weed mat	0.0	b	0.0	b	0.0	b	0.7	b	0.0	b	0.0	b
Wood chip	0.3	b	2.0	b	1.0	b	3.0	b	0.3	b	5.7	b
Wood chip + weed mat	0.3	b	1.3	b	0.7	b	6.7	b	0.3	b	1.0	b

Table 6.14 Mean weed numbers per plot found within *Sedum mexicanum* cv Acapulco Gold plot boundaries, built up after weed removal from previous observations. Column means sharing the same letter are not significantly different at p>0.05.

Treatment	Feb 2009		Apr 2009		Jun 2009		Aug 2009		Oct 2009		Jan 2010	
Bark nugget	1.7	c	1.0	c	0.3	b	0.3	b	0.0	c	0.0	d
Hand weed	26.7	a	28.7	a	56.0	a	95.0	a	36.7	a	30.3	a
Herbicide	10.3	b	22.3	ab	6.3	b	83.0	a	0.0	c	22.3	b
Paper	1.3	c	8.7	bc	3.3	b	11.0	b	14.0	b	25.3	ab
Sawdust	1.0	c	0.7	c	0.0	b	1.7	b	1.7	c	3.3	cd
Weed mat	0.7	c	0.0	c	0.0	b	0.3	b	0.0	c	1.3	cd
Wood chip	2.0	c	5.0	bc	4.0	b	6.3	b	0.0	c	8.7	c
Wood chip + weed mat	0.0	c	1.0	c	2.3	b	5.0	b	0.3	c	5.3	cd

The first observation in February was made a fortnight after herbicide application and hand weeding was performed. Therefore it reflected less weed build-up than for other assessment times. For the herbicide treated plots, weed counts included the dying weeds for the February, April, and January observations. No herbicides were applied on the herbicide treatment plots for the June, August, and October observations. As might be expected, across all species, the two treatments with bare soil had more weeds than the mulched plots (Tables 6.11-6.13). Among the bare soil plots, those where no herbicides were applied had the most weeds, though removal of weeds by herbicide rather than a hoe often did not stop weeds from re-establishing due to lack of residual activity with most products. However, the effects of simazine applied in the *Sedum mexicanum* herbicide plots in March produced a marked reduction in weed numbers during the June observation round (the April observation counts included semi-chlorotic weeds).

In *Coprosma acerosa* and *Persicaria capitata* plots, the mulch treatments were all comparable in their ability to stop weeds, except for the paper mulch. The paper mulch had degraded 6 months after application and could no longer prevent seeds from the soil bank from germinating. While the paper mulch was still present, weed numbers were kept low in the plots until June (Tables 6.12-6.14). In *Sedum mexicanum* plots, the two treatments with weed mat and the sawdust treatment had fewer weeds. This is discussed further in Section 6.7.3.

6.7.2 Results: Standardised weed mass found in plots

Table 6.15 shows the dry weed mass per square metre for weeds found outside the ground covers and also growing from within the canopy. As the weeds growing outside the ground cover canopy of *Sedum mexicanum* and *Coprosma acerosa* were largely independent of plant influence (assuming negligible impact from differences in the herbicide treatments), they were combined together for ANOVA in Table 6.15 to enlarge the sample size of the treatment plots. For *Persicaria capitata,* the sprawling growth habit of the stems all over the plot made it difficult to precisely determine whether the weeds had been growing outside or within the influence of the plant canopy. Hence, all weeds collected in the *Persicaria capitata* plots were assumed to be influenced by conditions within the canopy as the plant's reach extended throughout the whole plot area. The means in Table 6.15 within a column sharing the same letter are not significantly different at p = 0.05. Identification of the weeds found within the trial plots are listed in Table 6.16.

Table 6.15 Dry weed mass (g m^{-2}) of each treatment plot by species, with differentiation between weeds found within and beyond the ground cover canopy. Column means sharing the same letter are not significantly different at p>0.05.

Treatment	***Uncovered area of plots***			***Within ground cover canopy***				
	Coprosma + Sedum combined		Persicaria	*Coprosma*		Persicaria		Sedum*
Bark nugget	10.0	d	n.a.	0.0	b	32.5	abc	0.0
Hand weed	70.1	bc	n.a.	46.0	a	57.5	a	39.5
Herbicide	47.5	cd	n.a.	5.88	b	32.3	abc	47.9
Paper	115.1	a	n.a.	17.5	b	75.9	a	34.4
Sawdust	39.8	cd	n.a.	0.0	b	43.0	abc	38.1
Weed mat	10.1	d	n.a.	0.0	b	1.5	c	0.5
Wood chip	98.4	ab	n.a.	0.09	b	52.1	ab	44.8
Wood chip + weed mat	45.1	cd	n.a.	2.26	b	6.1	bc	0.0

*no significant difference between treatments due to large variability

Table 6.16 Weeds found in the establishment trial plots

Botanical name	Common name	Botanical name	Common name
Anagallis arvensis	scarlet pimpernel	***Lepidium didymum***	twin cress
Aphanes inexspectata	parsley piert	***Mentha pulegium***	pennyroyal
Capsella bursa-pastoris	shepherd's purse	***Oxalis exilis***	creeping oxalis
Cerastium glomeratum	annual mouse ear chickweed	***Persicaria maculosa***	willow weed
****Cirsium vulgare***	Scotch thistle	***Plantago lanceolata***	narrow-leaf plantain
Conium maculatum	hemlock	***Plantago major***	broad-leaf plantain
Conyza sumatrensis	broad-leaved fleabane	***Poa annua***	annual poa
Cotula australis	soldier's button	***Ranunculus sardous***	hairy buttercup
Crepis capillaris	hawksbeard	***Rorippa sylvestris***	creeping yellow cress
Dianthus armeria	Deptford pink	****Rumex obtusifolius***	broad-leaf dock
****Ehrharta erecta***	veld grass	***Senecio vulgaris***	groundsel
Epilobium ciliatum	tall willow herb	***Solanum nigrum***	black nightshade
Erodium moschatum	musky storksbill	****Sonchus asper***	prickly sow thistle
Euphorbia peplus	milkweed	***Sonchus oleraceus***	sow thistle
Galium aparine	cleavers	***Stachys arvensis***	staggerweed
Geranium molle	dove's foot	***Stellaria media***	chickweed
****Gnaphalium purpureum***	cudweed	***Taraxacum officinale***	dandelion
Holcus lanatus	Yorkshire fog	***Trifolium repens***	white clover
Hypochaeris radicata	catsear	***Urtica urens***	nettle
****Juncus bufonius***	toad rush	***Veronica serpyllifolia***	turf speedwell

* weeds which were also found within ground cover canopy in the establishment trial plots

6.7.3 Discussion: Assessment of weeds found in plots

Looking at the dry mass of weeds found outside of ground cover plant canopy influence in Table 6.15, the paper mulch treatment had the highest weed mass. This was because the paper had degraded 6 months after being laid down, and thereafter, no further handweeding or herbicide application occurred, so weeds established easily from the bare soil. Advances in Ecocover technology have since improved the durability of the product beyond 6 months (EcoCover 2007) but this longer-lasting form of the product was not tested in this trial.

Handweeded plots also resulted in high weed numbers and weed mass collected per unit area, which was expected for a treatment intended as an untreated control (Tables 6.12-6.15). The other bare soil treatment was the herbicide plots which had significantly lower weed mass than hand weeded plots (Table 6.15). This affirmed that herbicide use was effective in reducing weed invasion, and the results might be further improved with better herbicide selection (Tables 6.12-6.14).

Another very weedy treatment was the wood chip mulch. This may be a result of the frequent disturbance from rabbits and pūkeko (previously noted in Chapter 4) which burrowed and prodded with their beaks respectively; additionally, heavy rains during the trial period led to ponding and flooding on-site occasionally, which washed away some of the wood chips. These combined actions led to a thinning of the wood chip layer and reduced the ability of mulching to hinder weed seed germination. Sawdust plots also suffered frequent disturbance, but mainly from the animals; rainwater actually served to compact the sawdust and the alternate wetting and drying formed a slightly caked layer over the plots, which may account for the reduced weed presence compared to the larger mulch particle sizes in wood chip plots.

The treatments with the least weeds by absolute number and mass per unit area in this trial proved to be the larger bark nuggets and black weed mat (Tables 6.12-6.15). These were treatments which were relatively better able to resist movement from rainwater and animal disturbance. They stayed in place for 2 years with minor thinning out at the edges for bark nuggets and slight fraying of plastic fibre. As seen from Table 6.16, all weeds found were species with wind dispersal capability; hence weeds in the weed mat and bark nugget treatment presumably germinated from opportunistic wind-blown seeds. Similarly, weeds found in the wood chip over weed mat treatment were all weeds which landed amongst the wood chip and used the decaying wood chips and media for root establishment. There is high likelihood that most of the weeds which germinated within the plots were derived from wind-blown seeds rather than the weed seed bank in the soil.

Data collected for weed mass found within ground cover canopy in the *S. mexicanum* plots resulted in ANOVA where no significant differences were found between treatments (Table 6.15). This effect was due to the high variance in weed mass. It is very likely that disturbance by rabbits and pūkeko in random plots produced spot areas with exposed soil which did not hinder seed germination otherwise affected by the mulch treatments. The randomness of animal disturbance led to inconsistencies within and between treatments, hence resulting in an analysis with no significant differences despite the seemingly large differences in mean values. It is of interest to note that large particle sizes of the bark nuggets and the two treatments using weed mat continue to resist weed seed germination. These two materials were less affected by rabbit burrowing and avian prodding.

For the *Persicaria capitata* plots, the paper mulch treatment which degraded again resulted in the highest weed mass found. Other treatments producing relatively high weed mass results were the handweeded control which was not significantly different; and the wood chip mulch. This was similar to the results for weed mass of the uncovered area outside the ground cover canopy in the other two ground cover species. Weed mass found within the sawdust and herbicide plots was also similar to the results for the uncovered area. The weed mat treatment again proved to be best in resisting weed invasion, as it blocked light well from seeds in the soil and did not permit wind-blown seeds to establish successfully on top of the mat.

However, when wood chips were placed on top of the weed mat, the treatment no longer became effective in preventing weed germination. Since the weed mat was found to be unbroken, one can assume that the weed mat underneath the wood chips still managed to prevent weed seeds from germinating. The weeds found in these treatment plots were most likely to have been carried by the wind and lodged within the wood chip layer. The presence of the wood chip particles was likely to have provided additional surface area to catch wind-carried seeds. The various crevices of the wood chip particles were also likely to trap sufficient resources to enable successful germination of weed seeds. Yet when the scrambling *P. capitata* was grown with this treatment, the weeds found were less than those found in the exposed areas of *C. acerosa* and *S. mexicanum* plots. This suggests that the presence of a scrambling ground cover created a more competitive environment for germinating weed seeds than exposed areas of this treatment.

As seen from Table 6.16, nearly forty weed species were found growing in the plots of this trial. However, a closer inspection of the weeds collected in the bark nugget treatment plots shows that about 80% of the weeds were *Ehrharta erecta* (veld grass). This species seeds early and prolifically, especially in moist areas. TDR measurements of soil moisture (table 6.11) also showed that bark nugget treatment allows better moisture retention in soil, and the favourable conditions allowed one or two plants to produce prolific seeds.

Within *Coprosma acerosa* plant canopies, the exposed plots for treatments of hand weeding, herbicide assistance, and degraded paper mulch produced the highest weed mass, since seeds in the soil could receive light. However, the bark nugget layer, thicker than the minimum 7 cm described due to the larger size of each piece, the caked sawdust layer, and the black weed mat all resulted in no weeds found within the ground cover canopy during establishment. All these treatments shared the characteristic of being able to create a barrier between light and soil resources. The treatments with wood chip and wood chip over weed mat produced some weeds, possibly because the decaying wood chips provided a rooting medium for the wind-blown weed seeds (Table 6.15).

6.8 Overall Discussion

Coprosma acerosa is a prostrate shrub that grows mainly from a central stem and only roots occasionally from stem nodes. It is therefore not surprising that the two treatments using weed mat produced the largest spreading plants, since weed mat very effectively keeps out weed competition for soil resources. The paper mulch also produced good plant growth while it lasted, since it produced a similar barrier between light and soil resources. This prevented weed seeds from both wind-carried sources and the dormant seeds in the soil seed bank from germinating and establishing. However, plant growth suffered once the paper cover degraded. The wood chip treatment produced larger plants near the end of the trial, when it had thinned out considerably. The wood-based mulches did not produce larger plants, perhaps due to soil nitrogen immobilisation during the decay process. The bare soil plots produced the smallest plants, presumably due to increased weed competition and increased water loss from evaporation.

For the herbicide treated plants, there was also the possibility of a growth check on the plants as a side effect, although no visible damage symptoms were observed in this trial on *C. acerosa*. The weeds in the herbicide treated plots also remained in the plots after herbicide application, and so may have continued to exert competitive pressure on the ground cover plants if they recovered during the interim period between herbicide applications. Such effects would have been absent in handweeded plots and accounted for the better growth provided weed volume was low. Furthermore, the full results from Chapter 5 were not available at each herbicide application. With the knowledge from trials in Chapter 5 which showed that each of these three species were tolerant of a wide range of herbicides suited for control of different weed conditions, better results could have been obtained. Except for the simazine application in *Sedum mexicanum* plots, no other residual herbicides were used. The performance of the ground covers in this trial may improve in herbicide treated plots if well-informed decisions can be made about herbicide choices and suitable combinations.

Persicaria capitata, with its scrambling nature and freely rooting stem nodes, established best in treatments which allowed full access to bare soil, these being the handweeded and herbicide treated plots. The paper mulch plots also produced good plant growth after the paper had degraded. The weed mat treatment also produced larger plants despite not providing bare soil access. However, this may be a temperature related effect, as the black weed mat produced the highest soil temperatures during the day, and this treatment appeared to produce better results only in warmer months. It is likely that it did not perform well in wood-based mulches due to difficulty in accessing soil nutrients from the shallow roots from stem nodes. Amongst the three wood-based mulches, the wood chip treatment produced the largest plants, but presumably because this treatment had thinned out the most and so had more bare soil. The weediness of the plots also did not seem to deter *Persicaria capitata* growth; perhaps the freely scrambling nature of the stems enabled it to quickly root at the next most opportune spot.

Despite the speed with which *P. capitata* plants covered the whole plot area and the lush foliage in summer, this species is unfortunately very frost tender. An early frost in April caused a rapid decline in ground coverage as frost damage caused the leaf canopy to dwindle and the area covered became exposed in winter. This led to problems with ground cover establishment as weed seeds which germinated in spring shaded the new leaves of the ground cover. The prolific seeding of *P. capitata* was also limited in its ability to compete with weed seedlings, as the earlier germinating *P. capitata* seedlings were killed by late frosts. The weed deterrence ability of this species was unfortunately hampered by its deciduous habit.

Sedum mexicanum was noted to be susceptible to damage from rabbit burrowing and pūkeko prodding due to the brittle stems. The most heavily burrowed treatment was the sawdust plots; ironically, the resilience of *Sedum* stems led to the biggest plants to be found in sawdust plots. The scatter and subsequent regeneration from stem fragments led to best ground coverage. The next best treatments were the weed mat and bark nugget and paper mulches. These treatments also showed no evidence of rabbit burrowing, though some burrowing occurred on paper mulch plots after the paper degraded. The weed mat under wood chip treatment also dissuaded further damage from rabbit burrowing once the wood chips were scattered, hence this treatment managed to aid plant establishment without relying on regenerative chance. The bare soil in handweeded and herbicide plots had the most burrowing action. The wood chip treatment also revealed bare soil after the wood chip layer was scattered, and just as much damage to the plants was done as well. The better stem regeneration in sawdust may have been due to the improved friability of the sawdust particles after burrowing which aided root establishment. The better warmth retention of sawdust in summer months, plus the moisture absorbance, may have also contributed to successful recovery.

6.9 Conclusion

In general, ground cover plant species which do not, or poorly, root along their stems like *C. acerosa* probably perform best when planted with mulches which blanket the soil from light for as long as possible. This contrasts with ground cover plants with rooting stem nodes which perform better when contact with soil or friable media is permitted, which allows for more nutrients or warmth. If the plant species could also regenerate from plant fragments, chance damage may inadvertently promote its spread.

The performance of herbicide treatments had been handicapped in this trial because full information from the herbicide trials in Chapter 5 were not yet available, so the best herbicide solutions were not implemented to assist with ground cover establishment. The decision to allow the weeds to be left in the plots to die when the most effective herbicides were not used, also led to poorer mortality and may have allowed dying weeds to successfully set seed. With results from Chapter 5, the right herbicides may be used for more effective results.

Chapter 7 Herbicide trials for five ground cover species suitable for companion planting with turf grass

7.1 Introduction

In many amenity situations, grass lawn is still the preferred ground cover as it is widely available and easily installed. However, as noted in Chapter 2, some situations pose a challenge for the establishment and maintenance of turf, such as growing under the shade of a tree, fence, or building; and mowing around obstacles in the landscape or on steep inclines.

For such scenarios, a common practice would be to avoid planting grass altogether, and use herbicides to maintain a weed-free environment. However, bare soil could be deemed an eye-sore and other non-plant covers (eg. pebbles, pavers) in these areas do not necessarily provide the best aesthetics (Hands & Brown 2002). Alternative ground cover plants may be ideal since there is no need for mowing and judicious selection of species will allow a compatible fit to suit the specific environment. However, for aesthetic purposes, grounds managers may still require these alternatives to blend in visually with the landscape dominated by grass. Hence, it may be desirable to produce ground cover plants which can blend in with turf.

7.1.1 Objective

In this chapter, five species of ground cover plants with heights and appearance similar to turf when viewed from afar are studied as possible alternatives to turf. To assist growers and managers in the establishment and maintenance of these species, herbicide trials were carried out to determine the tolerance to herbicides of these potential ground cover species which may serve as a turf alternative. This information will be useful for selecting suitable herbicides to control weeds within the ground cover species if they are to be planted in close proximity to other trees and shrubs. At the same time, if the ground cover species strays beyond its intended boundaries into the adjacent grass lawn, appropriate herbicides are needed that can control the ground covers without harm to grass.

7.1.2 Species introduction: *Dichondra micrantha*

Dichondra micrantha is a small prostrate plant belonging to the Convolvulaceae family in a genus with only nine species (Milberg et al. 2000). All members of this small genus are perennial creeping herbaceous plants found in tropical and warmer climates. This species is widely naturalised in many parts of the world, including eastern Asia, northern and central America, and Europe (Gardner 1921). *Dichondra spp.* have also been suggested as an alternative to turf in USA, where

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records show it was cultivated in Texas as early as 1897 and made commercially available in the early 20th century (Austin 1998).

Some work on herbicide tolerance of *D. micrantha* was conducted in USA in the 1980s (Elmore 2000). There has also been some work in New Zealand where it has been suggested as a ground cover in orchards to reduce herbicide use in orchards (Harrington & Rahman 1998), or even replace the bare strips maintained by herbicide application in orchards (Harrington et al. 1999). The establishment of *D. micrantha* has been studied using seedling and stolon regrowth with herbicide assistance (Harrington & Zhang 1997); and also herbicide tolerance of *D. micrantha* plugs (Harrington et al. 2002). The long term use of *D. micrantha* as a weed control alternative was also evaluated (Harrington et al. 2005).

7.1.3 Species introduction: *Hydrocotyle microphylla*

Hydrocotyle is a genus in Araliaceae (previously in Apiaceae (Clarke 2007; Mabberley 2008; Baldwin et al. 2012)) containing about 100 species spread throughout the world in tropical and temperate regions. Many *Hydrocotyle* species are creeping perennials which favour aquatic or moist growing conditions, and spread through rhizomatous growth (Ruiz-Avila & Klemm 1996). Some *Hydrocotyle* species have also been cultivated as the ornamental aquatic plant pennywort, such as *H. verticillata,* and *H. leucocephala.* In New Zealand, *Hydrocotyle microphylla* is commonly found as a lawn weed in moist soils. This species spreads by stoloniferous growth with adventitious roots at its nodes. Due to its tolerance to some knock-down herbicides, it was also considered to be a potential ground cover plant (Harrington & Rahman 1998), and assessed for use in apple orchards (Harrington 1995; Hartley et al. 2000).

7.1.4 Species introduction: *Sagina procumbens*

Sagina is a relatively small genus of 19 species in the family Caryophyllaceae. A cultivated form *S. subulata* is sold as Irish Moss and grown in moist garden nooks. *Sagina procumbens* is a perennial herbacaeous plant with a fibrous root system and stems rarely taller than 5 cm. It forms a tight mat with thin interlocking leaves a little more than 1 cm long. It seeds easily after flowering in spring and summer, though it also spreads by rooting at stem nodes (Toole 1973). Herbicide tolerance work was also previously performed at Massey University on *S. procumbens* and it shows some promise as a cultivated ground cover plant, though it also commonly causes weed problems in nurseries due to its tolerance of oxadiazon (Harrington & Grant 1993).

7.1.5 Species introduction: *Soleirolia soleirolii*

Soleirolia (formerly *Helxine*) is a monotypic genus containing *S. soleirolii,* which is native to the islands of the Mediterranean region and a member of the Urticaceae family. The species is cultivated for its dense moss-like appearance of its foliage on long slender stems which creep along the soil surface (Flint & McAlister 1935, 1937). It is also able to reproduce vegetatively through rooting stolons. There has been no research conducted on the herbicide tolerance of this species, a knowledge gap which this thesis has attempted to fill.

7.1.6 Species introduction: *Veronica serpyllifolia*

With about 350 species, the genus *Veronica* is the largest within the family Plantaginaceae (reclassified from the Scrophulariaceae (Olmstead et al. 2001; Albach et al. 2005)). In garden centres, the genus is sold for its dainty flowers and commonly used as a border plant. Examples include *V. austriaca, V. peduncularis* and *V. spicata* (Singh 2004). The genus also contains some weed species, one of which is *V. serpyllifolia*. The species *V. serpyllifolia* is a low growing prostrate perennial herbaceous plant with rooting stem nodes. It is commonly found growing as a weed in lawns, pastures and open forests. It produces white flowers with purple veins from late spring and throughout summer. It is native to Europe (Rhoads & Block 2007). Other weedy *Veronica* species include *V. arvensis, V. filiformis,* and *V. persica.*

7.2 *Dichondra micrantha* herbicide trials

7.2.1 General comments on herbicides used and application method

Some herbicides were used in many of the trials described in this chapter. To avoid repetition, Table 7.1 shows some information about the herbicides used in at least one trial in this chapter.

All herbicide trials in this chapter were conducted at the Massey University Plant Growth Unit. Treatment were applied by a hand-held pump sprayer (as shown in Fig 5.1 of Chapter 5) at a distance of about 30 cm to ensure even coverage over the whole surface of the plant and planting bag. A dose of 2.0 ml of solution was applied to each PB ¾ bag which had a diameter of 9 cm when fully packed, which equates to a water rate of 3140 L ha^{-1}. Treatments were applied to each plant individually on a bench, before being transferred to assigned floor space in an unheated shade house, unless specifically mentioned. The plants were arranged in rows of 20 plants, with care taken that no part of the plants were touching each other during placement. The shade house was equipped with automated overhead sprinkler irrigation which was activated every morning for 10 minutes.

7.2.2 *Dichondra micrantha* trials: Methods

Two herbicide trials were conducted for *D. micrantha.* The plants for the first trial were grown from seed in seedling trays, which were sown on 10 March 2008. Four weeks later on 8 April 2008, when true leaves had emerged, plugs containing seedlings were transferred to PB ¾ bags containing potting mix with 3-month slow release Osmocote and dolomite. The plants were allowed to establish for 10 weeks before trial commencement. In the first herbicide trial, there were 18 herbicide treatments and one untreated control each with five replicates, allocated within a randomised block design.

Every 2-3 weeks, the plants were scored on a scale of 1-10, with 1 being healthy and 10 being completely necrotic. The first trial lasted 18 weeks from 20 June 2008 to 24 October 2008. There was no heating of the shadehouse for this trial. The mean maximum and minimum temperatures 3 weeks following the herbicide application were 12.8°C and 2.4°C respectively. A visual sample of the scores used for *D. micrantha* is illustrated in Figure 7.1.

Figure 7.1 (from left to right) *Dichondra micrantha* damage rating 1, 3, 6, 9

The treatment mixture of dicamba / MCPA / mecoprop used in this trial was a custom mix blended for this trial using Banvel, Dow Elanco MCPA, and Mec 40.

Table 7.1 Product list and description of herbicides used in trials reported within this chapter.

Active Ingredient	Product	Formulation (ec=emulsifiable concentrate; gr=water dispersible granules sc=soluble concentrate)
2,4-D	Pasturekleen	520g/L ethylhexylester (ec)
2,4-D/dicamba	Banvine	200 g/L 2,4-D + 100 g/L dicamba as amine salts (sc)
aminopyralid	Tordon Max	30 g/L as the triisopropylamine salt (sc)
amitrole	Amitrole 4L	400 g/L + 100 g/L ammonium thiocyanate (sc)
bentazone	Basagran	480 g/L (sc)
bromoxynil	Bromoxynil 40	400 g/L octanoate ester (ec) + 435-437 g/L hydrocarbon liquids.
bromoxynil/ ioxynil	Combine	200 g/L bromoxynil + 200 g/L ioxynil octanoate esters (ec)
bromoxynil/ ioxynil/ mecoprop	Axall	75 g/L bromoxynil, 75 g/L ioxynil, octonoate and heptanoate esters + 345 g/L mecoprop iso-octyl ester (ec)
clopyralid	Versatill	300 g/L amine salt (sc)
dicamba	Banvel	200 g/L dimethylamine salt (sc)
dicamba/ MCPA/mecoprop	Kiwicare Turfclean (Ready-to-use)	1.68g/L mecoprop, 0.42 g/L MCPA, 0.21 g/L dicamba (sc)
dicamba/ MCPA/mecoprop	Yates Turfix	200g/L mecoprop, 50g/L MCPA + 6.2g/L dicamba dimethylamine salts (sc)
diflufenican	Quantum	500 g/L (sc)
diquat/ paraquat	Preeglone	135 g/L paraquat + 115 g/L diquat dichloride and dibromide salts respectively (sc)
diuron	Karmex	800 g/kg (gr)
glufosinate	Buster	200 g/L ammonium salt (sc)
glyphosate	Transorb	540 g/L potassium salt (sc)
glyphosate	Butlers 360	360 g/L isopropylamine salt (sc)
haloxyfop	Gallant NF	100 g/L haloxyfop [(R)-isomer] methyl ester (ec)
linuron	Afalon	450 g/L suspension concentrate
MCPA	Dow Elanco MCPA	375 g/L potassium salt (sc)
mecoprop	Mec40	400 g/L diethanolamine salt (sc)
metsulfuron	Escort	600 g/kg methyl ester (gr)
oxadiazon	Foresite	380 g/L suspension concentrate
oxyfluorfen	Goal	240 g/L (ec)
paraquat	Gramoxone	250 g/L dichloride salt (sc)
pendimethalin	Stomp XTRA	455 g/L capsulated suspension
picloram/ triclopyr	Tordon Brushkiller XT	100 g/L picloram + 8 g/L aminopyralid amine salts + 300 g/L triclopyr butoxyethyl ester (ec). Also contains 367 g/L diethylene glycol
simazine	Gesatop	500 g/L (sc)
tribenuron	Granstar	750 g/kg methyl salt (gr)
triclopyr	Grazon	600 g/L butoxyethyl ester (ec)

To prepare for the second trial, new plants were germinated in early January 2009, and combined with healthy plants left over from Trial 1. The new plants were produced in a similar manner as before, and previously used plants also had Osmocote replenished during the interim period. Nineteen herbicide treatments and one untreated control were allocated to plants using a randomised block design replicated five times, with blocks grouping together plants of similar stages of development. The second trial lasted 20 weeks from 23 March 2009 to 14 August 2009. The mean maximum and minimum temperatures 3 weeks following the herbicide application were 18.8^{o}C and 7.0^{o}C respectively. From 19 May 2009 (8 WAT) till the end of the trial, the plants were moved to a heated glasshouse maintained at 20^{o}C.

7.2.3 *Dichondra micrantha* trials: Results

Scores of the plants in the first herbicide trial on *Dichondra micrantha* are shown in Table 7.2. *Dichondra micrantha* tolerated most of the herbicide treatments used in this trial.

The low variance in plant health between individuals, together with the good health of the untreated control plants, led to some treatments showing significant difference to the control despite a relatively low score. Generally, scores of 4 and below could be considered to be aesthetically acceptable and within normal range even for untreated plants, so they were deemed to be visually unaffected by the herbicide treatments. The poorer health rating for 2,4-D / dicamba treatment at 18 WAT was considered to be due to environmental causes since earlier periods showed no apparent ill-effects. The treatment mixture of dicamba / MCPA / mecoprop did not produce high damage scores, and can be considered to be mildly damaging to *D. micrantha*.

Hence, herbicides which appeared to be damaging to *Dichondra micrantha* in this trial were the picloram / triclopyr mixture, triclopyr used alone, and diflufenican.

Table 7.2 Mean scores of plant damage (1 = healthy, 10 = dead) for the first herbicide screening of *Dichondra micrantha* 1-18 weeks after treatment (WAT).

Active Ingredient	Dose (kg ai ha^{-1})	1 WAT	3 WAT	5 WAT	7 WAT	10 WAT	13 WAT	18 WAT
2,4-D/dicamba	1.3 /0.63	2.8	3.0	3.0*	2.2*	3.2*	3.4	5.6*
bromoxynil/ ioxynil/ mecoprop	0.24/0.24/1.1	3.4*	3.0	2.0	1.4	2.2	2.2	1.6
clopyralid/ haloxyfop/ tribenuron (low)	0.47/0.47/0.047	3.0	2.8	2.4	2.0	2.4	2.0	1.8
clopyralid/ haloxyfop/ tribenuron (medium)	0.94/0.94/0.094	2.8	3.0	2.4	2.2*	2.6	1.8	1.4
clopyralid/ haloxyfop/ tribenuron (high)	1.9/1.9/0.19	2.6	2.4	2.2	1.8	1.8	1.8	1.6
dicamba/ MCPA/mecoprop	0.21/0.45/2.6	2.8	3.0	3.0*	4.0*	4.6*	3.0	2.2
diflufenican	0.31	2.2	2.6	3.2*	5.2*	4.4*	5.0*	3.4
glyphosate (low)	1.1	3.0	2.6	2.4	2.4*	2.8	2.4	2.8
glyphosate (high)	2.3	2.8	3.2	2.4	2.0	2.4	2.4	2.4
glyphosate/ metsulfuron	1.1/0.094	3.0	2.0*	2.4	2.6*	2.8	2.6	3.8*
linuron	1.4	2.8	2.4	2.2	1.6	2.0	1.8	1.6
metsulfuron (low)	0.094	3.0	2.8	2.6*	2.2*	2.6	2.0	2.0
metsulfuron (high)	0.19	2.8	2.4	2.4	2.4*	3.0*	2.2	1.8
oxadiazon (low)	0.60	2.8	3.0	2.0	1.8	2.2	1.8	1.4
oxadiazon (high)	1.2	2.6	3.0	2.4	1.8	2.8	2.4	1.6
pendimethalin	1.5	2.2	2.2	2.2	1.6	2.0	1.8	2.4
picloram/ triclopyr	0.63/1.9	3.2*	3.4	3.6*	3.8*	3.4*	5.4*	8.4*
triclopyr	0.96	2.6	2.8	3.6*	7.0*	4.6*	6.0*	9.8*
untreated	n.a.	2.4	2.8	1.8	1.0	1.6	2.0	1.8
$LSD_{0.05}$		0.7	0.6	0.8	1.1	1.3	1.8	1.7

* indicates significant difference from the untreated control
$LSD_{0.05}$ = Least Significant Difference at p = 0.05.

The second herbicide trial for *Dichondra micrantha* was applied during the warmer month of March. Some treatments were repeated as a check and other repeated treatments used different rates (Table 7.3).

Table 7.3 Mean scores of plant damage (1 = healthy, 10 = dead) for the second herbicide screening of *Dichondra micrantha* 3-20 weeks after treatment (WAT).

Active Ingredient	**Dose (kg ai ha^{-1})**	**3 WAT**	**5 WAT**	**7 WAT**	**9 WAT**	**11 WAT**	**13 WAT**	**15 WAT**	**20 WAT**
2,4-D/dicamba	1.3/0.63	3.4*	3.4	3.8	5.0	5.0	5.6	5.8	1.8
bromoxynil/ioxynil /mecoprop	0.24/0.24/ 1.1	1.8	2.6	3.2	3.8	4.0	5.0	6.4	2.8
clopyralid/haloxyfop /tribenuron (low)	0.94/0.94/ 0.094	1.8	1.6	2.2	2.6	1.8	2.0	3.6	1.0
clopyralid/haloxyfop /tribenuron (high)	1.9/1.9 /0.19	2.8	2.6	2.8	3.6	3.0	3.6	4.2	1.0
dicamba/MCPA /mecoprop	0.22/0.44 /1.8	7.6*	9.0*	9.4*	10.0*	10.0*	10.0*	10.0*	10.0*
diflufenican (low)	0.11	1.8	1.6	2.0	1.8	1.2	2.0	2.2	1.0
diflufenican (high)	0.21	3.4*	3.6	3.8	4.6	3.2	3.8	4.4	2.0
glyphosate (low)	1.1	2.8	2.8	2.2	3.8	4.0	2.8	4.0	1.6
glyphosate (high)	2.3	3.2	4.6*	3.2	4.8	3.8	3.6	6.6	3.0
linuron	1.4	3.0	2.6	2.6	4.2	3.6	3.4	4.6	1.2
metsulfuron (low)	0.094	2.8	2.8	3.2	5.0	3.4	4.2	5.0	3.2
metsulfuron (high)	0.19	2.6	3.6	4.4*	5.0	4.8	4.2	6.2	2.8
oxadiazon (low)	0.76	2.0	2.4	3.0	4.4	2.8	4.4	4.2	3.0
oxadiazon (high)	1.6	2.0	2.4	2.6	3.6	2.8	4.2	5.2	2.8
pendimethalin (low)	2.2	2.0	2.4	2.2	2.4	3.4	3.0	4.6	1.2
pendimethalin (high)	4.3	2.4	3.0	2.4	3.6	3.6	3.8	4.6	3.0
picloram/triclopyr	0.63/ 1.9	8.2*	9.2*	9.6*	8.6*	8.4*	8.4*	8.4*	10.0*
triclopyr (low)	0.96	6.4*	7.4*	6.8*	8.4*	7.2*	8.0*	9.4*	8.2*
triclopyr (high)	1.9	7.8*	10.0*	9.6*	10.0*	10.0*	10.0*	10.0*	10.0*
untreated	n.a.	2.0	1.8	2.4	3.2	2.8	3.6	4.4	1.6
$LSD_{0.05}$		1.3	1.8	1.9	2.8	2.9	3.2	3.2	3.2

* indicates significant difference from the untreated control
$LSD_{0.05}$ = Least Significant Difference at p = 0.05.

Some herbicides again caused no damage to *D. micrantha* in the second experiment even when rates were increased and the spraying was performed in March, these being oxadiazon and pendimethalin (Table 7.3). Metsulfuron was re-tested with the same rates, and diflufenican was re-tested at lower rates during March. Both of these herbicides were again shown to be safe on *D. micrantha* despite spraying being done in the warmer season.

The 2,4-D/dicamba treatment previously indicated a significant difference at 18 WAT. This treatment in the second trial confirmed that there was no significant difference at 15 and 20 WAT from untreated plants, though some damage was detected (Table 7.3). Other herbicide treatments which again showed no ill-effect to the ground cover were the mixtures bromoxynil / ioxynil / mecoprop, and both rates of clopyralid / haloxyfop / tribenuron.

The mixture of dicamba/MCPA/mecoprop was previously mildly damaging to *D. micrantha* when applied in June (Table 7.2), but the application in March when it was warmer killed the plant by 9 WAT (Table 7.3).

Other herbicides which were damaging to *D. micrantha* were triclopyr and the picloram / triclopyr mixture. These were more severe in their damage effects when applied in March and the effects were evident even at 3 WAT (Table 7.3).

7.2.4 *Dichondra micrantha* trials: Discussion

The herbicide trials showed *D. micrantha* to be tolerant of metsulfuron, which confirmed previous work done by Harrington et al. (2002). This herbicide kills a wide range of weeds including some shrubby scrub weeds and grass species. Other than a knockdown action, it also has residual action, with a half-life of about 30 days; and may offer weed protection for a couple of months. This allows for a wide-range of dicotyledonous weeds to be controlled within swards of *D. micrantha*.

Other herbicides with residual action tolerated by *D. micrantha* were oxadiazon, pendimethalin and linuron. The results for oxadiazon at the tested rate confirmed prior work by Harrington and Zhang (1997) and Harrington *et al.* (2002) for older plants. Harrington and Zhang (1997) found that oxadiazon was not suitable as a pre-emergent treatment as it damaged *D. micrantha* seedlings and stolon fragments. In the current trials, *D. micrantha* showed tolerance to pendimethalin at a higher rate than the previous work cited, and linuron was previously found to be unsafe when used in combination with diuron (Harrington & Zhang 1997). These are also all contact herbicides, with the former two herbicides having extremely low solubility, making them ideal where depth protection is important, such as around trees. However, oxadiazon and pendimethalin need some moisture to be present after application to be effective, and may be unsuitable during dry seasons in sites with no irrigation.

Dichondra micrantha also showed tolerance to glyphosate, which is very useful as it enables this normally non-selective herbicide to behave selectively and remove weeds from a patch of *D. micrantha*. Other contact herbicides which are tolerated include bromoxynil and ioxynil which are selective to grasses. This would be useful as it allows *Dichondra micrantha* to be planted next to grass turf areas, where bromoxynil and ioxynil could remove broad-leaved weeds from the boundaries between the lawn and *D. micrantha* while not harming turf. The presence of mecoprop in the Axall product did not harm *D. micrantha,* so it may be inferred to be safe on *D. micrantha* too. Clopyralid and mecoprop are both hormone herbicides and kill a wide range of dicotyledonous weeds, but are also safe on turf. Another translocated herbicide which is selective in turf grasses tolerated by *D. micrantha* is tribenuron, which may have some persistent effect, especially if lime amendments were used in the soil (Rahman et al. 1996). The combination of clopyralid / haloxyfop / tribenuron was also tested successfully by Harrington *et al.* (2002) but at lower rates. The range of translocated hormone herbicides tolerated by *D. micrantha* also includes dicamba which was tested by Harrington and Zhang (1997).

To control *D. micrantha,* triclopyr and picloram may be used for spot knock-down action. This follows on from Harrington & Zhang's (1997) study where lower rates proved damaging to *D. micrantha* but did not kill it. An additional herbicide for controlling *D. micrantha* revealed by this trial was diflufenican.

This trial has shown a wide range of herbicides suitable for use on *Dichondra micrantha* as a companion plant to turf grass. Managers can easily prevent turf mixing into *D. micrantha* areas by applying haloxyfop. Herbicides for spot knock-down action against dicotyledonous weeds include common herbicides such as clopyralid, the more affordable glyphosate, and also metsulfuron and tribenuron to extend the range of weeds controlled. This could be followed up with residual herbicides if desired, with options listed above. Should *D. micrantha* spread beyond its intended boundaries it may be controlled by triclopyr and picloram, though turf may also be susceptible to some damage at higher rates, so prior testing would be advised.

7.3 Hydrocotyle trials

7.3.1 Hydrocotyle microphylla trials: Methods

Three herbicide trials were conducted for *Hydrocotyle microphylla. H. microphylla* plants were collected around Massey University grounds using a soil corer to form plugs of 5 cm diameter and propagated in PB ¾ bags containing potting mix with 3-month slow release Osmocote and dolomite. The plants were allowed to establish for 10 weeks before trial commencement.

The first trial for *H. microphylla* was conducted over 18 weeks from 20 June 2008 to 24 Oct 2008 involving 12 herbicide treatments and one untreated control randomly assigned to plants. The mean maximum and minimum temperatures 3 weeks following the herbicide application were 12.8°C and 2.4°C respectively. Examples of the visual scores used are shown in Figure 7.2. In the first trial, the treatment mixture of dicamba / MCPA / mecoprop used was a mix using Banvel, DowElanco MCPA and Mec40. More plants were then collected and prepared in a similar manner and established for 10 weeks before a second trial. The second herbicide trial involved 19 herbicide treatments and one untreated control with five replicates, for an 11-week duration from 29 May to 28 August 2009. The mean maximum and minimum temperatures three weeks following the herbicide application were 12.1°C and 2.5°C respectively. The herbicides used in these trials are shown in Table 7.1.

A third herbicide trial was set up for *H. microphylla* with plants collected from the same sites around the Massey University campus using plugs formed from a soil corer. The plants were allowed to establish for 10 weeks. Eighteen herbicide treatments and one untreated control with five replicates were set up in a randomised block arrangement. This trial lasted 9 weeks from 14 November 2009 to 16 January 2010. The mean maximum and minimum temperatures 3 weeks following the herbicide application were 17.7°C and 10.8°C respectively.

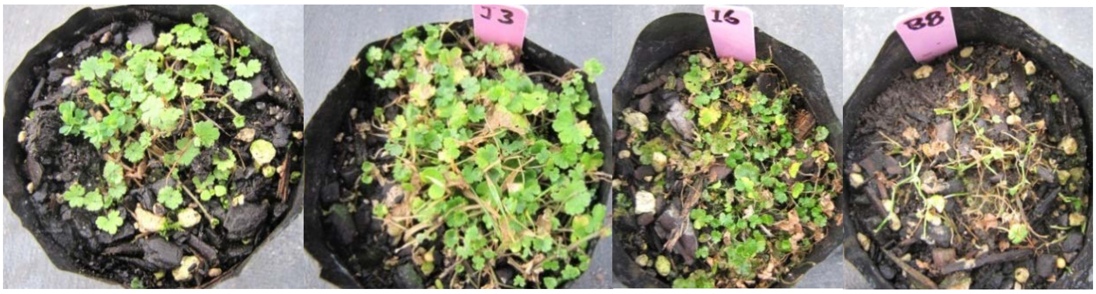

Figure 7.2 (from left to right) *Hydrocotyle microphylla* damage rating 1, 3, 6, 9

7.3.2 Hydrocotyle microphylla trials: Results

Results of the first trial are shown in Table 7.4. In this trial, four herbicides were found to be damaging to *H. microphylla*. The picloram / triclopyr mixture had an almost immediate effect on the plants. Using triclopyr alone or oxyfluorfen caused visible damage to the plants after about 3 weeks. Slowest to take effect was the amitrole treatment.

The clopyralid / haloxyfop mixture and diflufenican treatments were tolerated by *H. microphylla*, as the significant difference to the untreated control at 7 WAT was relatively low and not persistent during the trial.

Other herbicide treatments which were apparently tolerated by *H. microphylla* in this trial were dicamba, glyphosate, oxadiazon (both rates), tribenuron and the mixture of dicamba / MCPA / mecoprop, since all these treatments did not produce any mean score above 4.0.

Table 7.4 Mean scores of plant damage (1 = healthy, 10 = dead) for the first herbicide screening of *Hydrocotyle microphylla* 1-18 weeks after treatment (WAT).

Active Ingredient	Dose ($kg\ ai\ ha^{-1}$)	1 WAT	3 WAT	5 WAT	7 WAT	10 WAT	13 WAT	18 WAT
amitrole	1.26	3.0	3.4	3.8	4.2*	6.8*	5.2*	1.6
clopyralid / haloxyfop	0.942 / 0.942	3.2	3.6	3.0	3.6*	3.4	1.8	1.8
dicamba	0.44	3.0	3.6	2.8	2.4	3.2	1.6	1.6
dicamba/ MCPA/mecoprop	0.209/ 0.45 / 2.64	3.2	3.8	3.0	2.8	3.4	2.0	1.6
diflufenican	0.314	2.8	3.2	2.8	3.8*	3.4	1.8	2.0
glyphosate	1.13	2.8	3.4	3.2	3.2	3.6	1.8	1.6
oxadiazon (low)	0.785	3.0	3.0	3.2	3.4	3.6	2.0	2.2
oxadiazon (high)	1.57	3.0	3.0	3.0	3.0	3.0	2.0	1.8
oxyfluorfen	1.26	3.4	4.6*	4.4*	4.4*	4.0	2.0	1.4
picloram/ triclopyr	1.88/ 0.628	4.0*	7.0*	8.8*	9.0*	9.6*	6.8*	9.6*
tribenuron	0.0942	2.8	3.2	2.6	3.6*	3.6	1.6	1.8
triclopyr	0.96	3.4	6.0*	5.2*	2.6	3.8	3.6	2.0
untreated	n.a.	3.2	3.2	3.0	2.6	3.4	2.0	2.2
$LSD_{0.05}$		0.7	1.4	1.1	1.0	1.5	2.2	0.9

* indicates significant difference from the untreated control
$LSD_{0.05}$ = Least Significant Difference at p = 0.05.

The second herbicide trial for *H. microphylla* only showed useful results up to 3 WAT (Table 7.5) as the plants became necrotic thereafter, presumably caused by a fungal pathogen. The oxyfluorfen and triclopyr treatments again showed damage to the plants at 3 WAT. Amitrole treatment also showed significant damage to the *H. microphylla* even at 3 WAT during this trial.

The dicamba treatment was again tolerated by *H. microphylla* relatively well when applied at the same rate as Trial 1, but the higher dose tested in this trial produced damage to the plants. Another treatment which produced different results from Trial 1 was the mixture of dicamba / MCPA / mecoprop. It damaged the plant quickly even when observed at 3 WAT.

Table 7.5 Mean scores of plant damage (1 = healthy, 10 = dead) for the second herbicide screening of *Hydrocotyle microphylla* 3-11 weeks after treatment (WAT).

Active Ingredient	Dose (kg ai ha^{-1})	3 WAT	5 WAT	7 WAT	9 WAT	11 WAT
amitrole	12.6	8.8*	9.8	10.0	10.0	10.0
clopyralid/ haloxyfop (low)	0.628/ 0.628	3.6	6.6	7.8	4.8*	6.4*
clopyralid/ haloxyfop (high)	1.88/ 1.88	4.0	9.4	9.8	10.0	10.0
dicamba (low)	0.44	5.4	7.4	8.2	8.2	10.0
dicamba (high)	0.879	7.8*	8.6	10.0	10.0	10.0
dicamba/ MCPA/mecoprop	0.22/ 0.44/ 1.76	9.4*	10.0	10.0	10.0	10.0
diflufenican (low)	0.105	4.4	7.6	8.4	8.4	10.0
diflufenican (high)	0.209	4.8	8.4	9.6	10.0	10.0
glyphosate (low)	1.13	5.6	8.0	8.8	8.2	8.6
glyphosate (high)	2.26	6.2	8.2	10.0	8.4	10.0
oxadiazon (low)	2.04	7.6*	9.2	9.4	8.2	10.0
oxadiazon (high)	4.08	8.0*	10.0	10.0	10.0	10.0
oxyfluorfen (low)	1.51	8.6*	9.4	9.8	10.0	10.0
oxyfluorfen	3.01	8.8*	10.0	10.0	10.0	10.0
picloram/ triclopyr	0.628/ 1.88	9.8*	10.0	10.0	10.0	10.0
tribenuron (low)	0.0942	5.0	7.4	9.6	10.0	10.0
tribenuron (high)	0.188	5.2	9.4	10.0	10.0	10.0
triclopyr (low)	0.96	8.6*	9.8	10.0	10.0	10.0
triclopyr (high)	1.92	9.0*	10.0	10.0	10.0	10.0
untreated	n.a.	3.6	7.6	8.4	8.2	10.0
$LSD_{0.05}$		3.3	2.5	2.1	3.0	1.6

* indicates significant difference from the untreated control
$LSD_{0.05}$ = Least Significant Difference at p = 0.05.

Other herbicide treatments which were repeated in this trial but with higher doses were diflufenican, glyphosate, tribenuron and the mixture clopyralid / haloxyfop. All of these treatments did not show significant difference from the control at 3 WAT, although some did have quite high scores such as the higher rate of glyphosate.

The third trial again ran into problems with fungal infection, the results of which can be seen in Table 7.6. This was despite the application of Taratek (chlorothalonil 250 g ai L^{-1} and thiophanate-methyl 250 g ai L^{-1}) applied at 2ml L^{-1} on the plants at 2 WAT. Results up to 5 WAT are deemed to be useful for evaluation as the control plants appeared relatively normal up to this time.

Table 7.6 Mean scores of plant damage (1 = healthy, 10 = dead) for the third herbicide screening of *Hydrocotyle microphylla* 1-7 weeks after treatment (WAT).

Active Ingredient	Dose (kg ai ha^{-1})	1 WAT	3 WAT	5 WAT	7 WAT
amitrole	1.3	3.0*	5.0*	9.0*	8.6
clopyralid/ haloxyfop (low)	0.31/0.21	2.0	3.4	5.6	9.0
clopyralid/ haloxyfop (high)	0.63/0.42	2.8*	3.8	7.8*	9.4
dicamba	0.31	1.6	2.4	5.0	8.6
dicamba/ MCPA/mecoprop	0.084/0.68/2.7	3.2*	8.8*	10.0*	10.0*
diflufenican (low)	0.11	2.8*	4.4	5.0	7.4
diflufenican (high)	0.21	1.4	2.2	6.2*	8.2
glyphosate (low)	0.68	2.2	4.4	5.2	8.0
glyphosate (high)	1.7	2.4	4.6	5.4	8.8
oxadiazon (low)	1.6	4.8*	6.4*	7.4*	9.0
oxadiazon (high)	3.2	5.2*	8.6*	10.0*	9.4*
oxyfluorfen (low)	1.5	6.0*	5.8*	8.6*	9.8*
oxyfluorfen (high)	3.0	6.2*	9.0*	9.0*	9.8*
picloram/ triclopyr	0.21/0.63	4.8*	9.2*	10.0*	10.0*
tribenuron (low)	0.012	1.8	3.2	4.6	9.2
tribenuron (high)	0.024	2.2	4.0	5.8	8.4
triclopyr (low)	0.96	3.4*	7.8*	10.0*	10.0*
triclopyr (high)	1.92	4.2*	8.8*	10.0*	10.0*
untreated	n.a.	1.2	2.2	3.6	8.2
$LSD_{0.05}$		1.6	2.5	2.4	1.6

* indicates significant difference from the untreated control
$LSD_{0.05}$ = Least Significant Difference at p = 0.05.

The herbicides amitrole, oxadiazon, oxyfluorfen, triclopyr and the mixtures of dicamba / MCPA / mecoprop and picloram / triclopyr continued to be damaging to the *H. microphylla* plants, as in previous trials. The higher rates used for diflufenican and the mixture clopyralid / haloxyfop were damaging to *H. microphylla* while the low rates continued to be tolerated.

Herbicides treatments which were safe in this trial were the low rate of the clopyralid/ haloxyfop mixture, dicamba, glyphosate (two rates), and tribenuron (two rates).

7.3.3 *Hydrocotyle microphylla* herbicide trials: Discussion

H. microphylla appeared to tolerate glyphosate and tribenuron quite well in the trials, even when applied at higher rates and during warmer weather. The tolerated rates in this trial were also higher than that previously reported in Harrington & Rahman (1998). Dicamba was tolerated but care should be taken to use lower rates.

Since *H. microphylla* did not seem to tolerate the residual herbicides tested in this trial (such as oxadiazon and oxyfluorfen), establishment of *H. microphylla* may require repeated applications of knock-down herbicides. Should *H. microphylla* spread to areas where it is not intended, control can be achieved using amitrole or triclopyr.

7.4 *Sagina procumbens* herbicide trial

7.4.1 *Sagina procumbens* herbicide trial: Methods

One herbicide trial was conducted for *Sagina procumbens*. The plants were collected from around Massey University glasshouses and transplanted into PB ¾ bags. However, the plants did not take well to transplanting, and none survived in the PB ¾ bags. During the next collection, the plants were carefully scraped off where they were growing, and tamped down onto three shallow trays filled with potting mix. As the quantity collected was not large the collected plants were not used for the herbicide trial. Instead, once the *S. procumbens* plants fruited and died down in the trays, the stems and seed pods were thoroughly mixed into the tray and the resulting mixture carefully spread on top of PB ¾ bags filled with potting mix and Osmocote. The majority of these PB ¾ bags contained viable *S. procumbens* seeds which germinated into plants subsequently used in the herbicide trial. A 4 week period was allowed for plant establishment in the PB ¾ bags. By this time, the plants filled up about 65% of the top surface of the PB ¾ bags.

The herbicide trial for *S. procumbens* involved 26 herbicide treatments and one untreated control with 5 replicates each. The trial lasted 11 weeks from 10 July 2009 to 25 September 2009.

The trial was carried out in a heated glasshouse maintained at 20^{o}C. Examples of the scores used are illustrated in Figure 7.3.

Figure7.3 (from left to right) *Sagina procumbens* damage rating 1, 3, 6, 9

7.4.2 *Sagina procumbens* herbicide trial: Results

Of the herbicides tested for the *S. procumbens* trial, five herbicides were well tolerated (Table 7.7). They were: bentazone; clopyralid / haloxyfop mixture (two rates); oxadiazon (two rates); pendimethalin (two rates); and simazine. In addition, oxyfluorfen was also tolerated at the lower rate used in his trial.

A wide range of herbicides were observed to cause significant damage to *S. procumbens*, namely bromoxynil, dicamba, diflufenican, diuron, paraquat (both rates), triclopyr, the mixtures of bromoxynil / ioxynil / mecoprop, dicamba / MCPA / mecoprop and diquat / paraquat (both rates), and the lower rate of glyphosate used in this trial. Other herbicides were found to kill *S. procumbens* and these were aminopyralid, bromoxynil / ioxynil mixture, picloram / triclopyr mixture, and the higher rate of glyphosate.

Table 7.7 Mean scores of plant damage (1 = healthy, 10 = dead) for the herbicide screening of *Sagina procumbens* 1-9 weeks after treatment (WAT).

Active Ingredient	Dose (kg ai ha^{-1})	1 WAT	3 WAT	5 WAT	7 WAT	9 WAT
aminopyralid	0.047	2.0	6.0*	9.6*	10.0*	10.0*
bentazone	1.5	1.4	1.0	2.4	3.4	6.2
bromoxynil	0.42	2.0	5.0*	5.8*	4.8*	6.8*
bromoxynil/ioxynil	0.31/0.31	2.6	9.6*	10.0*	10.0*	10.0*
bromoxynil/ioxynil/mecoprop	0.24/0.24/1.1	1.6	3.8*	2.8	3.4	4.4
clopyralid/haloxyfop (low)	0.19/ 0.16	1.4	1.0	1.0	1.0	3.2
clopyralid/haloxyfop (high)	0.38/ 0.31	1.4	1.4	1.2	1.8	3.2
dicamba	0.16	2.0	5.6*	6.6*	6.6*	6.8*
dicamba/MCPA/mecoprop	0.22/0.44/1.8	2.2	5.6*	8.0*	8.0*	9.0*
diflufenican	0.11	1.8	4.0*	6.0*	5.6*	7.4*
diquat/paraquat (low)	0.24/0.28	8.4*	8.6*	8.0*	7.4*	7.4*
diquat/paraquat (high)	0.48/0.57	9.2*	9.6*	8.8*	8.0*	7.6*
diuron	1.5	1.6	6.6*	9.0*	8.8*	9.6*
glyphosate (low)	0.85	1.4	7.6*	9.0*	9.0*	9.2*
glyphosate (high)	1.7	1.8	9.8*	10.0*	10.0*	9.6*
oxadiazon (low)	0.17	1.2	1.0	1.4	1.6	4.0
oxadiazon (high)	0.34	1.6	1.0	2.2	3.2	5.4
oxyfluorfen (low)	0.75	1.4	1.4	1.2	1.6	4.0
oxyfluorfen (high)	1.5	3.4*	1.8	1.2	2.6	5.4
paraquat (low)	0.31	6.0*	5.8*	7.2*	5.8*	7.8*
paraquat (high)	0.63	9.4*	9.4*	9.0*	9.2*	9.4*
pendimethalin (low)	0.57	1.2	1.0	1.0	1.8	5.0
pendimethalin (high)	1.1	1.4	1.4	2.0	2.2	5.2
picloram/triclopyr	0.21/ 0.63	1.6	6.4*	9.6*	9.8*	10.0*
simazine	1.6	1.8	1.0	2.0	2.6	6.4*
triclopyr	0.96	1.8	7.2*	8.6*	8.8*	9.0*
untreated	n.a.	1.4	1.0	1.0	1.2	3.8
$LSD_{0.05}$		1.3	2.1	2.2	2.8	2.7

* indicates significant difference from the untreated control
$LSD_{0.05}$ = Least Significant Difference at p = 0.05.
11 WAT results not shown due to deterioration of control plants

7.4.3 *Sagina procumbens* herbicide trial: Discussion

Sagina procumbens had to be established from seeds accomplished by mixing crushed plant material including seed heads into a potting mix. After plants have germinated, residual herbicides can be applied to extend the weed-free period. It should be noted that the plants were not apparently damaged by the initial contact action of these residual herbicides. Germination of seedlings was still possible after residual herbicide treatment. Three residual herbicides were tolerated well by *S. procumbens* when applied by themselves: oxadiazon, oxyfluorfen, and pendimethalin. Though simazine appeared to be tolerated initially by the established plants, some damage occurred at 9 WAT. This confirms what was previously reported by Harrington and Grant (1993) for oxadiazon and pendimethalin, but the tested rate in this trial for oxyfluorfen showed higher tolerance than previously reported by the same paper.

Although the bromoxynil / ioxynil / mecoprop mixture appeared to be tolerated at the rate applied, the treatment of bromoxynil / ioxynil killed the plant. Therefore, the bromoxynil / ioxynil / mecoprop mixture can not be recommended. Similarly, the higher rate of oxyfluorfen damaged the plants, and any recommendation to use the lower rate should be cautiously done.

After initial establishment, weeds may be controlled with spot treatment of knock-down herbicides. Tolerance to haloxyfop will enable easy control of grass weeds. Some dicotyledonous weeds can also be controlled using clopyralid. The tolerance to clopyralid was also previously reported by Harrington and Grant (1993). The other option to control broad-leaved weeds is the use of the contact herbicide bentazone.

7.5 *Soleirolia soleirolii* herbicide trials

7.5.1 *Soleirolia soleirolii* herbicide trials: Methods

Two *S. soleirolii* plants in PB 2 bags were purchased from a nursery. The plants were subsequently divided and spread on shallow seed trays for propagation purposes. Once ten trays were filled with *S. soleirolii* plants, they were divided again and transplanted into PB ¾ bags containing potting mix and Osmocote for establishment. After about 6 weeks, the first of two herbicide trials was conducted for *S. soleirolii.*

The first trial was set up from 31 March 2009 to 14 August for a total of 19 weeks. Twenty-three herbicide treatments and one untreated control each with five replicates were set up in a randomised complete block design. The mean maximum and minimum temperatures 3 weeks following the herbicide application were 18.8°C and 6.5°C respectively. From 19 May (7 WAT) onwards, the plants were moved to a heated glasshouse maintained at 20°C. The water rate used was 3140 L ha^{-1}, as described in Section 7.2.2 for the *Dichondra micrantha* trial. Examples of the scores used are illustrated in Figure 7.4.

A second trial was set up from 15 November 2009 to 14 March 2010, lasting 19 weeks. 21 herbicide treatments and one untreated control each with 5 replicates were set up in a completely randomised design. All plants were in PB ¾ bags prepared in a similar method to the previous trial. Plants were kept in an unheated shade-house. The mean maximum and minimum temperatures 3 weeks following the herbicide application were 17.8°C and 10.9°C respectively.

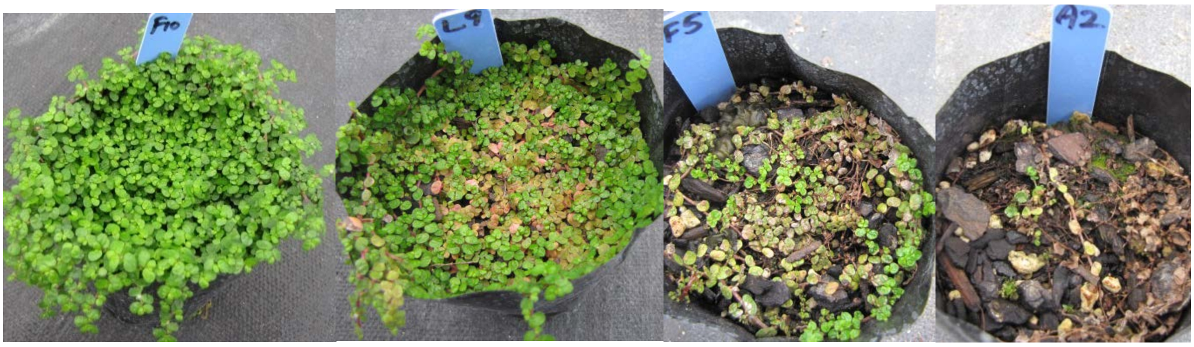

Figure 7.4 (from left to right) *Soleirolia soleirolii* damage rating 1, 3, 6, 9

7.5.2 *Soleirolia soleirolii* herbicide trials: Results

Results of the first herbicide trial for *Soleirolia soleirolii* are presented in Table 7.8. Ten treatments were found to be tolerated by *S. soleirolii* at the trialled rates, these were: 2,4-D, bentazone, dicamba, glufosinate, glyphosate, haloxyfop, MCPA, simazine, as well as the mixtures bromoxynil / ioxynil / mecoprop, and diquat / paraquat. Two treatments which killed *S. soleirolii* 7 weeks after application were aminopyralid and picloram / triclopyr. The other treatments caused visual damage to the plants but *S. soleirolii* recovered from their effects within 19 weeks, except for those plants treated with metsulfuron and triclopyr.

Table 7.8 Mean scores of plant damage (1 = healthy, 10 = dead) for the first herbicide screening of *Soleirolia soleirolii* 3-19 weeks after treatment (WAT).

Active Ingredient	**Dose (kg ai ha^{-1})**	**3 WAT**	**5 WAT**	**7 WAT**	**9 WAT**	**11 WAT**	**13 WAT**	**15 WAT**	**19 WAT**
2,4-D	1.09	1.6	2.0	2.2	2.2	2.0	1.6	1.4	1.0
aminopyralid	0.0628	5.6*	9.0*	10.0*	10.0*	10.0*	10.0*	10.0*	10.0*
amitrole	1.26	3.8*	4.2*	4.4*	3.4*	3.6*	3.4*	3.6*	2.2
bentazone	1.51	1.8	1.8	2.0	2.0	2.2	1.6	1.2	1.0
bromoxynil/ ioxynil/ mecoprop	0.236/ 0.236/ 1.08	1.2	1.6	1.6	2.2	2.4	1.8	2.4	1.6
clopyralid	0.314	2.6	5.2*	4.8*	5.2*	6.8*	5.4*	6.8*	2.0
dicamba	0.209	2.2	2.6	2.2	2.0	2.2	1.8	2.0	1.4
dicamba/ MCPA/mecoprop	0.22/ 0.44/ 1.76	3.2*	3.4*	3.6*	3.4*	3.4*	1.6	1.8	1.2
diflufenican	0.105	4.2*	4.6*	5.0*	4.8*	4.0*	3.2*	2.2	1.2
diquat/ paraquat	0.193/ 0.226	1.2	1.2	1.6	2.4	1.8	1.8	1.8	1.2
diuron	1.67	5.2*	7.0*	1.4	2.2	2.4	1.0	1.4	2.2
glufosinate	1.05	1.4	2.0	2.2	2.4	2.2	2.2	2.2	1.0
glyphosate	0.377	1.6	2.0	2.4	2.2	2.0	2.2	2.4	1.0
haloxyfop	0.314	1.8	2.2	2.0	2.0	1.6	1.6	1.8	2.0
MCPA	1.18	1.6	1.8	2.6	2.2	2.4	1.8	2.2	1.4
metsulfuron	0.0942	1.8	3.6*	3.4*	4.2*	4.8*	3.8*	5.8*	3.6*
oxadiazon	1.57	6.0*	7.2*	7.8*	6.2*	6.8*	5.2*	5.0*	1.4
oxyfluorfen	0.628	7.6*	7.6*	8.0*	7.4*	7.6*	5.4	5.4*	2.2
pendimethalin	1.36	2.6	2.8	3.6*	4.6*	3.8*	2.8	3.4*	1.4
picloram/ triclopyr	0.209/ 0.628	6.6*	9.4*	10.0*	10.0*	10.0*	10.0*	10.0*	10.0*
simazine	1.57	2.0	2.2	2.6	2.2	1.8	1.4	1.4	1.0
tribenuron	0.0942	2.8	4.0*	3.4*	3.2*	3.0	2.4	2.2	1.6
triclopyr	0.44	4.6*	8.0*	6.0*	4.0*	5.6*	4.4*	4.4*	4.6*
untreated	n.a.	1.4	1.4	1.4	1.4	1.6	1.2	1.4	1.0
$LSD_{0.05}$		1.5	1.7	1.8	1.8	1.8	1.8	1.8	1.7

* indicates significant difference from the untreated control
$LSD_{0.05}$ = Least Significant Difference at p = 0.05.

In the second trial, many of the treatment rates were increased but *S. soleirolii* continued to tolerate their effects (Table 7.9). The results of this trial can be seen in Table 7.9. The lower rates of glufosinate, simazine and the bromoxynil / ioxynil / mecoprop mixture used were the same as the previous trial, and tolerance was again confirmed (mean score of less than 4 was deemed visually acceptable, although normal growth rate may have been affected). These three treatments also had higher rates tested in the second trial, and the increased rate of glufosinate was found to be damaging, while no serious damage was observed with the higher rates of the other two treatments. Amitrole and diflufenican were applied at the same rates as in the first herbicide screening and similar levels of damage were confirmed, though the plants subsequently recovered.

Other herbicide treatments were tested in the second trial with increased rates but still did not cause noticeable damage to *S. soleirolii.* These were 2,4-D, bentazone, dicamba, the dicamba/ MCPA/mecoprop mixture, haloxyfop, and MCPA.

Like the glufosinate treatment discussed earlier, the herbicide treatments glyphosate and the diquat/paraquat mixture also caused damage to *S. soleirolii* when application rates were increased above the rates used in the first herbicide screening where they appeared safe to use.

A new treatment of glufosinate/simazine mixture caused some damage to the *S. soleirolii* plants when the same rates applied separately did not, although the plants recovered soon after. Pendimethalin and tribenuron caused damage in Trial 1, and were re-tested in Trial 2 with lower rates (still useful for weed control); these were tolerated by *S. soleirolii.* However, even when metsulfuron was applied at a lower rate in the second trial, there was still visible damage to the *S. soleirolii* plants.

Table 7.9 Mean scores of plant damage (1 = healthy, 10 = dead) for the second herbicide screening of *Soleirolia soleirolii* 1-17 weeks after treatment (WAT).

Active Ingredient	Dose (kg ai ha^{-1})	1 WAT	3 WAT	5 WAT	7 WAT	9 WAT	11 WAT	13 WAT	15 WAT	17 WAT
2,4-D	2.18	1.0	1.0	1.0	1.2	2.2	1.4	4.0	2.2	3.8
amitrole	1.26	2.6*	4.2*	3.2*	1.8	2.0	2.4	3.6	2.2	3.0
bentazone	3.01	1.8	1.0	1.0	1.0	2.0	1.6	2.8	3.0	3.8
bromoxynil/ ioxynil/ mecoprop (low)	0.236/ 0.236/ 1.08	2.2*	2.4	1.0	1.6	2.8	2.0	2.8	2.0	2.2
bromoxynil/ ioxynil/ mecoprop (high)	0.471/ 0.471/ 2.17	2.8*	3.2*	1.6	1.2	1.4	1.8	2.4	2.6	3.4
dicamba	0.419	1.0	1.0	1.2	1.2	2.6	3.4	3.4	2.4	3.4
dicamba/ MCPA/mecoprop	0.0844/ 0.68/ 2.72	1.0	1.0	1.0	1.0	2.4	1.8	3.4	2.4	3.2
diflufenican	0.105	3.4*	6.8*	7.0*	8.2*	8.8*	4.0	6.6*	2.6	3.0
diquat/ paraquat	0.361/ 0.424	8.0*	1.4	1.0	1.0	1.6	1.4	2.6	3.2	4.0
glufosinate (low)	1.05	1.0	3.6*	1.0	1.0	1.2	1.8	3.2	2.0	3.0
glufosinate (high)	2.09	6.6*	6.4*	4.2*	1.0	1.2	3.6	2.2	2.8	3.2
glufosinate/ simazine	1.05/ 1.57	4.6*	3.8*	1.8*	1.0	1.2	2.6	3.2	3.6*	4.6*
glyphosate (low)	0.848	1.2	1.2	1.6	1.0	1.0	1.6	1.2	1.6	2.6
glyphosate (high)	1.7	1.6	1.2	1.0	1.4	3.8*	5.8*	6.2*	2.0	3.0
haloxyfop	0.523	1.8	1.2	1.0	1.0	2.0	2.2	3.4	3.2	3.8
MCPA	2.36	1.0	1.0	1.0	1.2	1.8	2.2	3.6	2.2	3.0
metsulfuron	0.0314	2.0*	3.0*	4.6*	6.0*	6.6*	2.4	5.0*	3.4	5.0*
pendimethalin	0.714	1.8	1.4	1.8*	2.6*	2.2	2.6	2.8	2.2	3.0
simazine (low)	1.57	2.6*	1.6	1.0	1.0	2.2	1.2	3.8	2.4	3.2
simazine (high)	3.14	1.8	2.6*	1.0	1.2	2.0	3.6	3.4	5.6*	6.8*
tribenuron	0.0196	2.0*	2.2	1.2	1.0	1.0	1.6	1.6	1.4	3.2
untreated	n.a.	1.0	1.0	1.0	1.2	2.0	2.0	2.6	2.0	3.2
$LSD_{0.05}$		0.8	1.5	0.7	0.6	1.4	2.3	1.8	1.5	1.3

* indicates significant difference from the untreated control
$LSD_{0.05}$ = Least Significant Difference at p = 0.05.

7.5.3 Field observations of *Soleirolia soleirolii*

In order to build up stock plants for this project, a plot of Rangitikei shallow sandy loam measuring 12 m by 2 m was sprayed with glyphosate at 1 kg ai ha^{-1} and rotary hoed before being planted up with *Soleirolia soleirolii.* The *Soleirolia soleirolii* was grown in trays and cut into pieces measuring 10 cm by 10 cm with the roots intact within the potting media. A total of 40 pieces were evenly spaced about 30 cm apart and planted into the area. As part of its maintenance regime, different herbicide treatments were applied to various sections of this plot. It was noted that the ground cover plants responded well to applications of glyphosate alone (0.41 kg ai ha^{-1}), and glyphosate (0.41 kg ai ha^{-1}) combined with simazine (1.5 kg ai ha^{-1}). The glyphosate removed weed competition from the site, allowing *S. soleirolii* to establish and spread. The addition of the residual herbicide simazine extended the weed-free period, allowing for greater spread. The use of simazine alone (1.5 kg ai ha^{-1}) and glufosinate (1.0 kg ai ha^{-1}) did not allow this species to achieve comparable spread. The poor results for the simazine were due to the poor knock-down ability of this herbicide, hence simazine used by itself did not adequately remove pre-existing weed competition from the treated area. In contrast, poor results were obtained with the glufosinate because it stunted the growth of *S. soleirolii.*

7.5.4 *Soleirolia soleirolii* trials: Discussion

The tolerance of *S. soleirolii* to glyphosate means this broad-spectrum herbicide can be used for most of the weed control within ground covers composed of this species. Should any weed be glyphosate-resistant, other translocated knock-down herbicides which may be used safely with *S. soleirolii* include tribenuron, 2,4-D, MCPA, mecoprop and dicamba. If the weeds are still mostly in the seedling stage, contact-action herbicides bentazone, bromoxynil and ioxynil are also available to control dicotyledonous weeds. To control grass weeds, haloxyfop may be used without harming *S. soleirolii.*

In areas or periods when bare patches exist within *S. soleirolii,* residual herbicides that can stop weeds establishing in these patches are simazine and pendimethalin. However, if simazine would be used, it should not be combined with glufosinate as the additive effects of those two herbicides in combination can cause damage to *S. soleirolii.* Instead, glyphosate should be used in combination with simazine, as field trials produced excellent spread of the ground cover plant with this combination.

To control *S. soleirolii* in the event that it grows where not wanted, the trials here found that both aminopyralid and a mixture of picloram/triclopyr are effective knock-down herbicides.

7.6 *Veronica serpyllifolia* herbicide trials

7.6.1 *Veronica serpyllifolia* herbicide trials: Methods

Three herbicide trials were performed for *Veronica serpyllifolia*. The plants were collected from around the Massey University glass houses and pastures. Plants transplanted into PB ¾ bags were used in this trial after 6 weeks of establishment in potting mix and Osmocote. This trial tested 18 herbicide treatments and one untreated control with five replicates each. The trial lasted 18 weeks from 20 June 2008 to 24 October 2008 and was conducted in a shadehouse. The mean maximum and minimum temperatures three weeks following the herbicide application were 12.8^{o}C and 2.4^{o}C respectively. Figure 7.5 illustrates some of the scores used.

Figure 7.5 (from left to right) *Veronica serpyllifolia* damage rating 1, 5, 9

To prepare for the second herbicide trial, more plants were propagated in a similar manner to Trial 1. The second trial lasted 21 weeks from 17 March 2009 to 14 August 2009. It involved 18 herbicide treatments and one untreated control with five replicates each in a completely randomised design. The mean maximum and minimum temperatures three weeks following the herbicide application were 19.4^{o}C and 8.1^{o}C respectively.

Due to the poor transplanting success of *V. serpyllifolia*, a third herbicide trial was conducted. The plants in the third trial were produced using crushed seed heads mixed into the potting mix, instead of transplanting. The third trial lasted 19 weeks from 3 October 2009 to 25 Feb 2010. A total of 23 herbicide treatments and one untreated control were tested in this trial with five replicates each in a completely randomised design. The mean maximum and minimum temperatures 3 weeks following the herbicide application were 14.4^{o}C and 5.5^{o}C respectively.

7.6.2 *Veronica serpyllifolia* herbicide trials: Results

Results of the first herbicide trial can be seen in Table 7.10. The plants used for control deteriorated at 10 WAT after they were infected with a fungus, though they subsequently recovered at 13 WAT. All treatments tested on *V. serpyllifolia* either caused death of the plants or significant visible damage. The *V. serpyllifolia* plants recovered from six of the herbicide treatments, these were clopyralid, diflufenican (lower dose), haloxyfop, metsulfuron, oxadiazon, and tribenuron. All other herbicide treatments caused death in this trial.

Table 7.10 Mean scores of plant damage (1 = healthy, 10 = dead) for the first herbicide screening of *Veronica serpyllifolia* 1-18 weeks after treatment (WAT).

Active Ingredient	Dose (kg ai ha^{-1})	1 WAT	3 WAT	5 WAT	7 WAT	10 WAT	13 WAT	18 WAT
2,4-D/dicamba	1.26/ 0.628	3.6	6.0*	8.6*	9.6*	10.0*	10.0*	8.4*
bromoxynil/ ioxynil/ mecoprop	0.236/ 0.236/ 1.08	3.6	4.4	5.4*	6.6*	9.4*	9.8*	10.0*
clopyralid	0.942	2.6	3.6	3.4	5.4*	5.4	3.8	4.2
dicamba/ MCPA/mecoprop	0.209/ 0.45/ 2.64	4.4*	5.4*	8.0*	10.0*	10.0*	10.0*	10.0*
diflufenican (low)	0.157	3.0	3.8	5.8*	8.4*	9.6*	9.0*	9.0*
diflufenican (medium)	0.314	3.4	3.8	5.8*	9.0*	9.0*	9.2*	10.0*
diflufenican (high)	0.628	3.2	4.0	4.6	8.6*	9.2*	10.0*	10.0*
diuron	2.51	3.2	3.8	9.0*	10.0*	10.0*	10.0*	10.0*
glufosinate	1.26	3.8	7.6*	9.4*	10.0*	10.0*	10.0*	10.0*
glyphosate	2.26	3.0	3.4	4.6*	7.8*	9.4*	10.0*	8.2*
haloxyfop	0.942	3.2	3.4	5.0*	5.4*	5.8	2.6	2.4
linuron	1.41	3.6	3.4	8.2*	9.6*	10.0*	10.0*	9.6*
MCPA	11.8	3.6	6.0	10.0*	10.0*	10.0*	10.0*	10.0*
metsulfuron	0.0942	3.0	3.2	5.4*	7.6*	9.2*	9.6*	4.8
oxadiazon	0.775	3.2	3.2	4.2	5.8*	5.4	2.6	2.0
pendimethalin	1.55	3.6	3.4	3.8	7.4*	8.8*	10.0*	4.8
picloram/ triclopyr	0.628/ 1.88	3.6	5.4*	8.8*	10.0*	10.0*	10.0*	10.0*
tribenuron	0.0942	3.8	4.2	4.2	6.2*	8.4*	7.2*	5.4*
untreated	n.a.	3.0	3.4	2.6	3.8	6.0	2.4	2.0
$LSD_{0.05}$		1.0	1.3	2.2	1.6	1.8	1.8	3.1

* indicates significant difference from the untreated control
$LSD_{0.05}$ = Least Significant Difference at p = 0.05.

Table 7.11 Mean scores of plant damage (1 = healthy, 10 = dead) for the second herbicide screening of Veronica serpyllifolia 3-21 weeks after treatment (WAT).

Active Ingredient	Dose (kg ai ha^{-1})	3 WAT	5 WAT	7 WAT	9 WAT	11 WAT	13 WAT	15 WAT	21 WAT
2,4-D/dicamba	1.26/ 0.628	4.0	6.0	7.4*	8.2*	8.8*	9.6*	8.2	8.2*
bromoxynil/ ioxynil/ mecoprop	0.236/ 0.236/ 1.08	5.6*	7.0*	7.2	8.2*	8.8*	9.2*	9.4*	8.6*
clopyralid	0.942	3.2	5.0*	5.2	5.4*	7.2	8.6*	8.4	8.2*
dicamba/ MCPA/mecoprop	0.22/ 0.44/ 1.76	8.6*	10.0*	10.0*	10.0*	10.0*	10.0*	10.0*	10.0*
diflufenican (low)	0.0523	4.2	4.6	5.8	8.0*	9.0*	9.8*	10.0*	10.0*
diflufenican (med)	0.105	4.0	6.0	7.8*	9.2*	9.6*	10.0*	10.0*	10.0*
diflufenican (high)	0.209	4.0	5.2	5.8	9.6*	10.0*	10.0*	10.0*	10.0*
diuron	2.51	7.8*	8.2*	8.6*	10.0*	10.0*	10.0*	9.0*	10.0*
glufosinate	1.26	9.4*	10.0*	10.0*	10.0*	10.0*	10.0*	10.0*	10.0*
glyphosate	2.26	6.4*	8.0*	8.6*	10.0*	10.0*	10.0*	10.0*	10.0*
haloxyfop	0.942	3.6	4.0	5.4	5.6*	6.2	7.8	6.4	5.2
linuron	1.41	8.4*	10.0*	10.0*	10.0*	10.0*	10.0*	10.0*	10.0*
MCPA	1.18	3.6	4.6	5.2	4.0	6.2	6.4	5.4	5.0
metsulfuron	0.0942	6.0*	8.8*	9.6*	10.0*	10.0*	10.0*	10.0*	10.0*
oxadiazon	0.754	4.2	4.2	4.2	6.0*	7.0	8.4*	6.8	7.8*
pendimethalin	2.15	3.4	4.0	5.2	7.2*	8.8*	9.8*	9.4*	9.6*
picloram/ triclopyr	0.628/ 1.88	5.4*	7.0*	8.4*	9.0*	9.4*	9.8*	8.4	10.0*
tribenuron	0.0942	5.8*	7.2*	7.6*	8.4*	7.6*	8.4*	6.8	6.0
untreated	n.a.	3.0	3.2	4.6	2.8	5.4	6.6	6.0	3.4
$LSD_{0.05}$		2.0	2.9	2.7	2.5	1.8	1.5	2.7	3.3

* indicates significant difference from the untreated control
$LSD_{0.05}$ = Least Significant Difference

The control plants in the second trial appeared in relatively good health until 9WAT, when fungal leaf spots were observed. Within this 9-week period, six herbicide treatments killed *V. serpyllifolia,* these being: diuron, glufosinate, glyphosate, linuron, metsulfuron and the mixture dicamba / MCPA / mecoprop. Two other herbicides which caused extreme damage to the plants were diflufenican (two lower rates and one higher rate than the first trial) and the picloram / triclopyr mixture. Another seven treatments that damaged *V. serpyllifolia* plants within 9 WAT were: 2,4-D / dicamba, bromoxynil / ioxynil / mecoprop, clopyralid, haloxyfop, oxadiazon, pendimethalin and tribenuron. Of these latter herbicide treatments, the dose for pendimethalin was increased to simulate bare ground treatment under orchards. The only treatment which did not harm *V. serpyllifolia* was the MCPA, with the dose in the second trial being the appropriate rate used in crops, unlike that in the first trial.

In the third trial, the results which can be seen in Table 7.12, the herbicide doses for most treatments were reduced. However, the control plants were again infected by fungal pathogens at 7 WAT. The following herbicide treatments still caused some visible damage to *V. serpyllifolia* within 5 weeks of treatment despite the lower dose: 2,4-D / dicamba, dicamba / MCPA / mecoprop, diuron (1.67 kg ai ha^{-1}), glyphosate, linuron (both doses), metsulfuron, pendimethalin and tribenuron (0.0236 kg ai ha^{-1}).

Table 7.12 Mean scores of plant damage (1 = healthy, 10 = dead) for the third herbicide screening of *Veronica serpyllifolia* 3-19 weeks after treatment (WAT).

Active Ingredient	Dose (kg ai ha^{-1})	3 WAT	5 WAT	7 WAT	9 WAT	11 WAT	13 WAT	15 WAT	17 WAT	19 WAT
2,4-D/dicamba	0.628/ 0.314	5.8*	6.4	7.6	8.2*	8.0	8.2	7.6	7.6	7.6
bromoxynil/ ioxynil/ mecoprop	0.157/ 0.157/ 0.722	2.0	3.4	4.0	5.4	6.0	5.4	5.8	5.6	5.6
clopyralid (low)	0.236	2.4	2.6	4.6	4.4	5.4	4.0	4.0	5.4	5.4
clopyralid (high)	0.471	3.0	4.6	5.0	4.6	4.2	4.0	7.2	7.0	7.0
dicamba/ MCPA/mecoprop	0.0844/ 0.68/ 2.72	8.8*	9.4*	9.4*	8.8*	9.4*	8.8	8.6	9.2	9.2
diflufenican	0.105	3.2	5.4	7.6	9.0*	9.8*	9.2*	8.2	8.6	8.6
diuron (low)	0.837	2.4	3.6	4.0	4.2	4.6	4.0	4.0	3.4	3.4
diuron (high)	1.67	9.2*	9.6*	9.6*	10.0*	10.0*	10.0*	8.6	10.0*	10.0
glufosinate	0.837	10.0*	10.0*	9.6*	9.8*	10.0*	10.0*	10.0*	10.0*	10.0
glyphosate	0.68	6.2*	7.0	8.4*	8.8*	8.6*	8.4	8.6	8.8	8.8
haloxyfop (low)	0.131	2.0	4.0	4.2	5.8	7.6	6.8	7.6	7.0	7.0
haloxyfop (high)	0.262	2.2	3.6	3.8	5.2	4.4	3.8	4.8	4.4	4.4
linuron (low)	0.424	5.8*	7.2*	8.0	6.2	5.6	4.6	3.4	2.6	2.6
linuron (high)	0.848	7.6*	8.0*	7.8	7.8*	7.4	7.4	7.0	7.2	7.2
MCPA	1.18	6.2*	8.2*	9.6*	10.0*	10.0*	10.0*	10.0*	10.0*	10.0
metsulfuron	0.0314	6.2*	8.2*	9.4*	8.6*	9.6*	8.6	8.0	6.6	6.6
oxadiazon (low)	0.795	3.8	6.4	6.0	6.4	6.8	4.6	4.6	6.2	6.2
oxadiazon (high)	1.59	3.4	5.2	6.2	5.8	5.6	5.4	5.4	6.0	6.0
pendimethalin	1.38	2.8	3.8	5.6	6.4	6.6	6.6	7.2	7.0	7.0
picloram/ triclopyr (low)	0.105/ 0.314	3.4	4.4	5.0	5.6	6.0	3.6	5.4	4.0	5.8
picloram/ triclopyr (high)	0.209/ 0.628	2.8	3.8	4.4	4.8	6.4	6.2	6.0	5.8	4.0
tribenuron (low)	0.0118	4.4	6.6	7.2	4.6	6.0	6.8	7.8	7.4	7.4
tribenuron (high)	0.0236	5.0	7.2*	6.8	4.6	4.6	3.2	4.2	4.6	4.6
untreated	n.a.	3.2	4.8	6.0	4.8	5.0	5.4	5.6	5.4	6.4
$LSD_{0.05}$		2.2	2.2	2.2	2.8	3.2	3.7	3.7	4.0	4.0

* indicates significant difference from the untreated control
$LSD_{0.05}$ = Least Significant Difference at p = 0.05.

With the lower doses in this trial, more herbicide treatments were tolerated by *V. serpyllifolia*: clopyralid (both doses tested), diflufenican, diuron (0.8 kg ai ha^{-1}), haloxyfop (both doses), oxadiazon (including one dose higher than previously trialled), pendimethalin, tribenuron (0.011 kg ai ha^{-1}), bromoxynil / ioxynil / mecoprop and picloram / triclopyr (both doses).

7.6.3 *Veronica serpyllifolia* trial: Discussion

The series of herbicide trials for *Veronica serpyllifolia* did not turn out well. The plants seemed particularly susceptible to fungal leaf spots after about 1 month in the shadehouse. For the first two trials, transplanting shock likely lowered the constitution of the plants. The first trial was also carried out at low temperatures. The third trial used plants produced from seed, though plants in the control group also did not look good 1 month into the trial.

With poor cultivation results in the shade house, the readings are not reliably consistent. However, some herbicides were found in the second and third trials (discounting the first trial due to low temperatures) to give *Veronica serpyllifolia* a rapid and strong knock-down effect. These herbicides were glyphosate, glufosinate, and dicamba; and the residual herbicides diuron and linuron.

This species was selected for inclusion in these trials initially because *Veronica* species are typically difficult to control in a number of situations. They are tolerant of many herbicides used in turf, including MCPA, clopyralid, dicamba and triclopyr / picloram mixtures (Harrington 2000). However the difficulty of cultivation for *Veronica serpyllifolia* makes this a difficult plant to recommend as a ground cover for weed control.

7.7 Conclusion

Of the five species tested in this chapter, *Dichondra micrantha* and *Soleirolia soleirolii* hold the most promise to be advocated as a turf companion planting or turf alternative. These two species prove resistant to a wide range of herbicides, both residual and selective knock-down herbicides, which make establishment and maintenance of the species feasible. At the same time, selective herbicides are also available for use as a control measure if they become weedy.

Ironically, while the other three species are common lawn or greenhouse weeds, they proved difficult to propagate and cultivate. The trials also revealed *Veronica serpyllifolia* did not take well to the cultivation methods in these trials and no recommendation can be made for this plant. *Hydrocotyle microphylla* proved to have poor resistance to residual herbicides, hence potentially reducing maintenance options for this species to spot applications of knock-down herbicides and hand-weeding. The range of tolerance to selective knock-down herbicides is also not as wide as for *D. micrantha* and *S. soleirolia*. *H. microphylla* also required a moist environment and is not suitable for sites with sun exposure. Overall, the findings in these trials did not make *Hydrocotyle microphylla* an attractive species for ease of cultivation and establishment. *Sagina procumbens* can only be propagated by seed and attempts at stolon establishment were futile. The herbicide trials revealed that *Sagina procumbens* could continue to germinate after residual herbicide application, allowing for planting out in the field using seeds under a weed-free environment aided by residual herbicides, thus facilitating establishment. Its performance in the field will be tested in the next chapter.

Chapter 8 Field trials with turf-compatible ground cover species

8.1 Introduction

Following the herbicide trials of potted ground cover plants suitable for use beside turf described in Chapter 7, this chapter focuses on testing the response of these plant species to herbicides under field conditions, and also looking at whether these herbicides can successfully control weeds that establish within the ground covers. A trial has also been described in which the ground cover plants were planted under a row of Veronese poplars (*Populus euroamericana* 'Veronese'). This demonstrated their suitability to be used in amenity horticultural situations. The trial under trees was of particular interest, as it is not easy for turf grass to establish under trees where there is increased competition for light, water, and soil nutrients (Baldwin et al. 2009), in addition to the difficulties with mowing. Hence, success in this trial would mean the ground cover species might be used to "green" the soil surface up to the base of trees, and reduce regular herbicide application under trees.

8.2 Establishment of initial ground cover plots at Fruit Crops Unit (FCU)

An open area of Manawatu silt loam over sand measuring 12 m by 10 m at Massey University Fruit Crop Unit was used to establish plots of five ground cover plant species: *Dichondra micrantha* (dichondra), *Hydrocotyle microphylla* (hydrocotyle), *Sagina procumbens* (pearlwort), *Sedum mexicanum* 'Acapulco Gold' (sedum), and *Veronica serpyllifolia* (turf speedwell). The species were established in rectangular plots of 3 m by 2 m, and the plots were arranged in randomised complete block design. Five plots each containing a different species made up one block and there were four blocks in total. The layout of the planting plan is shown in Figure 8.1.

Prior to use for this trial, the area was planted with perennial ryegrass and white clover. Before transplanting the ground cover plants into the plots, glyphosate (Roundup Renew) was applied to the area at the rate of 0.2 kg ai ha^{-1} on 24 March 2008, then the area was rotary hoed twice to remove all pre-existing vegetation.

Each species was transplanted into the plots from both PB ¾ bags and sods prepared from seed trays with numbers depending on availability. When transplanting the contents of PB ¾ bags, only the top 4 cm (about one third of the bag volume) which contained the root zone of the plants was transplanted. Sods from seed trays were of a similar depth. In each plot containing *D. micrantha,* 32 PB¾ bags were transplanted into an eight by four grid spaced 0.4 m apart. *H. microphylla* plants were transplanted into a nine by five grid spaced 0.5 m apart width-wise and 0.3 m apart lengthwise. The transplants in each plot consisted of contents from 15 PB ¾ bags and 12 pieces of seedling sods 9 cm by 6 cm cut out from seed trays. Each *S. procumbens* plot was transplanted with contents from nine PB ¾ bags and 15 sods of 9 cm by 6 cm cut out from trays. In addition, seed heads mixed in potting media were also sprinkled along the middle rows of each plot. Each plot of *S. mexicanum* was established using transplants from 24 PB ¾ bags. For each of the *V. serpyllifolia* plots, a five by nine grid spaced 0.3 m apart was marked out, and two stolon fragments were planted at each point.

Block 1	*Sedum mexicanum*	*Dichondra micrantha*	*Sagina procumbens*	*Hydrocotyle microphylla*	*Veronica serpyllifolia*
Block 2	*Sagina procumbens*	*Hydrocotyle microphylla*	*Sedum mexicanum*	*Veronica serpyllifolia*	*Dichondra micrantha*
Block 3	*Dichondra micrantha*	*Sedum mexicanum*	*Veronica serpyllifolia*	*Sagina procumbens*	*Hydrocotyle microphylla*
Block 4	*Veronica serpyllifolia*	*Sagina procumbens*	*Hydrocotyle microphylla*	*Dichondra micrantha*	*Sedum mexicanum*

Figure 8.1 Layout plan of planting plots at Massey University Fruit Crops Unit

The plots were established on 19 April 2008, then clopyralid and haloxyfop was applied to all plots at 0.3 kg ha^{-1} and 0.15 kg ha^{-1} respectively on 23 April 2008. In addition oxadiazon was applied at 1.5 kg ha^{-1} to the pearlwort plots. The clopyralid and haloxyfop treatment was repeated on 5 August 2008 at the same rates. The plots were mowed bi-monthly from July 2008 to a height of 30 mm, except for *Sedum mexicanum* which was mowed to 80 mm.

8.2.1 Determining rate of growth by point analysis

One month (18-19 May 2008) after planting the plots, point analysis was performed within each plot. This was repeated 9 months after planting on 9 January 2009. Point analysis was performed using a point analysis frame with three needles spaced 10 cm apart from each other in a straight line. The needles were held at right angles above the ground, and each needle was lowered at randomly selected positions around each plot until the planted ground cover species was contacted, otherwise a null count was recorded. Each plot had 450 points sampled. This number exceeds the sample size of 350 points recommended in the paper by Hofmann & Ries (1990) to adequately estimate a sample mean within 10% of the population mean at the 90% confidence level, for a pasture area of 12 m by 67 m to estimate the area covered with live plants. The frame was randomly placed within the plot, but the frame was moved progressively to cover both its length and width of 3 m by 2 m.

8.2.2 Determining rate of growth by point analysis: Results and discussion

Sagina procumbens was able to spread out most quickly after transplanting, covering about three-quarters of the plot area after 9 months (Table 8.1). *Hydrocotyle microphylla* and *Dichondra micrantha* also produced good results, covering about half the plot area in 9 months. *Sedum mexicanum* did not expand its coverage, possibly due to inability to recover from the stress of regular mowing. The worst performing species was *Veronica serpylilifolia*, which was no longer detected at the time point analysis was carried out. In fact, *Veronica serpyllifolia* had died out by August. This was probably due to poor survival of transplanted stolons, and it was apparent that another technique for establishing swards of this species would be necessary.

Table 8.1 Mean plot coverage by ground cover species 1- and 9-months after planting

Species	Period	Block 1 (%)	Block 2 (%)	Block 3 (%)	Block 4 (%)	Average (%)
Dichondra micrantha	May 2008 Jan 2009	2.0 40.0	2.7 54.0	2.0 36.7	2.4 52.7	2.3 46.7
Hydrocotyle microphylla	May 2008 Jan 2009	2.7 48.0	3.1 54.7	4.0 64.0	2.9 31.3	3.2 51.2
Sagina procumbens	May 2008 Jan 2009	3.1 72.7	3.8 74.0	1.3 83.3	2.0 60.7	2.6 74.5
Sedum mexicanum	May 2008 Jan 2009	7.6 3.3	5.3 4.0	4.0 4.0	3.1 2.7	5.0 3.5
Veronica serpyllifolia	May 2008 Jan 2009	0.4 0.0	1.8 0.0	0.7 0.0	0.4 0.0	0.8 0.0

8.3 Herbicide trial 1 at FCU

The objective of this trial was to show that results from herbicide trials with potted plants reported in Chapter 7 could be used to safely control weeds within field plots of the various ground cover species.

8.3.1 Herbicide trial 1 at FCU: Materials and methods

This trial involved the four species of ground covers that did establish successfully: *Dichondra micrantha, Hydrocotyle microphylla, Sagina procumbens,* and *Sedum mexicanum*. On 10 October 2008, each plot had plastic plant labels positioned at six points across the plot, which marked the centres for placement of circular wire frames 30 cm in diameter. Each of these circular areas served as experimental units for assessment of herbicide treatments, hereafter referred to as patches.

Before spraying, the rectangular plots were visually assessed for weed presence as well as proportion of ground cover plant, estimated visually. The *Dichondra micrantha*, *Hydrocotyle microphylla*, and *Sedum mexicanum* plants covered 12-20% of their respective patches. Those patches all had *Cerastium glomeratum* (annual mouse-ear chickweed), *Lepidium didymum* (twin cress), and *Veronica persica* (scrambling speedwell) present, with each weed species taking up about 10-30% of the area. Grass weeds were also present, making up about 15% of the plots and consisting of a mix of *Poa annua* and *Vulpia bromoides.*

The *Sagina procumbens* plots had a slightly different composition due to the additional treatment of oxadiazon during establishment. They were composed with more of the intended ground cover, with *Sagina procumbens* occupying about 60% of the plot area. The main weed was *C. glomeratum,* which took up more than 20% of the plot area, and while *V. persica* was also present in every *Sagina procumbens* plot, it only occupied less than 5% of each area. The grass weeds appeared only sporadically and *L. didymum* was totally absent. Instead, *Stellaria media* (chickweed) was present across all treatment replicates (occupying about 5-10% of the area) for *Sagina procumbens* where it was only sporadically spotted in the other plots without the oxadiaxon treatment. Other weeds which were occasionally found in the plots include *Capsella bursa-pastoris* (shepherd’s purse), *Lamium purpureum* (red dead-nettle), and *Rumex obtusifolius* (broad-leaved dock).

Treatments involved applying 20 ml of herbicide solution to each circular area using a hand-held pump sprayer to simulate spot spraying. This equated to 2830 L ha^{-1}, and was applied on 10 Oct 2008. Treatments that were applied are listed in Table 8.2, with the products previously detailed in

Tables 5.1 and 7.1. The treatments were allocated in a randomised complete block design. Blocks were assigned in a roughly north-south orientation, due to the topography being graded with the north end slightly lower and moister. The plots were assessed at 10-day intervals up to 30 days for the effects of the herbicide treatments on specific weeds, then overall weed mortality was assessed at 40 days after treatment. Assessment was done visually and the plants and major weeds were scored from 1-10, with 1 being healthy and 10 being dead.

8.3.2 Herbicide trial 1 at FCU: Results

The results of the first trial are presented in Tables 8.2-8.5. Overall weed mortality of the treatment area was assessed visually after 40 days and presented as mean percentages.

Despite the relatively high water rate, overall weed mortality at 40 DAT was very high across all plots, with only the oxadiazon treatment showing lower weed mortality. The ground cover species selected for this trial generally tolerated the treatments well (Tables 8.2-8.5), with the exception of damage caused by glyphosate treatments on *Sedum mexicanum*. However, glyphosate was tolerated for use on *Dichondra micrantha* and *Hydrocotyle microphylla,* together with oxadiazon (Tables 8.2 and 8.3). *Sagina procumbens* also appeared to tolerate oxadiazon well. Other herbicides tolerated by *S. procumbens* were pendimethalin and oxyfluorfen (Table 8.5). *Hydrocotyle microphylla* was slightly affected by oxyfluorfen but recovered well (Table 8.3). Although *Sedum mexicanum* was susceptible to glyphosate, it tolerated amitrole, simazine and metsulfuron well (Table 8.4). Metsulfuron also caused no damage to *Dichondra micrantha* (Table 8.2).

Table 8.2 Herbicide damage scores of *Dichondra micrantha* plants and main weeds present in plots at various days after treatment (DAT), with overall weed mortality after 40 days.

Herbicide	**GLYPH**	**GLYPH**	**GLYPH + OXADZ**	**METSF**	**OXADZ**	**UNTRT**	**$LSD_{0.05}$**
Rate (kg ai ha^{-1})	1.0	2.0	1.0 + 0.68	0.085	0.70	---	---
Dichondra micrantha							
Score 10 DAT	1.0	1.3	1.3	1.0	1.0	1.0	*0.4*
Score 20 DAT	1.3	1.5	1.5	2.0*	1.3	1.3	*0.7*
Score 30 DAT	1.0	1.2	1.0	1.0	1.0	1.0	*0.3*
Cerastium glomeratum (annual mouse-ear chickweed)							
Score 10 DAT	3.3	7.0*	3.0	3.3	4.5	2.3	*3.6*
Score 20 DAT	9.3*	9.0*	9.3*	8.0*	3.3	1.8	*1.7*
Score 30 DAT	10.0*	9.5	7.0	10.0*	7.0	4.5	*5.9*
Grass species (*Poa annua, Vulpia bromoides*)							
Score 10 DAT	4.3*	4.8*	3.3*	3.3*	2.7	1.3	*1.7*
Score 20 DAT	6.3*	8.3*	4.3	3.3	2.3	3.0	*3.3*
Score 30 DAT	5.5	6.5*	2.0	2.5	1.0	1.0	*5.1*
Lepidium didymum (twin cress)							
Score 10 DAT	4.0*	4.3*	4.5*	4.5*	3.3	2.3	*1.5*
Score 20 DAT	5.3*	7.0*	6.8*	6.3*	2.5	2.5	*3.4*
Score 30 DAT	4.8	10.0*	6.8*	9.8*	7.8*	1.0	*5.4*
Veronica persica (scrambling speedwell)							
Score 10 DAT	3.7	3.5	1.5	3.8	3.5	1.3	*3.1*
Score 20 DAT	4.3	5.3*	3.3	5.0*	1.5	1.3	*2.9*
Score 30 DAT	3.3	8.5	5.5	9.0	4.5	4.3	*5.8*
Overall weed mortality (%) 40 DAT	86.0	91.2	56.0	90.0	52.0	9.0	*35.7*

GLYPH = glyphosate; METSF = metsulfuron; OXADZ = oxadiazon; UNTRT = untreated;
$LSD_{0.05}$ = least significant difference at 5% critical value
*significantly different from untreated control at p>0.05

Cerastium glomeratum (chickweed) was well controlled by the glyphosate and metsulfuron treatments (Table 8.2). Oxadiazon did not give consistent results, being most damaging in the *Hydrocotyle microphylla* plots (Table 8.3). However, the combination of glyphosate with oxadiazon seemed to provide better knock down of *C. glomeratum* (Table 8.2). Another herbicide combination which worked well with glyphosate to control this weed was simazine (Table 8.4). Other herbicides which showed good control results were oxyfluorfen (Tables 8.3 and 8.5) and amitrole (Table 8.4). Pendimethalin was not found to be effective in controlling *C. glomeratum* (Table 8.5).

Pendimethalin was useful, however, in controlling *Veronica persica*, though higher rates may be needed to achieve desired results (Table 8.5). Similarly, higher rates of glyphosate provided a better check against *V. persica* (Tables 8.2 to 8.4). Alternatively, lower rates of glyphosate may be combined with oxyfluorfen (Table 8.3) or simazine (Table 8.4) for excellent results. If mixtures are not favoured, metsulfuron could be a viable choice (Tables 8.2 and 8.4). Amitrole was slightly damaging to *V. persica*, but it soon recovered (Table 8.4).

Table 8.3 Herbicide damage scores of *Hydrocotyle microphylla* plants and main weeds present in plots at various days after treatment (DAT), with overall weed mortality after 40 days.

Herbicide	GLYPH	GLYPH	GLYPH + OXYFL	OXADZ	OXYFL	UNTRT	$LSD_{0.05}$
Rate (kg ai ha^{-1})	1.0	2.0	1.0 + 0.68	0.70	0.68	---	---
Hydrocotyle microphylla							
Score 10 DAT	2.0	2.5	2.0	2.3	2.8	2.0	*1.2*
Score 20 DAT	2.0	3.3*	2.3	1.8	3.0*	1.3	*1.1*
Score 30 DAT	1.0	1.7*	1.0	1.0	1.0	1.0	*0.6*
Cerastium glomeratum (annual mouse-ear chickweed)							
Score 10 DAT	4.8	6.0	5.0	3.3	4.0	5.3	*4.2*
Score 20 DAT	9.0*	9.5*	8.7*	4.7	6.7	3.0	*4.1*
Score 30 DAT	10.0*	9.5*	10.0*	9.3*	9.0*	6.3	*1.9*
Grass species (*Poa annua, Vulpia bromoides*)							
Score 10 DAT	3.3	6.8*	7.3*	3.0	5.3	2.7	*2.7*
Score 20 DAT	5.0	8.5*	7.3*	2.5	3.8	4.0	*3.7*
Score 30 DAT	9.3*	9.5*	9.8*	1.0	3.3*	1.0	*2.0*
Lepidium didymum (twin cress)							
Score 10 DAT	5.0	6.8*	7.8*	4.7	5.5*	3.0	*2.4*
Score 20 DAT	10.0*	7.5*	6.0*	5.3*	5.3*	1.0	*4.0*
Score 30 DAT	10.0*	8.5	8.3	4.3	4.5	5.5	*6.2*
Veronica persica (scrambling speedwell)							
Score 10 DAT	1.7	3.5	1.0	1.5	4.0	1.3	*4.6*
Score 20 DAT	1.3	4.0	10.0*	1.0	4.7	1.0	*4.1*
Score 30 DAT	2.0	8.5*	10.0*	3.3	8.0*	2.0	*5.8*
Overall weed mortality (%) 40 DAT	69.0	93.7	98.7	30.0	84.0	46.0	*39.1*

GLYPH = glyphosate; OXADZ = oxadiazon; OXYFL = oxyfluorfen; UNTRT = untreated;
$LSD_{0.05}$ = least significant difference at 5% critical value
*significantly different from untreated control at p>0.05

Lepidium didymum (twin cress) is another weed which may require a higher dose of glyphosate on occasion to control (Table 8.2), though it was generally well controlled with glyphosate (Tables 8.3 and 8.4). Combinations with glyphosate which gave good results were oxadiazon (Table 8.2), oxyfluorfen (Table 8.3), and simazine (Table 8.4). Oxadiazon when used on its own gave variable results (effective in Table 8.2; tolerated in Table 8.3), and oxyfluorfen when used alone did not provide satisfactory results (Table 8.3). Metsulfuron proved consistently effective in controlling *L. didymum* (Tables 8.2 and 8.4), while amitrole was another viable option (Table 8.4).

Table 8.4 Herbicide damage scores of *Sedum mexicanum* plants and main weeds present in plots at various days after treatment (DAT), with overall weed mortality after 40 days.

Herbicide	**AMTRL**	**GLYPH**	**GLYPH**	**GLYPH + SIMZN**	**METSF**	**UNTRT**	**$LSD_{0.05}$**
Rate (kg ai ha^{-1})	11.3	2.04	4.08	2.01 + 1.42	0.0849	---	---
***Sedum mexicanum* 'Acapulco Gold'**							
Score 10 DAT	1.3	2.8	2.5	2.8	2.0	1.8	*2.1*
Score 20 DAT	3.0	4.5*	5.5*	4.5*	3.5	1.8	*2.4*
Score 30 DAT	3.5	4.3	7.5*	5.0	3.5	2.3	*3.4*
Cerastium glomeratum (annual mouse-ear chickweed)							
Score 10 DAT	5.0	3.0	4.0	5.7	3.3	3.8	*5.3*
Score 20 DAT	8.0*	7.0	8.0*	8.3*	8.3*	3.5	*3.9*
Score 30 DAT	8.0	9.5	10.0	10.0	9.8	8.0	*2.1*
Grass species (*Poa annua, Vulpia bromoides*)							
Score 10 DAT	4.5	6.5	7.5*	7.0	2.8*	3.7	*4.4*
Score 20 DAT	6.5*	8.5*	5.8*	9.0*	6.5*	2.0	*3.7*
Score 30 DAT	7.8	10.0	10.0	10.0	6.3	5.0	*5.6*
Lepidium didymum (twin cress)							
Score 10 DAT	4.5	4.7	3.5	5.5	2.5	5.5	*5.0*
Score 20 DAT	3.5	8.0	5.5	6.0	5.5	1.5	*6.6*
Score 30 DAT	10.0*	8.3*	10.0*	9.5*	10.0*	1.5	*2.7*
Veronica persica (scrambling speedwell)							
Score 10 DAT	3.3	3.0	2.5	2.5	2.8	1.0	*3.2*
Score 20 DAT	4.5*	5.3*	7.0*	7.5*	7.0*	1.3	*1.7*
Score 30 DAT	9.3	8.5	8.8	8.8	9.3	8.3	*2.1*
Overall weed mortality (%) 40 DAT	83.8	95.0	96.3	100.0	95.0	38.8	*27.4*

AMTRL = amitrole; GLYPH = glyphosate; METSF = metsulfuron; SIMZN = simazine; UNTRT = untreated; $LSD_{0.05}$ = least significant difference at 5% critical value
*significantly different from untreated control at p>0.05

None of the herbicide treatments selected specifically targeted grass weed species, however, glyphosate is a broad-spectrum herbicide and it was the only treatment which caused considerable damage to *Poa annua* and *Vulpia bromoides* (Tables 8.2 to 8.4). Generally, higher rates of glyphosate were more damaging, but combination treatments worked well too. Glyphosate was combined with oxyfluorfen (Table 8.3) and simazine (Table 8.4) which produced severely damaging results.

No treatments on the Sagina procumbens plots managed to effectively kill Stellaria media (chickweed). However, they did produce significantly damaging effects while S. procumbens remained unharmed (Table 8.5). Many of the winter annual plants were dying naturally by 30 DAT, especially C. glomeratum.

Table 8.5 Herbicide damage scores of *Sagina procumbens* plants and main weeds present in plots at various days after treatment (DAT), with overall weed mortality after 40 days.

Herbicide	**OXADZ**	**OXADZ**	**PENDM**	**PENDM**	**OXYFL**	**UNTRT**	**$LSD_{0.05}$**
Rate (kg ai ha^{-1})	0.699	1.40	1.93	3.86	0.679	---	
Sagina procumbens (pearlwort)							
Score 10 DAT	1.0	1.3	1.0	1.3	1.3	1.5	0.6
Score 20 DAT	1.0	1.0	1.0	1.0	1.0	1.0	0.0
Score 30 DAT	1.0	1.0	1.0	1.0	1.0	1.0	0.0
Cerastium glomeratum (annual mouse-ear chickweed)							
Score 10 DAT	4.0	4.7	4.5	4.8	7.0	5.0	3.2
Score 20 DAT	4.7	4.0	4.0	5.3	5.0	3.5	2.2
Score 30 DAT	8.0	9.0	8.0	7.5	7.5	7.8	2.3
Stellaria media (chickweed)							
Score 10 DAT	2.0*	3.0*	3.0*	4.0*	4.0*	1.0	1.9
Score 20 DAT	1.0	2.0	1.0	1.0	1.0	1.5	1.1
Score 30 DAT	3.0	4.0	2.0	3.0	2.0	2.0	4.3
Veronica. persica (scrambling speedwell)							
Score 10 DAT	1.0	2.5*	3.0*	3.5*	3.0*	1.0	0.8
Score 20 DAT	1.0	4.3	3.0	3.5	1.0	1.0	6.8
Score 30 DAT	4.0	7.3	8.5	10.0*	5.0	3.8	6.2
Overall weed mortality (%) 40 DAT	88.8	98.8	92.5	95.0	93.8	78.8	*14.4*

OXADZ = oxadiazon; OXYFL = oxyfluorfen; PENDM = pendimethalin; UNTRT = untreated;
$LSD_{0.05}$ = least significant difference at 5% critical value
*significantly different from untreated control at p>0.05

8.3.3 Herbicide trial 1 at FCU: Discussion

A key result from the field trials was that the ground cover species tolerated the herbicides just as well as in the shadehouse trials. This confirmed that the herbicides were safe to use in field scenarios.

The trial also successfully demonstrated that the relatively high water volume used in spot spraying from a hand-held sprayer did not affect herbicide efficacy against weeds that they might be expected to control. This was intended to simulate spot spraying from a hand-gun. There was a concern that the herbicides were not affecting ground cover species simply because the surfactant concentration within herbicide products had been diluted too much, preventing herbicides from entering plants properly. However, although ground cover plants were still unaffected by most herbicides, weeds were generally controlled as well as might be expected by these products.

However, the results for glyphosate, especially at the lower rate, showed that not all weeds were killed, which may have been less effective than normal. This may have been caused by the reduced efficacy of the surfactants in the commercial product, due to dilution. This may be improved by the addition of extra surfactant to glyphosate if it is to be used at such water rates, though this might affect selectivity to ground cover species.

Although oxadiazon is often used as a pre-emergence herbicide, it was tested here on weeds for its contact action. It worked well in some instances, namely on *Lepidium didymum* (Tables 8.2 and 8.3) and *Veronica persica* (Table 8.5).

The grass species in the trials, *Poa annua* and *Vulpia bromoides,* also displayed good control by glyphosate. This is a significant result as *Vulpia bromoides* is tolerant of haloxyfop (Yu et al. 2004), which could otherwise selectively remove grass weeds from the ground cover species. This makes *Vulpia bromoides* a troublesome grass weed. With the ground covers tested tolerant to glyphosate, *Vulpia bromoides* can now be selectively removed.

The *Cerastium glomeratum* was also well-controlled by a range of herbicides (Tables 8.2-8.4) but this weed is a winter annual which naturally dies back at the same time anyway, as evidenced by the health ratings in the untreated control.

8.4 Herbicide trial 2 at FCU

This trial focused on the tolerance of ground cover plants to mixtures of a knock-down herbicide added to a residual herbicide. If successfully tolerated by the ground cover plants, these mixtures would provide more options for ground cover management, as existing vegetation can be killed off while preventing weed seedling germination for an extended period of time to minimise competition during the establishment of ground covers.

8.4.1 Herbicide trial 2 at FCU: Materials and Methods

A second herbicide trial was established on these field plots in February 2009. This time, each of the plots in Figure 8.1 was divided into quarters, giving four mini-plots (hereafter called quadrats) each measuring 1.5 m x 1.0 m. During the period between this trial and the previous one, *Veronica serpyllifolia* plants became established from seeds sown into the plots in January 2009.

On 23 February 2009, each quadrat was visually assessed for percentage area covered by the ground cover plants (*D. micrantha, H. microphylla, S. procumbens, S. mexicanum,* and *V. serpyllifolia*). Quadrat areas which were deemed to contain less than 10% ground cover plants were not used in the trial. As a result, two out of the five species, namely *S. mexicanum,* and *V. serpyllifolia* had only 3 replicates. The other species, *D. micrantha, H. microphylla,* and *S. procumbens* had 4 replicates each. There were three herbicide treatments and one untreated control in this trial, and the treatments were assigned in a randomised complete block design. Blocking was performed in rows in a north-south orientation. The northernmost row of planting plots was blocked together as it tended to be moister. In contrast, the southernmost row was blocked together as it was better drained. Each single plot contained one ground cover species, but the herbicide treatment allocated to each quadrat was randomly determined.

The mean coverage of *D. micrantha, H. microphylla,* and *S. procumbens* in the plots were 78.8%, 71.3%, and 65.9% respectively. *V. serpyllifolia* plots had a mean coverage of 25.8%, while *S. mexicanum* only covered 12.5% of the plot area. The poor coverage of *S. mexicanum* was further evidence that it is not suitable as a mowed ground cover species

For this trial, the larger area of the quadrats necessitated a switch from the hand-held pump sprayer to a backpack sprayer using a single flat fan nozzle calibrated to produce an output of 3000 L ha^{-1}. Spray application was carried out on 26 February 2009. Pacing was rehearsed and timed with a metronome to ensure spray output was close to the intended rate. The plots were visually assessed fortnightly using the same scoring system as the previous trial where 1=healthy and 10=dead. Scores of less than 4 were considered to be acceptable as untreated plants also scored within this range.

Dichondra micrantha plants were treated with mixtures of metsulfuron and oxadiazon. *Hydrocotyle microphylla* plants were treated with mixtures of glyphosate and oxadiazon. *Sedum mexicanum* were treated with a mixture of metsulfuron with simazine. For all the above, the herbicide mixtures were applied on the plants at three different rates. A mixture of clopyralid and oxadiazon was tested on both *Sagina procumbens* and *Veronica serpyllifolia*. However, only *V. serpyllifolia* was sprayed with three different rates of the mixture. *S. procumbens* was treated with two rates of clopyralid and oxadiazon and one rate of a clopyralid/pendimethalin mixture.

8.4.2 Herbicide trial 2 at FCU: Results

The *Dichondra micrantha* plants were found to tolerate a mixture containing up to 0.09 kg metsulfuron ha^{-1} and 0.741 kg oxadiazon ha^{-1} (Table 8.6).

On the other hand, the *Hydrocotyle microphylla* plants showed visible damage symptoms even at low rates of glyphosate and oxadiazon but they recovered well 6 weeks later (Table 8.7).

Table 8.6 Herbicide damage scores of *D. micrantha* plants at various days after treatment (DAT)

Treatment	**metsulfuron with oxadiazon**				
Rate (kg ai ha^{-1})	0.045 + 0.371	0.09 + 0.741	0.18 + 1.48	**untreated**	***$LSD_{0.05}$***
Score 2 WAT	2.00	3.00*	3.25*	1.00	*1.16*
Score 4 WAT	2.25	3.50*	5.00*	1.25	*1.57*
Score 6 WAT	2.75	2.75	3.00	2.25	*1.11*
Score 8 WAT	2.50	2.75	**3.75***	2.50	*1.22*

* significantly different from the untreated control

Table 8.7 Herbicide damage scores of *H. microphylla* plants at various days after treatment (DAT)

Treatment	**glyphosate with oxadiazon**				
Rate (kg ai ha^{-1})	0.54 + 0.371	1.08 + 0.741	2.16 + 1.48	**untreated**	***$LSD_{0.05}$***
Score 2 WAT	2.50*	3.50*	4.50*	1.00	*1.18*
Score 4 WAT	5.75*	6.50*	9.75*	1.00	*2.54*
Score 6 WAT	1.75	1.00*	1.00*	2.50	*1.07*
Score 8 WAT	1.50	1.00	3.25	2.00	*3.55*

* significantly different from the untreated control

Table 8.8 Herbicide damage scores of *S. procumbens* plants at various days after treatment (DAT)

Treatment	clopyralid with oxadiazon		clopyralid + pendimethalin		
Rate (kg ai ha^{-1})	0.9 + 0.741	0.9 + 1.48	0.9 + 2.05	untreated	$LSD_{0.05}$
Score 2 WAT	1.75*	2.75*	3.25*	1.00	*0.67*
Score 4 WAT	2.25*	3.25*	5.25*	1.00	*0.67*
Score 6 WAT	1.00	2.75	4.25*	1.50	*1.30*
Score 8 WAT	1.25	1.25	1.25	1.00	*0.67*

***** significantly different from the untreated control

The mixture of clopyralid and oxadiazon was tested on both *Sagina procumbens* and *Veronica serpyllifolia*. This mixture was tolerated well by both species. *Veronica serpyllifolia* was not affected by this mixture up to rates of clopyralid at 1.8 kg ai ha^{-1} and oxadiazon at 1.48 kg ai ha^{-1} (Table 8.10). *Sagina procumbens* tolerated this mixture at rates of clopyralid at 0.9 kg ai ha^{-1} and oxadiazon at 1.48 kg ai ha^{-1} (Table 8.8). The other treatment on *S. procumbens* using pendimethalin and clopyralid resulted in visible plant damage (Table 8.8).

The trial with *Sedum mexicanum* showed that this species tolerated the mixture of metsulfuron at the rate of 0.09 kg ai ha^{-1} and simazine at 4.5 kg ai ha^{-1} (Table 8.9)

Weeds present in the plots were noted to be killed by the mixtures applied.

Table 8.9 Herbicide damage scores of *S. mexicanum* plants at various days after treatment (DAT)

Treatment	metsulfuron with simazine				
Rate (kg ai ha^{-1})	0.045 + 2.25	0.09 + 4.5	0.18 + 9.0	untreated	$LSD_{0.05}$
Score 2 WAT	3.00	**3.67***	**5.33***	1.67	*1.88*
Score 4 WAT	3.67	4.67	**8.33***	2.00	*3.12*
Score 6 WAT	3.67	4.33	5.67	3.00	*4.71*
Score 8 WAT	3.00	5.33	**6.67***	2.33	*4.31*

***** significantly different from the untreated control

Table 8.10 Herbicide damage scores of *V. serpyllifolia* plants at various days after treatment (DAT)

Treatment	clopyralid with oxadiazon				
Rate (kg ai ha^{-1})	0.45 + 0.371	0.9 + 0.741	1.8 + 1.48	untreated	$LSD_{0.05}$
Score 2 WAT	1.00	**2.67***	**2.67***	1.00	*1.54*
Score 4 WAT	1.00	1.00	1.00	1.00	*n.a.*
Score 6 WAT	1.00	1.00	1.67	1.00	*1.09*
Score 8 WAT	1.33	1.67	1.00	1.00	*0.77*

***** significantly different from the untreated control

8.4.3 Herbicide Trial 2 at FCU: Discussion

All the ground cover species tested, with the exception of *Sedum mexicanum*, appeared to be suitable for cultivation on a large scale with a combination of residual and knock-down herbicides. This would greatly facilitate their establishment over a larger area, and showed promising potential at this stage. However, *Sedum mexicanum* plants showed poor tolerance to constant mowing, and despite setting the mowing height to 8 cm, the plants did not spread out laterally.

8.5 Ground cover trial under poplar trees

Chapter 7 identified herbicides which can selectively remove weeds within ground cover species proposed to be suitable for planting alongside turf grass. This new knowledge was followed up with field trials in this chapter to establish the ground cover plants. The results of these trials showed up differences in the behaviour of the ground cover species. In the following section, a trial is described in which the ground cover plants were planted under trees to simulate actual usage of ground cover plants under trees in an urban park situation. This concluded our series of trials, and would permit recommendations on the best species as companion planting with turf grass in amenity horticulture.

8.5.1 Ground cover trial under poplar trees: Materials and methods

Five species of ground cover plants were planted under trees. The ground covers used in this trial were *Dichondra micrantha* (dichondra), *Hydrocotyle microphylla* (hydrocotyle), *Sagina procumbens* (pearlwort), *Soleirolia soleirolii* (baby's tears), and *Veronica serpyllifolia* (turf speedwell).

The ground cover plants were cultivated from seed and stolon transplants in seeding trays filled with potting mix and Osmocote in a shade house at the Plant Growth Unit for 3 months from 23 July to 16 October 2009.

A row of 80 poplar trees (*Populus euroamericana* 'Veronese') at the Massey University Fruit Crop Unit was used for the trial. The trees were transplanted 2 years before the commencement of the trial, and were about 6 metres tall. Existing vegetation under the poplar trees was cleared using herbicides. Of particular note was the presence of the perennial weed, creeping buttercup (*Ranunculus* repens), which had developed an extensive stolon system at the site. Therefore, on 9 July 2009, a mixture containing 2.7 kg ha^{-1} glyphosate, 2.25 kg ha^{-1} MCPA and 0.2 kg ha^{-1} dicamba was applied under the row of poplar trees. The MCPA and dicamba were intended to be absorbed by the *R. repens* and control the weed through translocation, to bolster the non-selective translocated action of glyphosate. This was followed up with two more applications on 31 July and 18 Aug 2009 with 0.211 kg paraquat ha^{-1} and 0.180 kg diquat ha^{-1}. All herbicides in this trial were applied using a Solo 425 knapsack sprayer at 103 kPa; the water rate applied was 937 L ha^{-1}.

The four trees at each end of the row were designated buffer trees. The row was divided into five blocks with each block consisting of 13 trees. Treatments were assigned to trees in a randomised complete block format. There were six treatments, with five of them being to surround a tree with each of the five ground cover species, and the sixth treatment being to keep the soil bare around a tree using frequent applications of the non-residual herbicide glufosinate. During the periods when herbicides were not applied, this sixth treatment served as an untreated control to indicate weed pressure. Within each block, every second tree was randomly assigned a treatment, The poplar trees between those with treatments served as buffer trees, to allow space for the ground cover plants to spread so that they would be unlikely to overlap and cause mutual competition. The poplar trees were planted 1 metre apart, and the area within 0.5 m from the tree base on either side of the poplar row was mowed monthly to a height of 40 mm, to simulate turf maintenance and to remove competition from larger weeds. The row of poplar trees was not irrigated during the trial period to simulate specimen tree planting in amenity horticulture.

Planting of ground cover plants was performed on 16 Oct 2009. A square area of 60 cm by 60 cm with the tree trunk at the centre was marked out. Using a soil auger, a total of 12 soil plugs of 5 cm diameter and depth were removed from around the tree trunk, at distances of 15 cm and 30 cm away from the centre of the trunk (Figure 8.2). The spaces created by the soil auger were replaced with identically-sized plugs of ground cover plants. To provide ample space for ground cover expansion, the bases of trees adjacent to where the ground covers were planted were kept bare. As the ground cover plants grew over time, the spaces between the plugs closed up (Fig 8.3).

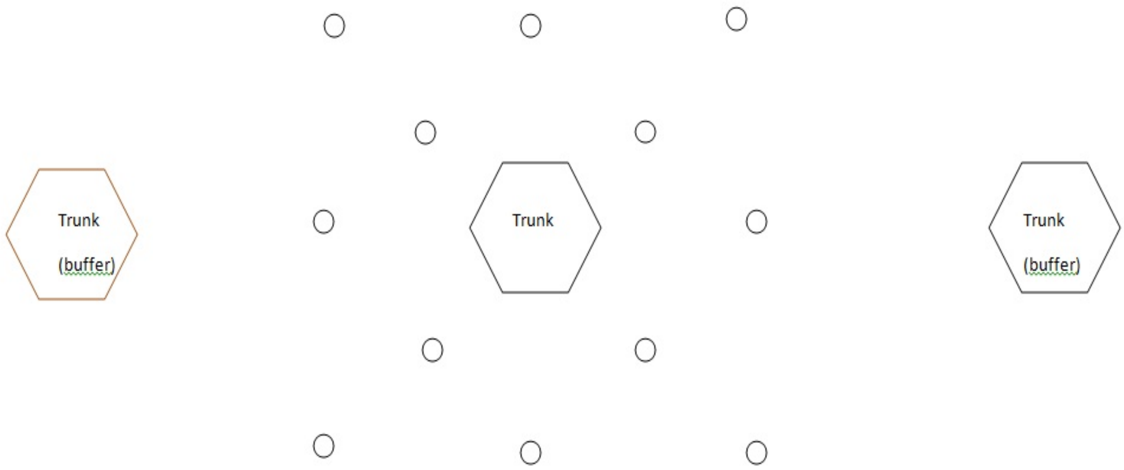

Figure 8.2 Planting layout of ground cover plants under poplar trees.

Figure 8.3 ***Dichondra micrantha*** **under poplar tree, nine months after transplanting. The ruler represents a length of 50 cm**

After planting, herbicides were applied as necessary to assist in the establishment of ground cover plants (Table 8.11). Monthly mowing to a height of 40 mm also ameliorated some weed pressure. The choice of herbicides used relied on the results of herbicide trials performed previously. The application on 1 Nov was of residual herbicides (see Table 8.11) which were tolerated by the ground cover plants, to extend the period for the ground cover plants to establish without weed competition.

By early January, the effects of the residual herbicides had declined. The weeds *Lepidium didymum* (twin cress), *Veronica persica* (scrambling speedwell), *Crepis capillaris* (hawksbeard), *Rumex obtusifolius* (broad-leaved dock), and *Ranunculus repens* (creeping buttercup) were the main species found growing under the poplars. All plots were sprayed with haloxyfop on 13 January and 22 February 2009 at 0.9 kg ai ha^{-1} to control grass weeds.

Creeping buttercup was more prevalent in the plots planted with pearlwort and baby's tears, with minor presence of some annual broad-leaved weeds and grass. In the pearlwort plots, oxyfluorfen was applied for its contact knock-down action. Similarly in the baby's tears plots, MCPA was selected to help control creeping buttercup.

In the other ground cover plots, tribenuron was applied to control the annual broad-leaved weeds, which were more prevalent than the creeping buttercup. In the dichondra plots, clopyralid was added to broaden the range of weeds controlled, because *Dichondra micrantha* tolerated it well.

The treatments were applied using the backpack sprayer at a water rate of 937L ha^{-1}. Details of the herbicide products are similar to those presented in Chapters 5 and 7.

Table 8.11 Herbicides for broad-leaved weeds used during establishment of ground cover plants under poplar trees.

Spray date: 1 Nov 2009			***Spray date: 7 January 2010***	
Ground cover species	Herbicide	Rate (kg ai ha^{-1})	Herbicide	Rate (kg ai ha^{-1})
Dichondra micrantha	oxadiazon	1.4	clopyralid + tribenuron	0.28/0.028
Hydrocotyle microphylla	oxadiazon	0.71	tribenuron	0.011
Sagina procumbens	oxadiazon	1.4	oxyfluorfen	0.34
Soleirolia solerolii	simazine	1.4	MCPA	1.1
Veronica serpyllifolia	oxadiazon	0.71	tribenuron	0.011
Control	glufosinate	1.9	glufosinate	1.9
Spray date: 21 Feb 2010			***Spray date: 4 June 2010***	
Ground cover species	Herbicide	Rate (kg ai ha^{-1})	Herbicide	Rate (kg ai ha^{-1})
Dichondra micrantha	diflufenican	0.094	tribenuron	0.019
Hydrocotyle microphylla	clopyralid	0.28	2,4-D	0.98
Sagina procumbens	oxadiazon + clopyralid	0.71/0.28	pendimethalin	0.43
Soleirolia solerolii	glyphosate + simazine	0.38/ 1.4	clopyralid + MCPA	0.28/0.70
Veronica serpyllifolia	clopyralid	0.28	picloram + triclopyr	0.094/0.28
Control	glufosinate	1.9	glufosinate	1.9

By mid-February, weed numbers had begun to increase, and another round of herbicide application occurred. The intention was again to apply herbicides with soil persistence to assist in ground cover establishment. Residual herbicides were applied on *Dichondra micrantha* (diflufenican), *Soleirolia soleirolii* (simazine, mixed with glyphosate for additional knock-down capability), and *Sagina procumbens* (oxadiazon, mixed with clopyralid). For *Veronica serpyllifolia*, the herbicide trials did not provide clear results on tolerance of residual herbicides, and hydrocotyle was also found to be poorly tolerant of tested residual herbicides. Therefore, clopyralid was chosen, as it is a translocated herbicide with some soil persistence.

Sampling of the plots under the poplar trees to determine the composition of the area was carried out on 10 Mar, 14 Apr, 14 May, 15 Jun, 16 Aug, 7 Oct, and 9 Dec 2010. Observations were performed by placing a quadrat frame measuring 25 cm by 10 cm within a square area of 1.2 m by 1.2 m centred on the base of the poplar tree. The quadrat was randomly placed around the tree within the planted area five times, and the plant species composition and proportion within the quadrat was recorded. The initial proportion of area taken up by the ground cover plants directly after plug transplanting was 1.05%.

8.5.2 Ground cover trial under poplar trees: Results

Four months after transplanting under the poplar trees, the area covered by the ground cover plants in a 1.2 m square area around the tree increased nearly 10-fold from 1.65% to 14.2% for hydrocotyle, 12.4% for pearlwort, 15.4% for *Soleirolia soleirolii*, 17.0% for *Veronica serpyllifolia*; with the top performer dichondra covering an average of 77.8% of the plot areas. The stark difference for *Dichondra micrantha* is most likely due to the C4 physiology of this species being more advantageous in periods of warm and dry weather, enabling it to spread out about five times more than the other species (Table 8.12). However, at 1 year after planting, *Soleirolia soleirolii* increased its spread (48.6%) while *Dichondra micrantha* maintained about the same area covered (75.6%) (Table 8.14). *Sagina procumbens* also more than doubled the area occupied by December (34.2%), compared to the growth in March (12.4%) (Tables 8.12 and 8.14).

Table 8.12 Percentage (%) of ground cover plots under poplar trees occupied by ground cover species, the perennial weed *Ranunculus* repens, other weeds and bare soil in March and April 2010. Column means sharing the same letter are not significantly different at p>0.05.

March 2010								
Species	**Planted cover**		***Ranunculus repens***		**Other weeds**		**Bare soil**	
D. micrantha	77.8	a	2.0	bc	2.6	b	17.6	d
H. microphylla	14.2	b	6.8	b	11.8	a	67.2	b
S. procumbens	12.4	b	27.6	a	6.6	ab	53.4	c
S. solerolii	15.4	b	1.6	c	11.6	a	71.4	b
V. serpyllifolia	17.0	b	4.2	bc	13.0	a	65.8	b
Control	n.a.		0.0	c	0.0	b	100.0	a
$LSD_{0.05}$	8.3		5.1		6.8		8.9	
April 2010								
Species	**Planted cover**		***Ranunculus repens***		**Other weeds**		**Bare soil**	
D. micrantha	87.4	a	3.1	bc	1.2	b	8.3	e
H. microphylla	4.2	c	8.1	b	8.8	a	78.8	b
S. procumbens	16.1	b	22.0	a	1.9	b	60.0	d
S. solerolii	21.6	b	0.4	c	8.8	a	69.2	c
V. serpyllifolia	20.4	b	3.9	bc	8.9	a	66.8	cd
Control	n.a.		0.2	c	1.9	b	97.9	a
$LSD_{0.05}$	9.4		5.9		4.6		9.1	

Table 8.13 Percentage (%) of ground cover plots under poplar trees occupied by ground cover species, the perennial weed *Ranunculus* repens, other weeds and bare soil in May, June, August, and October 2010. Column means sharing the same letter are not significantly different at p>0.05.

May 2010								
Species	**Planted cover**		***Ranunculus repens***		**Other weeds**		**Bare soil**	
D. micrantha	87.2	a	5.1	c	5.8	b	1.8	c
H. microphylla	8.0	c	14.6	b	36.8	a	40.6	ab
S. procumbens	19.2	b	49.0	a	3.0	b	28.8	b
S. solerolii	18.0	b	3.2	c	41.0	a	37.8	b
V. serpyllifolia	18.8	b	10.2	bc	35.2	a	35.8	b
Control	n.a.		2.0	c	42.9	a	50.5	a
$LSD_{0.05}$	8.4		9.3		12.4		12.5	

June 2010								
Species	**Planted cover**		***Ranunculus repens***		**Other weeds**		**Bare soil**	
D. micrantha	77.9	a	12.5	b	2.4	b	7.2	e
H. microphylla	6.5	d	20.6	b	28.0	a	44.9	b
S. procumbens	15.2	cd	55.2	a	6.0	b	23.6	d
S. solerolii	32.0	b	4.5	c	35.9	a	27.6	cd
V. serpyllifolia	20.6	bc	7.0	c	35.3	a	37.0	bc
Control	n.a.		4.3	c	14.4	b	74.9	a
$LSD_{0.05}$	11.4		9.9		12.2		12.1	

August 2010								
Species	**Planted cover**		***Ranunculus repens***		**Other weeds**		**Bare soil**	
D. micrantha	89.2	a	1.6	b	5.4	c	4.0	e
H. microphylla	7.7	c	7.8	b	39.1	b	45.4	ab
S. procumbens	18.6	b	58.0	a	2.2	c	21.2	cd
S. solerolii	25.8	b	2.0	b	59.2	a	13.0	de
V. serpyllifolia	16.6	bc	7.8	b	42.3	b	33.3	bc
Control	n.a.		4.2	b	31.2	b	52.0	a
$LSD_{0.05}$	9.2		8.4		11.3		12.2	

October 2010								
Species	**Planted cover**		***Ranunculus repens***		**Other weeds**		**Bare soil**	
D. micrantha	79.6	a	6.4	cd	14.0	b	0.0	d
H. microphylla	12.2	d	22.0	b	55.8	a	10.0	bc
S. procumbens	28.4	bc	70.0	a	0.4	c	1.2	d
S. solerolii	38.6	b	4.0	d	53.2	a	4.2	cd
V. serpyllifolia	20.2	cd	16.6	b	51.0	a	12.2	b
Control	n.a.		14.6	bc	60.4	a	25.0	a
$LSD_{0.05}$	10.7		9.8		11.6		7.9	

Table 8.14 Percentage (%) of ground cover plots under poplar trees occupied by ground cover species, the perennial weed *Ranunculus* repens, other weeds and bare soil in May, June, August, and October 2010. Column means sharing the same letter are not significantly different at p>0.05.

December 2010								
Species	**Planted cover**		***Ranunculus repens***		**Other weeds**		**Bare soil**	
D. micrantha	75.6	a	4.2	c	12.3	b	6.8	C
H. microphylla	12.4	d	10.0	bc	42.8	a	34.8	Ab
S. procumbens	34.2	c	27.6	a	6.0	b	32.2	B
S. solerolii	48.6	b	8.7	bc	35.7	a	7.0	C
V. serpyllifolia	13.2	d	12.2	b	36.1	a	38.5	Ab
Control	n.a.		8.0	bc	46.1	a	45.9	A
$LSD_{0.05}$	11.9		6.0		13.0		11.9	

The *Ranunculus repens* which was a pre-existing perennial weed at the site was not completely eradicated during bed preparation despite the efforts made. As each ground cover species received different herbicide treatments, the effectiveness of control also varied across the ground cover species.

The *Ranunculus repens* was well controlled by the MCPA applied in the *S. soleirolii* plots, which was applied in January and June 2010 (Tables 8.12). By the end of the year in December, the weed was kept better controlled in the *D. micrantha* plots (Table 8.14), this could have been achieved by the tribenuron, which had been shown to be effective on *R. repens* (Dixon & Clay 2004). Throughout the year, the worst control of *R. repens* was observed in the *S. procumbens* plots.

The effects of the February herbicide applications had started to wear off by May (Table 8.13). The weeds in general observed at this time are listed in Table 8.15. The main weeds in the baby's tears plots which had been treated with glyphosate and simazine were *Veronica persica* (scrambling speedwell, 15% ground cover), *Trifolium repens* (white clover, 10% ground cover) and *Crepis capillaris* (hawksbeard, 4.4% ground cover); so a clopyralid/ MCPA mix was applied. The dichondra plots covered most of the plot area (more than 87%) and there was a variety of weeds found, but none were consistent throughout the replicates. After tribenuron was applied on the *D. micrantha* plots, *Crepis capillaris* and *Leontodon taraxacoides* became more common, as tribenuron has weaker activity on Asteraceae. A similarly wide range of weeds were found in pearlwort plots with no clear dominant weed species. Pendimethalin was applied to pearlwort due to the good tolerance shown in the herbicide trials. To spot treat the various weeds in hydrocotyle, 2,4-D was applied to selectively remove the weeds from the intended ground cover. However, this led to a shift in the subsequent weed composition to *Veronica persica* (scrambling speedwell, 10% in end-June, and 23% in August). A similar shift to scrambling speedwell as the main weed in turf speedwell plots was due to the weed and the ground cover being in the same genus of *Veronica* probably showing similar tolerance to the picloram/triclopyr herbicide treatment. Prior to the herbicide application in June, other weeds present were *Plantago major, Plantago lanceolata,* and *Lepidium didymum.*

Amongst the ground cover planted plots, the areas planted with *Dichondra micrantha* generally had fewer annual weeds than the other plots over the period when no herbicide assistance was given between June and December (Tables 8.13 and 8.14).

Table 8.15 Weeds found under poplar trees in April and May 2010.

Botanical name	Common name
Amaranthus powellii	redroot
Anagallis arvensis	scarlet pimpernel
Capsella bursa-pastoris	shepherd's purse
Cerastium glomeratum	annual mouse-ear chickweed
Crepis capillaris	hawksbeard
Epilobium ciliatum	tall willow herb
Galium aparine	cleavers
Geranium molle	dove's foot
Hypochaeris radicata	catsear
Lamium purpureum	red dead nettle
Leontodon taraxacoides	hawkbit
Lepidium didymum	twincress
Malva parviflora	small-flowered mallow
Plantago lanceolata	narrow-leaved plantain
Plantago major	broad-leaved plantain
Poa annua	annual poa
Ranunculus repens	creeping buttercup
Rumex obtusifolius	broad-leaved dock
Sonchus oleraceus	sow thistle
Taraxacum officinale	dandelion
Trifolium repens	white clover
Veronica persica	scrambling speedwell
Vulpia bromoides	vulpia hair grass

As for the presence of bare soil within the planted areas, *Dichondra micrantha* had the least bare soil visible throughout the trial period due to its rapid expansion. The ground cover species which spread out the least over the period of one year was the *Hydrocotyle microphylla* (Tables 8.12-8.14).

8.5.3 Ground cover trial under poplar trees: Discussion

The *Dichondra micrantha* plants tolerated the herbicide treatments very well, and grew to take up more space as weeds were controlled each time after herbicide treatment was applied. It is not surprising that *D. micrantha* rapidly spread out to occupy more than 75% of the available space four months after transplanting, as it is the only C_4 plant species in the trial, which would be more efficient in the warm and dry conditions of summer during which this was observed. This suggests that adequate cover can be achieved over one summer using *D. micrantha* plug transplants to initially cover about 1.5% of the intended area, which would be economically attractive.

The herbicide applications appeared to last for two months each time for the trial site, as observations taken in May and August showed the herbicides wearing off and weed numbers increase after the late February and early June herbicide applications. The use of diflufenican and tribenuron kept *Ranunculus repens* well under control in the *Dichondra micrantha* plots. It appears that the good range of herbicides found to be tolerated by *Dichondra micrantha* gives good flexibility for weed control in the field if applied at the correct times and the most appropriate option is selected for the weeds present. However, one of the reasons to use ground cover plants is to suppress weeds using the plant itself with reduced reliance on herbicides. *Dichondra micrantha* performed well in this regard. It spread across the most area in the shortest time, and kept both the perennial weed *R. repens*, as well as other annuals weeds in check. This performance compared well with the other ground covers tested, and also the unplanted control treatment, especially for the herbicide-free period from July to December.

Hydrocotyle microphylla showed the least growth in this trial and consistently proved to cover the least area. The decision to withhold active irrigation, to simulate planting under specimen trees which may not be irrigated, obviously affected this species, which normally grows in moist soils. Growth conditions were also made more challenging with the application of clopyralid and 2,4-D, which was applied mainly to control *R. repens* but was not previously shown to be well tolerated by *H. microphylla*. The lack of an adequate treatment which targets *R. repens* while not harming *H. microphylla* hindered plot maintenance. This in turn caused the *H. microphylla* plots to have the weediest plots in the planted areas, making *Hydrocotyle microphylla* a difficult species to recommend. The use of 2,4-D, which was previously untested on *H. microphylla*, showed better control of *R. repens* than clopyralid in these plots, with little noticeable damage to the *H. microphylla*.

Sagina procumbens plants showed a steady increase in plant density as time passed, although at a slow pace. From an initial coverage of 1.05% at planting, it spread out to 12.4% in 4 months, then nearly tripled its occupied area to 34.2% a year later in December 2010. However, it did not show any competitive ability against the perennial *Ranunculus repens,* and allowed it to expand the most due to no suitable herbicides being available to control it, until October. The decline in October of *R. repens* was not due to the herbicide applications in February and June, as the effects would have worn off by then. The drier conditions as summer set in and the stress from monthly mowing probably contributed to the decline in *Ranunculus repens* vigour, normally a wetland species (Lynn & Waldren 2003), which allowed *S. procumbens* to extend its occupied area. However, *S. procumbens* also did not fare well in dry conditions, turning brown during extended periods without rain, but re-greening once wet conditions returned.

There were also few other weeds present in the *S. procumbens* plots over the period of the trial. This was due to the residual effects of the pendimethalin and oxadiazon applied, but it seemed to have little effect on the perennial *R. repens* which was already present before the trial started.

Another plant species which showed a steady increase in area occupied after transplanting was the *Soleirolia soleirolii*. The increase exhibited by this species was greater than that for *S. procumbens* discussed earlier. The residual action of simazine appeared to have worn out within 2½ - 3 months. The June application of MCPA and clopyralid only provided short term weed control as weed proportions soared in August. However, after the August observation, *S. soleirolii* experienced rapid growth as the temperatures increased, and successfully expanded its growth area as the weeds *Lamium purpureum* (red dead nettle, 3% ground coverage from June to August) and *Veronica persica* (scrambling speedwell, 19% ground coverage from June to August), which are more common in the cooler seasons, declined. Both weeds were no longer observed in the *Soleirolia soleirolii* plots by December. *R. repens* appeared to be kept in check between August to December. As no herbicides were applied during this period, this observation might be attributable to the warmer and drier summer climate, since *R. repens* prefers a moist habitat.

Veronica serpyllifolia did not expand its covered proportion of the allocated area during the observation period and actually declined in area occupied in December compared to March. This is likely due to the herbicide applications keeping its growth in check, as *V. serpyllifolia* did not expand its occupied area even when weed proportions declined after herbicide application. As the temperatures increased from October, the soil became drier without irrigation, and both weed and ground cover populations declined with a concurrent increase in exposed soil area. All in all, *Veronica serpyllifolia* cannot be recommended as a ground cover plant. The herbicide trials showed that cultivation of this species even from seed is problematic as it repeatedly succumbed to fungal infection in the shade house. There were few herbicides which appeared to be tolerated by the plant, and field planting showed that the herbicides which did not kill it outright appeared to slow its growth and establishment. Finally, this species did not cope well without irrigation when it became warm and dry in summer.

The 'control' areas showed that with consecutive sprays of glufosinate in January and February 2010, the areas can be kept relatively free of weeds for about a month. Once the weeds successfully invaded the area, weed coverage grew exponentially from 1.9% of the area in April to 42.9% in May. Once that happened, a single spray of glufosinate in early June could not completely deter the weed invasion, and weeds were still observed in the subsequent assessments, with the area covered varying according to seasonal growth conditions. This showed that spot application of a non-selective contact herbicide to maintain a vegetation-free condition at the base of trees can be both a labour and resource-intensive proposition. At the very least, judicious application of a residual herbicide in response to local weed conditions should be recommended. However, for this trial, the 'control' areas served as indicators of weed pressure and therefore only received non-selective herbicide applications at the same time as the other ground cover plants.

8.6 Conclusion

Herbicides have been successfully identified which could be used selectively over the various ground cover species. However, although herbicides may not kill the plants, they may however check their growth, as appear to have happened in the case of *Hydrocotyle microphylla* and *Veronica serpyllifolia.* Other herbicides allowed the ground cover species to continue growing and this was clearly shown in *Dichondra micrantha*, *Soleirolia soleirolii,* and to a lesser extent in *Sagina procumbens.* Where ground cover plants were established, weeds were seldom able to grow amongst the ground cover plants (Table 8.13). Planting very low ground cover plants as companion planting to turf in areas where turf would be difficult to maintain is therefore a feasible proposition, and possibly a better and more aesthetic alternative than trying to keep these areas bare of vegetation. The key therefore lies in rapidly establishing ground cover plants over the designated areas.

This trial has found that using a ground cover plant species with C4 photosynthetic physiology allows for a more rapid spread when planted in late spring, especially in areas which are warm and less well irrigated. C3 ground cover plant species can also achieve adequately dense foliage but may require initial planting to be at a higher planting density, or to be planted in autumn. Regardless of the rate of spread of ground cover species, each species may still exhibit seasonal dieback or foliage reduction due to various factors. Such periods make them prone to weed invasion; but this can be ameliorated with the aid of herbicide treatments. Thus it is advantageous if ground cover species can be carefully selected and screened to show tolerance to a wide variety of herbicides, so that selective weed control amongst the ground cover plants can be implemented.

In this trial, *Dichondra micrantha* (dichondra) and *Soleirolia soleirolii* (baby's tears) showed tolerance to both knock-down and residual herbicides, allowing for a good range of herbicide options to selectively control both annual and perennial weeds. The ground cover plants also spread well under the trees without irrigation. Where the dichondra and baby's tears grew into mowable areas, their short stature also enabled them to be mowed regularly without harm, which also contributed to an integrated weed management program.

Between the two species *Dichondra micrantha* and *Soleirolia soleirolii,* the *D. micrantha* is the more competitive against weeds. The *Ranunculus repens* was well controlled in *S. soleirolii* plots due to the availability of herbicides which could selectively weaken it. However, many other weeds continued to be observed within the *S. soleirolii* plots, at levels comparable with the unplanted control. Therefore, *Soleirolia soleirolii* may be recommended for planting in areas difficult to mow, but may require herbicide intervention for maintenance.

As herbicide trials for *Sagina procumbens* showed tolerance to few herbicides, it is likely that this species will encounter competition from perennial weed species against which no suitable herbicide can selectively be used without also harming *Sagina procumbens.* The encounter in this field trial with *Ranunculus repens* is one such example, and results showed that *Sagina procumbens* had poor competitive ability against this weed in the absence of herbicide assistance. The same concern could be raised regarding annual weed species as well. In addition to the relative lack of herbicide options, *Sagina procumbens* could not be recommended as it turned brown in the summer heat during the dry periods, re-greening only after rain. This does not meet the aesthetic requirements for a managed landscape.

Both *Hydrocotyle microphylla* and *Veronica serpyllifolia* were not suitable for conditions without irrigation in summer, and there was a lack of herbicides which were well-tolerated by the plants without checking their growth. Hence these species could not be recommended either.

The use of ground cover plants in areas where mowing or turf establishment is challenging can be successfully implemented provided there is good tolerance by the ground cover species to a wide range of herbicides with differing modes of action to spot-treat any weed invasion which may occur when the ground cover foliage is less dense, and mowing over the area where ground cover plants are established can all contribute to a feasible integrated weed management plan.

Chapter 9 Conclusion

9.1 Project overview

Research in weed science has contributed much to agriculture, forestry and management of natural resources. However, despite advances in weed science, weeds continue to challenge the agricultural sector with an estimated 10% of production lost to weeds (Kim 2001). This is due to weed populations being able to adapt in response to weed control methods, especially in the case of herbicide-resistant weed populations, suggesting a need to move beyond relying solely on herbicides for weed control (Buhler et al. 2000)

Herbicides were widely introduced during the Green Revolution between the 1940s to 70s, driven by an urgent need to respond to changes in the sector (LeBaron et al. 2008). There was a reduction of menial labour available for field work as urbanisation swept across the world, forcing innovations which highlighted mechanical solutions, and scientific research producing improvements to crop species which enabled larger harvests at lower unit costs. The development of herbicides was geared toward greater agricultural output by allowing selective weed removal within crops. During this period, weed control rapidly evolved away from menial hand weeding and mechanical cultivation, which were not conducive to maintaining good soil structure (Six et al. 2000; Buckley & Schmidt 2001), to highly targeted weed removal using novel herbicides without detriment to crop yields (Zimdahl 2002). Herbicides contribute best to sustainable agriculture when there are multiple options as is the case for major crops. However, a significant problem is lack of herbicides registered for use when growing plants that are not major crops (Hall et al. 2000).

The science of urban greenery is fast becoming a merger of arboriculture, ornamental horticulture and forest management studies (Jahnige 2004). Awareness is growing that weed control in urban environments is an increasingly complex operation, not simply achieved by the application of the latest herbicide. Indeed, weed science is not synonymous with herbicide development. New knowledge-based and systems approach-based decision processes are recognised to be crucial for weed management in the urban environment. The systems approach is complex, with variables involving human behaviour (Johnson & Huggins 1999). There is a dearth of knowledge about mechanisms of weed interactions in response to maintenance regimes in the amenity horticulture sector (Hall et al. 2000). Several papers (Booth & Swanton 2002; Davis et al. 2009) have urged weed science to be developed as a broadly integrating discipline, instead of a study circumscribed by a narrowly-defined set of tools, namely herbicides. This has come about because weed scientists working in field crop research are more likely to be funded by private rather than public sources (Davis et al. 2009). Alternative weed management methods such as biological control have not attracted much interest from the agrochemical industry for commercialisation, due to perceived difficulties in implementation for consistent results (Hall et al. 2000). Hopefully the research done for this thesis will advance the use of ground cover plants for managing weeds, with a reduced reliance of herbicide use for weed control in urban areas.

9.2 Thesis findings

The work presented in this thesis showed that the presence of ground cover plants reduced weed invasion compared to leaving the soil bare. This thesis also presented comparisons in weed suppression provided by ornamental ground cover species differing in growth form and taxa, which are seldom seen in the literature. Results showed that weeds can be suppressed very well by many different types of ground cover, despite differing significantly in form and size. The role of ground cover plants in weed suppression is mainly in blocking out light to ensure that weed seeds remain dormant by phytochrome action. In species where there is no light requirement for seed germination, the presence of well-established ground cover plants is intended to out-compete weed seedlings for light, water, and soil resources. The primary attribute required by a ground cover plant for weed suppression would therefore be to possess a dense foliage canopy to block out light from reaching the soil.

The importance of ground cover plants blocking out light to deter weed establishment is shown by the deciduous nature of *P. capitata*. In winter, the plant was defoliated; and the presence of an extensive stem and root network did little to prevent weed invasion as the plant was dormant. Weed mass collected from *P. capitata* plots when the plant was dormant in winter was much greater than weed mass collected from ground cover plants which were evergreen. In fact weed mass per unit area from defoliated *P. capitata* plots was similar to that from bare soil areas. In contrast, evergreen species with dense foliage in winter and which blocked out red light from the soil surface, such as the native species *Acaena inermis* and *Coprosma acerosa*, resulted in almost no weed invasion during winter (see Chapter 3). This illustrated the importance of the presence of green leaves to block out red light from reaching the soil surface. When a ground cover combines both traits in an evergreen plant with extensive rooting stems, then the plant can still be effective in deterring weeds so long as the R:FR is reduced to about 0.3 as in the case of *Muehlenbeckia axillaris* and *A. inermis*.

With a successful ground cover plant layer, weed seeds in the soil remain dormant because the quality of light filtered through the ground cover canopy does not allow the breaking of phytochrome-inhibited germination. Weeds which do crop up within ground cover plants are either perennial weeds with regenerative underground structures not killed by herbicides or soil tilling; or weed seeds which were able to germinate due to gaps in the ground cover canopy allowing light through to break seed dormancy. These may be seeds carried by environmental or animal carriers, or seeds which were already present in the soil.

The foliage canopy of ground cover plants should not be assumed to remain dense 12 months of the year. In the case of *Grevillea lanigera*, *Sedum mexicanum*, and *Veronica peduncularis,* the canopy was moderately dense during the vegetative phase and reduced R:FR to about 0.33. However, once the plants started flowering, relatively less red-light absorbing leaves were present in the canopy space, leading to ratios of red light increasing compared with far-red light and subsequent increases in weeds within the ground covered area. If the ground cover plants had irregularly-shaped margins such as invaginations, it could also create areas where light is not blocked and weeds seemingly grew within ground covered areas (Section 3.5.5). This thesis showed that weeds germinate opportunistically within ground cover plant canopies when gaps appear, and the pervasiveness of perennial weeds in areas planted with ground cover was observed not only in experimental trials, but also in mature pre-existing populations. This showed the importance of perennial weeds being thoroughly eradicated from a site before ground covers are planted.

Information on which translocated herbicides can be tolerated by ground cover species is useful for managing perennial weeds once they do appear. For example, results from Section 5.2.2 showed that *Sedum mexicanum* tolerated the translocated herbicides amitrole, clopyralid, metsulfuron and tribenuron well. Gardeners tending to a bed of *Sedum mexicanum* could prepare small hand held sprayers of individual herbicides and spot-apply a suitable herbicide on broad-leaved weeds as necessary. The gardener tending to the *Pimelea prostrata* plants monitored in Chapter 4 was unable to get the *Elytrigia repens* controlled by hand-weeding despite repeated attempts. If she had prepared a spray bottle of haloxyfop, the persistence of this perennial weed would have been better checked.

The success of ground cover plants can be facilitated during the establishment phase with either mulches or herbicides. During observations of actual usage of ground covers locally (Chapter 4), many sites planted with ground cover were also mulched to improve weed deterrence. This aided in resisting the establishment of weeds from the soil seed bank through gaps within ground covers which, once established, may be difficult for ground cover plants to outcompete.

This thesis showed that the type of mulch material best suited to assist in the establishment of ground cover plants differs according to plant form (Chapter 6). For plants growing from a single primary stem with little or no secondary rooting (*Coprosma acerosa*, Chapter 6), it is best to use long-lasting synthetic mulches such as plastic weed mat. This greatly reduces the likelihood of germination from the soil seed bank (Section 6.5). Plants with a scrambling habit and/or with freely rooting nodes (eg *Muehlenbeckia axillaris* and *Acaena inermis*, Chapter 3), or that easily produce seeds upon maturity (*Persicaria capitata*, Chapters 3 & 6), or re-grow from fragments (*Sedum mexicanum*, Chapters 3 & 6), would establish best when there is unfettered access to the soil surface which allows the plant to develop its rooting network rapidly. Such plants establish best with regular hand weeding bolstered by spot spraying of herbicides. Alternatively, soil cover such as light wood chip particles which are prone to thinning out after disturbance over a period of time, or a paper product such as EcoCover which degrades after 4-6 months, may be ideal. These methods keep the area weed-free while the plant is juvenile and establishing, but allow the plant's reproductive methods to function well at the opportune time. Plants with the ability to regenerate from fragments (like the succulent plant *Sedum* mexicanum) may also cover the intended planting site more rapidly if such fragments were spread over the intended site.

This thesis has shown that if weeds should manage to establish within ground covers, herbicides have been identified from screening trials that are suitable for removing these weeds without harming the desired ground cover plant, and also herbicides to remove the ground cover plants if they should escape into lawn areas. The herbicide trials performed over the course of this thesis provided new information for herbicide applications in the ornamental and amenity horticulture sectors. For instance, *Coprosma acerosa* 'Taiko' (Section 5.2.3) and *Soleirolia soleirolii* (Section 7.5.4) were found to be tolerant of a range of herbicides. Both these species were able to tolerate glyphosate for control of most species, haloxyfop for grass weed control, MCPA for control of some broad-leaved weed species, and simazine for longer-term soil residual weed control action. This research work also showed that when herbicides are applied at high water rates such as 3000 L ha^{-1}, the herbicidal activity of commercial products without additional surfactant remains good. This was of concern as many commercial formulations contain surfactants for aiding the activity of active ingredients, and the surfactant property may be weakened at high water rates. However, the rate of 3000 L ha^{-1} was chosen in trials to simulate spot spraying by a heavy handed gardener who may over-drench plants.

This project showed that while the planting of ground cover plants can reduce herbicide usage, judicious applications of herbicides to ground covers will enhance their weed deterrence if tested beforehand to be tolerated by the ground cover plant. Unfortunately, most herbicides are tested and developed for the agricultural sector; hence, herbicide information for amenity horticulture is limited. The work in this thesis (Chapters 5 and 7) overcomes some of this knowledge gap, thereby facilitating herbicide use for those ground cover plants that were studied.

Ground cover plants may be used in landscape design as a transition between lawn and shrubs or trees (Foley 1972; Holmes & Buchanan 2005; Lonnee et al. 2011). A possible transition from grass lawn to tree bases or areas such as slopes which are difficult to mow or maintain good grass growth is to use ground cover plants as a non-grass lawn (Simpson 1992; American Horticultural Society 2000). Ground cover species trialled for this purpose in this thesis include *Dichondra micrantha, Hydrocotyle microphylla, Sagina procumbens, Soleirolia soleirolii,* and *Veronica serpyllifolia.* These species may have been variously regarded as a weed by some sectors and at some locations, but this thesis hopes to ascribe the use of ground cover planting to encourage an opportunity for their cultivation in the horticultural industry. Of these, the species which most easily spread across soil in a dense foliage mat with a range of herbicides available for assistance during establishment and heavy weed pressure were *D. micrantha,* and *S. soleirolia*. The other species were deemed less promising as they had restrictive habitat requirements (prone to drying out), and tolerated fewer herbicides which restricted weed management options. Other species with similar growth forms and found to have similarly wide tolerances of herbicides could be developed for ground cover plant use as well.

In an effort to mitigate concerns that exotic introductions may become the next biological invasion to native ecology (discussed further below), this project worked with a number of New Zealand native species as ground cover plantings, namely in the form of *Acaena inermis* 'Purpurea', *Coprosma acerosa* 'Taiko', *Hebe chathamica, Muehlenbeckia axillaris,* and *Pimelea prostrata,* to provide suitable options which would ameliorate criticism. Herbicide trials conducted on *Coprosma acerosa* 'Taiko' showed great promise for using herbicides as an aid during establishment and subsequent maintenance (Section 5.2.3). Although herbicide trials were not performed for the other species in this thesis, *Muehlenbeckia axillaris* and *Acaena inermis* 'Purpurea' demonstrated good spread over one year (Section 3.5.1) and also resisted weed invasion well (Section 3.5.6). The *Pimelea prostrata* could also provide dense foliage cover but tended to become sparser during winter time, necessitating more attention (Sections 3.5.5 and 4.5.1L). The effectiveness of *Hebe chathamica* to deter weeds was not not adequately assessed in this thesis, as it was growing over wood mulched soil, and was also spaced out with little interlocking growth during the period it was monitored.

9.3 Promoting use of ground cover plants in landscape decision-making

Among the arguments for the promotion of ground cover plants in this thesis, are the attraction of a maintenance regime with less herbicide and labour-intensiveness in the control of weeds; and as a turf grass replacement with reduced mowing needs, especially in difficult areas such as at tree bases, on slopes, or next to structures such as a wall. Of course, alternative choices to grass are available such as plastic or mineral-based cover like stone chips. However, landscape research shows an emotive appeal in being close to greenery (Matsuoka & Kaplan 2008).

Prediction of landscape preferences suggests that the type of contents and their spatial arrangement in relation to each visual element is important (Tveit et al. 2006). Ground cover plants lend themselves well to visual concepts of landscape design by bridging across disparate dimensions (for example, between trees and lawn); transitioning between the built-up and natural areas; and demarcating a change in land use (such as between public access and private-use areas). Research has shown that people greatly preferred nature scenes which are open, yet with clear spatial definition (Kaplan & Kaplan 1989; Sullivan 1994). Ground cover plants fulfill this role very well. Such scenes allow a viewer to know what to expect and judge where they may safely venture.

In a study of landscape preferences, respondents who viewed a photo of Highway Route 45 in the US (Illinois) with plain agricultural land and sky, improved the picture's rating by 11% after the addition of 'prairie flowers' on either side of the road (Sullivan & Lovell 2006). The 'prairie flowers' could effectively be replaced with flowering ground cover plants to achieve the same preference. Research has also shown that when a vegetation cover suppresses weed germination, the weed seed bank in the soil declines (Mirsky et al. 2010).

A more economically tangible benefit for replacing roadside turf with ground cover plants would be the savings from not having to mow ground cover plants. This eliminates costs associated with equipment acquisition, maintenance, fuel, and storage. In addition, it eliminates the risk of having a slower moving mower vehicle on roads with fast moving cars, or the potentially reduced visibility from tall grass on bends and near sign-posts when mowing is not carried out in a timely fashion (Yelverton & Gannon 2010).

Ground cover plants as turf grass alternatives are also being advocated in arid regions for being adaptable to drought and high salinity conditions, in addition to weed suppression and erosion prevention abilities. The ground cover plants *Carpobrotus acinaformis, Glaucium flavum* and *Achillea millefolium* have been identified in Iran as successfully meeting all the above objectives, in addition to being of good aesthetic quality (Shooshtarian & Salehi 2012). There is evidence that affluent landscape consumers are starting to show a preference for 'desert' landscape (or xeriscape) for its aesthetic appeal and practicality of lower water and labour-intensiveness (Larsen & Harlan 2006). This has encouraged further research into drought-tolerant ornamental herbaceous perennials (Zollinger et al. 2006). More ground cover plants may be included in this wave of interest, if xeriscaping gains further popularity.

No matter what style of landscape is preferred or suitably adopted around the world, the requirement to keep out unwanted plants in planned landscapes will always exist. These can range from manicured gardens to utility areas such as roadsides, or even interim plant cover for land areas awaiting site development. Ground cover plants perform this function subtly by being part of the landscape, and a successful ground cover plant could reduce labour, capital, and time costs for weed control. However, as each site has unique constraints and resources, no one ground cover species can be recommended as a generic solution. Instead, each country and region will need to identify plants best suited for the site. This thesis has shown that a ground cover plant which can spread rapidly to provide a dense, unbroken foliage canopy will be most effective. It should be evergreen, with little seasonal variation in canopy density. Its spread may be through vigorous growth of stems from a single rooted location; or rely on stoloniferous or rhizomatous spread and rooting; or by producing seeds which can allow the species to recover rapidly after experiencing adverse conditions on site. The final plant characteristics chosen will depend on species availability and site conditions, but herbicides can greatly assist in plant establishment and subsequent maintenance through controlled judicious application with minimal impact to the environment. Therefore, herbicide trials are highly recommended, and the species which tolerates a wide range of herbicides will provide the greatest flexibility in options for herbicide assistance.

9.4 Threat of species new to cultivation being invasive

With the introduction of any plant species into cultivation, there will be concern that a new ecological threat may be introduced once it crosses the boundaries of its natural distribution (Genovesi & Shine 2004). This arises because plants outside their native environments could become more vigorous due to the new environments being more favourable for their growth than the original, and a release from predatory pressures (Blossey & Notzold 1995). Invasive exotic plants are recognised as causing major losses to agricultural, managed amenities, and natural ecosystems. These species also cause inconvenience to land-use planning for public and private properties. Invasive species are second only to habitat loss as a threat to biodiversity, and weed scientists, ecologists and land managers are putting in major effort to tackle this problem (Hall et al. 2000).

New Zealand also has its share of invasive plant species formerly introduced as cultivated ground cover plant species. In addition to *Plectranthus ciliatus* which was noted in Chapter 4 to be in the National Plant Pest Accord (NPPA) of New Zealand, *Tradescantia fluminensis* (wandering Jew), and *Vinca major* (periwinkle) are other notable examples.

Tradescantia fluminensis is native to South America and does not set seed in New Zealand, but is able to regrow from plant fragments. It is thought to have spread throughout the country due to human traffic from discarded garden waste (Butcher & Kelly 2011). *T. fluminensis* poses a serious threat to native forest regeneration as the dense smothering ground cover prevents the germination of tree seedlings (Kelly & Skipworth 1984) and leads to a decrease in forest species diversity (Standish et al. 2001). *Vinca major* has a similar smothering effect which may displace forest species, and can spread from plant fragments (DiTomaso & Healy 2007).

However, opinion is divided over whether plants with exotic status represent a strong predictor in the quality of their invasiveness potential, or possible detriment to the native environment (Fuller & Irvine 2010). For instance, studies involving 328 gardens across six major UK cities showed that urban gardens support a high diversity of plants, even though many are exotic species and gardeners conscientiously keep them at low densities (Bernholt et al. 2009; Loram et al. 2011). Studies also suggest that the invasiveness of exotic plants could depend more on human-mediated spread through transport links (especially the dumping of garden waste along roadsides) than real biological qualities for invasiveness (Mortensen et al. 2009; Rauschert et al. 2010).

Baker (1991) proposed that plants become invasive because the introduced plant has undergone mutation which increased its aggressiveness; or that the plant has managed to exploit a previously unoccupied niche in the new ecological system. An example of opportunistic ecological exploitation is found in *Impatiens parviflora* which has become successful in central European forests as its root zone is shallower than the indigenous trees and shrubs, hence filling in a niche without developing any new aggressiveness (Heger & Trepl 2003). Indeed, *I. parviflora* has few of the traits listed by Baker (1965) as hypothetically desirable for a weed and is even susceptible to drought, which ought to have limited its spread as a weed. This again shows how the success of each invasive species hinges on the confluences of both its inherent traits and the available environment.

So attempts to characterize the likelihood of invasiveness of exotic species have not met with consistent success, and appear to be dependent upon the context of environmental resource and phenotype plasticity of the species' interactions (Daehler 2003). The invasiveness of a woody species was proposed to be predictable based on three traits: short juvenile period; short interval between major seed production; and low seed mass (Rejmánek & Richardson 1996). The former two traits pair well together to produce early and consistent reproduction which leads to rapid population growth for the species, provided that survival and establishment of seedlings is usually successful (Caplat et al. 2012). Smaller seeds could be important for a potentially weedy species for a number of reasons. Such seeds may be produced in greater numbers (Henery & Westoby 2001) and disperse further (Greene & Johnson 1992, 1993); have reduced chilling requirements (Tomback & Linhart 1990); and possibly improved germinability (Grime et al. 1988; Baloch et al. 2001; DiTommaso et al. 2005). Yet, *Tradescantia* fluminensis and *Vinca major* are two invasive weed species in New Zealand which do not set seed, and instead proliferate through vegetative reproduction. Another predictive trait recently proposed was the specific leaf area (ratio of leaf area to dry weight) of the potentially invasive plant (Lake & Leishman 2004). However, such studies have been criticised (Hayes & Barry 2008) for being taxa-specific (Rejmánek & Richardson's work was based on *Pinus sp.*) , and site-specific (Lake and Leishman's 2004 work was done in Sydney) .

Apart from plant traits, complex models have also been proposed to be a more holistic approach. Models which propose to predict invasion process need to consider both the introduced plant species and its new environment (Heger 2001; Heger & Trepl 2003). A third factor recently put forth proposes to include the traits of plants native to the environment in question (Moles et al. 2008); but none claim to be infallible as the authors acknowledge the complexity of these ecological interactions. Therefore, unless site conditions for proposed ground cover planting can first be evaluated with due consideration to the potential introduced species, no useful evaluations of the potential weediness of the ground cover species proposed in this thesis can be made.

As resident native species have undergone extensive selection in their home environments across many generations, few introduced species are able to better colonize their new habitats in superior fashion unless there has been a significant change in the environmental conditions following the introductions of the exotic species (Moles et al. 2008). An example of a native species which has become a problem in New Zealand is the *Hydrocotyle microphylla* trialled in this thesis; it is a weed of turf growing in moist soils (Sykes et al. 1988). This is also in accordance to the view that human intervention in a natural habitat is the pre-cursor for a plant to be regarded as weedy (Baker 1991). The term 'weed' in this case defined as a plant "in any specified geographical area, its populations grow entirely or predominantly in situations markedly disturbed by man (without, of course, being deliberately cultivated plants)" (Baker 1965).

Amongst the ground cover species evaluated in this thesis, some species may become weedy; though probably not to the extent of being a threat to native flora. *Persicaria capitata* has freely rooting stolons, and sets seed profusely; but it has a deciduous habit and is extremely frost tender, and is likely to grow as an annual in most parts of New Zealand if weedy. *Muehlenbeckia axillaris,* on the other hand, suppressed weeds well in the trials in Chapter 3, and is also a sprawling plant with freely rooting stolons. As it is a native, it is valued for its ability to suppress exotic weeds in native bush. It has also been credited for stabilizing coastal slopes and maintaining biodiversity in these difficult areas (Patrick 2006). However, outside of New Zealand, it could become weedy, although no literature was found to indicate this at the time of writing. The promising ground cover species that could replace turf in difficult areas, *Dichondra micrantha* and *Soleirolia soleirolii*, might also have the potential to become turf weeds. However, herbicide controls have been determined for these species in this thesis, so control solutions are available; though control of *Dichondra micrantha* with a picloram/triclopyr mix may also damage some turf. Ultimately, each species in this thesis could be evaluated for risk of invasiveness, which may occur when conditions are optimal. However, the herbicide trials performed in this thesis provide herbicide control options to mitigate this possibility.

In the course of this thesis, effective weed control is not dependent on just the appropriate choice of ground cover plants with the optimum plant characteristics. As the perfect ground cover plant does not exist, best results are obtained through an integrated approach to weed control. A good ground cover species can reduce labour intensiveness and herbicide use in weed control, but the occasional hand weeding or judicious spot application of herbicide to control weeds which emerge opportunistically through the foliage gap will also help maintain ground cover dominance on-site. Herbicide screening is therefore an important step in the selection of ground cover plant species, to ensure a wide array of herbicide options is available to control any invading weed; whether annual or perennial in nature; wind-blown; trafficked by fauna; or from the soil seed bank. The use of mulch or artificial cover material during the establishment of young ground cover plants also contributes to the success of ground cover plants when it later matures. Selection of mulch type should then suit the growth habit of the ground cover plant as discussed in Chapter 6.

Weed scientists with expertise on weed management for agricultural systems can contribute much to invasive species research, as many of the same issues are also challenging land managers faced with invasive plants on their properties (Davis et al. 2009).The use of ground cover plants to deter weeds is, in effect, an attempt to modify the environment such that it is no longer feasible for weed seeds to germinate and establish in the area.

References

Adams RP 2011. Junipers of the world: The genus *Juniperus*. Trafford Publishing, Bloomington. 436 pp.

Akemo MC, Regnier EE, Bennett MA 2000. Weed suppression in spring-sown rye (*Secale cereale*) - pea (*Pisum sativum*) cover crop mixes1. Weed Technology 14: 545-549.

Albach DC, Martínez-Ortega MM, Chase MW 2004. *Veronica*: Parallel morphological evolution and phylogeography in the Mediterranean. Plant Systematics and Evolution 246: 177-194.

Albach DC, Meudt HM, Oxelman B 2005. Piecing together the "new" Plantaginaceae. American Journal of Botany 92: 297-315.

Albertsson A-C 1978. Biodegradation of synthetic polymers. II. A limited microbial conversion of 14C in polyethylene to 14CO2 by some soil fungi. Journal of Applied Polymer Science 22: 3419-3433.

Almeida DdO, Klauberg FO, Almeida HC, Gebler L, Felipe AF 2011. Soil microbial biomass under mulch types in an integrated apple orchard from southern Brazil. Scientia Agricola 68: 217-222.

American Horticultural Society 2000. The American Horticultural Society gardening manual. Dorling Kindersley. 420 pp.

Amoroso G, Frangi P, Piatti R, Fini A, Ferrini F, Faoro M 2011. Evaluation of shrubs for side slope greening and protection in urban landscape. Hort Technology 21: 359-366.

Andersen DF, Garisto M-A, Bourrut J-C, Schonbeck MW, Jaye R, Wurzberger A, DeGregorio R 1996. Evaluation of a paper mulch made form recycled materials as an alternative to plastic film mulch for vegetables. Journal of Sustainable Agriculture 7: 39-61.

Anderson GR, Jenner EL, Mumford FE 1969. Temperature and pH studies on phytochrome. Biochemistry 8: 1182-1187.

Anon. 1968. Tough groundcovers conquer the trouble spots in the garden. New Zealand Gardener 25: 589, 615.

Anon. 2006. A Landscaper's Guide to Mulch. In ed. Sacramento, California Integrated Waste Management Board. Pp. 16.

Appenroth KJ, Lenk G, Goldau L, Sharma R 2006. Tomato seed germination: regulation of different response modes by phytochrome B2 and phytochrome A. Plant, Cell and Environment 29: 701-709.

Appleton BL, Derr JF 1990. Use of geotextile discs for container weed control. HortScience 25: 666-668.

Appleton J 1996. The experience of landscape. John Wiley & Sons, Chichester. 282 pp.

Aremu AO, Ndhlala AR, Fawole OA, Light ME, Finnie JF, Staden Jv 2010. In vitro pharmacological evaluation and phenolic content of ten South African medicinal plants used as anthelmintics. South African Journal of Botany 76: 558-566.

Armitage AM 1994. Ornamental Bedding Plants. CAB International, Wallingford. 175 pp.

Armitage AM 2004. Armitage's garden annuals: a color encyclopedia. Timber Press. 368 pp.

Armitage AM, Kaczperski MP 1994. Traditional versus plug production. In: Holcomb EJ ed. Bedding Plants Ball Publishing, Batavia. Pp. 113-126.

Arnold MA, McDonald GV 2009. Groundcovers, organic and inorganic mulches, and masonry surfaces differentially affect establishment and root zone characteristics of urban trees. Arboriculture & Urban Forestry 35: 232-240.

Arnold TH, Killick DJB 2002. Medicinal and magical plants of southern Africa: an annotated checklist. National Botanical Institute. 203 pp.

Ashrafuzzaman M, Halim MA, Ismail MR, Shahidullah SM, Hossain MA 2011. Effect of plastic mulch on growth and yield of chilli (*Capsicum annuum* L.). Brazilian Archives of Biology and Technology 54: 321-330.

Atucha A, Merwin IA, Brown MG 2011a. Long-term effects of four groundcover management systems in an apple orchard. HortScience 46: 1176-1183.

Atucha A, Merwin IA, Purohit CK, Brown MG 2011b. Nitrogen dynamics and nutrient budgets in four orchard groundcover management systems. HortScience 46: 1184-1193.

Austin D 1998. The indiscriminate vector: Human distribution of *Dlchondra micrantha* (Convolvulaceae). Economic Botany 52: 88-106.

Baker HG 1965. Characteristics and modes of weeds. In: Baker HG, Stebbins GL ed. The genetics of colonizing species. Academic Press, New York. Pp. 147-172.

Baker HG 1991. The Continuing Evolution of Weeds. Economic Botany 45: 445-449.

Baker ML 2007. Contributions to a catalogue of alien plants in Tasmania II. Papers and Proceedings of the Royal Society of Tasmania 141: 187-196.

Baldwin BG, Goldman DH, Keil DJ, Patterson R, Rosatti TJ 2012. The Jepson Manual: Vascular Plants of California. University of California Press. 1568 pp.

Baldwin CM, Liu HB, McCarty LB, Luo H, Wells CE, Toler JE 2009. Impacts of altered light spectral quality on warm season turfgrass growth under greenhouse conditions. Crop Science 49: 1444-1453.

Baldwin N, Whitton B 1992. Cyanobacteria and eukaryotic algae in sports turf and amenity grasslands: A review. Journal of Applied Phycology 4: 39-47.

Baloch HA, DiTommaso A, Watson AK 2001. Intrapopulation variation in Abutilon theophrasti seed mass and its relationship to seed germinability. Seed Science Research 11: 335-343.

Balota EL, Auler PAM 2011. Soil carbon and nitrogen mineralization under different tillage systems and permanent groundcover cultivation between orange trees. Revista Brasileira de Fruticultura 33: 637-648.

Basavarajappa MP, Rajasekhar DW 2001. Effect of mulching on chilli mosaic transmitted by insect vector. Insect Environment 7: 64-65.

Baskin JM, Baskin CC 1971. Germination ecology of *Phacelia dubia* var. *dubia* in Tennessee Glades. American Journal of Botany 58: 98-104.

Baskin JM, Baskin CC 1990. Seed germination ecology of poison hemlock, *Conium maculatum*. Canadian Journal of Botany 68: 2018-2024.

Batlla D, Kruk BC, Benech-Arnold RL 2000. Very early detection of canopy presence by seeds through perception of subtle modifications in red:far red signals. Functional Ecology 14: 195-202.

Bayly MJ, Kellow AV 2006. An illustrated guide to New Zealand Hebes. Te Papa Press, Wellington. 388 pp.

Beard JB, Green RL 1994. The role of turfgrass in environmental protection and their benefits to humans. Journal of Environmental Quality 23: 452.

Beckham J 1994. Tree edging border. In ed. Google Patents, United States Patents. Pp.

Bell NC 2009. Evaluation of growth, flowering, and cold hardiness of ceanothus in western Oregon. Horttechnology 19: 411-417.

Benech-Arnold RL, Sánchez RA, Forcella F, Kruk BC, Ghersa CM 2000. Environmental control of dormancy in weed seed banks in soil. Field Crops Research 67: 105-122.

Bernholt H, Kehlenbeck K, Gebauer J, Buerkert A 2009. Plant species richness and diversity in urban and peri-urban gardens of Niamey, Niger. Agroforestry Systems 77: 159-179.

Betts K 2008. Why small plastic particles may pose a big problem in the oceans. Environmental Science and Technology 42: 8995.

Bewley JD, Black M 1994. Seeds: Physiology of development and germination. Plenum Press, New York. 445 pp.

Billeaud LA, Zajicek JM 1989. Influence of mulches on weed control, soil pH, soil nitrogen content and growth of *Ligustrum japonicum*. Journal of Environmental Horticulture 7: 155-157.

Bisgrove R 2010. Urban horticulture: future scenarios. In: Gianquinto GP, Orsini F ed. Acta Horticulturae. Pp. 33-46.

Bleasdale JKA 1960. Studies on plant competition. In: Harper JL ed. The Biology of Weeds. Blackwell Scientific Publishers, Oxford. Pp. 133-142.
Bloom A, Bloom R 2001. Gardening with conifers. Frances Lincoln, London. 192 pp.
Blossey B, Notzold R 1995. Evolution of increased competitive ability in invasive nonindigenous plants: A hypothesis. Journal of Ecology 83: 887.
Bollen WB, Lu KC 1957. Effect of Douglas fir sawdust mulches and incorporations on soil microbial activities and plant growth Soil Science Society of America Journal 21: 35-41.
Booth BD, Swanton CJ 2002. Assembly Theory Applied to Weed Communities. Weed Science 50: 2-13.
Borthwick HA, Hendricks SB 1960. Photoperiodism in plants. American Association for the Advancement of Science 132: 1223-1228.
Borthwick HA, Hendricks SB, Toole EH, Toole VK 1954. Action of light on lettuce-seed germination. Botanical Gazette 115: 205-225.
Borthwick HA, Hendricks SB, Parker MW, Toole EH, Toole VK 1952. A reversible photoreaction controlling seed germination. Proceedings of the National Academy of Sciences of the United States of America 38: 662-666.
Boyer M 2007. Getting to know mulch. In ed. Lawn and Garden Retailer. Illinois, Scranton Gillette Communications. Pp. 58-59.
Brantley EA, Davis DD, Kuhns LJ 2001. Influence of mulch characteristics on sporulation by the artillery fungus *Sphaerobolus stellatus*. Journal of Environmental Horticulture 19: 89-95.
Brault D, Stewart KA, Jenni S 2002. Optical properties of paper and polyethylene mulches used for weed control in lettuce. HortScience 37: 87-91.
Brenchley WE 1917. The effect of weeds upon cereal crops. New Phytologist 16: 53-76.
Brown MW, Glenn DM 1999. Ground cover plants and selective insecticides as pest management tools in apple orchards. Journal of Economic Entomology 92: 899-905.
Brown MW, Tworkoski T 2004. Pest management benefits of compost mulch in apple orchards. Agriculture, Ecosystems & Environment 103: 465-472.
Buchanan R 2000. Taylor's Master Guide to Landscaping. Houghton Mifflin Company. 372 pp.
Buckles D, Triomphe B, Sain G 1998. Cover crops in hillside agriculture. International Maize and Wheat Improvement Center, Ottawa. 230 pp.
Buckley D, Schmidt T 2001. The structure of microbial communities in soil and the lasting impact of cultivation. Microbial Ecology 42: 11-21.
Buhler DD, Liebman M, Obrycki JJ 2000. Theoretical and practical challenges to an IPM approach to weed management. Weed Science 48: 274-280.
Burger J, Davis V, Franklin J, Zipper C, Skousen J, Barton C, Angel P 2009. Tree-compatible ground covers for reforestation and erosion control. In Initiative ARR ed., Appalachian Regional Reforestation Initiative. Pp.
Burton GW 1992. Breeding improved turfgrasses. In: Waddington DV, Carrow RN, Shearman RC ed. Turfgrass. Agronomy. American Socirty of Agronomy, Madison. Pp. 759-774.
Bussière F, Cellier P 1994. Modification of the soil temperature and water content regimes by a crop residue mulch: experiment and modelling. Agricultural and Forest Meteorology 68: 1-28.
Butcher ER, Kelly D 2011. Physical and anthropogenic factors predict distribution of the invasive weed *Tradescantia fluminensis*. Austral Ecology 36: 621-627.
Butler WL, Norris KH, Siegelman HW, Hendricks SB 1959. Detection, assay and preliminary purification of the pigment controlling photoresponsive development of plants. Proceedings of the National Academy of Sciences 45: 1703-1708.
Byrne SE 1993. Mulch pads and methods. In Patent US ed. Google patents. United States of America. Pp. 5.
Cadisch G, Schunke RM, Giller KE 1994. Nitrogen cycling in a pure grass pasture and a grass-legume mixture on a red latosol in Brazil. Tropical Grasslands 28: 43-52.

Calabria L, Cuba GT, Hwang SM, Marra JCF, Mendonca MF, Nascimento RC, Oliveira MR, Porto JPM, Santos DF, Silva BL, Soares TF, Xavier EM, Damasceno AA, Milani JF, Rezende CHA, Barbosa AAA, Canabrava HAN 2008. Ethnobotanical and ethnopharmacological survey of medicinal plants in Indianopolis, Minas Gerais, Brazil (Levantamento etnobotanico e etnofarmacologico de plantas medicinais em Indianopolis, Minas Gerais, Brasil). Revista Brasileira de Plantas Medicinais 10: 49-63.
Calkins JB, Swanson BT 1998. Plant cold acclimation, hardiness, and winter injury in response to bare soil and groundcover-based nursery field management systems. Journal of Environmental Horticulture 16: 82-89.
Canaway P 1975. Turf wear: A literature review. Journal of the Sports Turf Research Institute 51: 92-103.
Cantliffe DJ 2009. Plug transplant technology. Horticultural Reviews 35: 397-436.
Caplat P, Nathan R, Buckley YM 2012. Seed terminal velocity, wind turbulence, and demography drive the spread of an invasive tree in an analytical model. Ecology 93: 368-377.
Carroll J 1943. Effects of drought, temperature and nitrogen on turf grasses. Plant Physiology 18: 19.
Cave Y 2002. Succulents for the contemporary garden. Random House, Auckland. 176 pp.
Cave Y, Paddison V 1999. The gardener's encyclopaedia of New Zealand plants. Godwit, Auckland. 320 pp.
Chalk D 1988. Hebes and Parahebes. Timber Press, Portland. 152 pp.
Chatizwa I 1997. Mechanical weed control: the case of hand weeders. 1997 Brighton crop protection conference: weeds. Proceedings of an international conference, Brighton, UK, 17-20 November 1997.: 203-208.
Chatto B, Wooster S 2000. Beth Chatto's Gravel Garden: Drought-resistant Planting Through the Year. Frances Lincoln. 192 pp.
Chaudhari AP, Gaikwad CB, Tiwari TK, Nikam AS, Bhende SN, Bagwan IR 2007. Effect of weed control on nutrient uptake, weed weight and yield of groundnut. International Journal of Agricultural Sciences 3: 193-195.
Chavas J-P, Chambers RG, Pope RD 2010. Production economics and farm management: A century of contributions. American Journal of Agricultural Economics 92: 256-375.
Chen SSC 1968. Germination of light-inhibited seed of *Nemophila insignis*. American Journal of Botany 55: 1177-1183.
Cheng Z, Zhao S, Duo L 2008. Physiological and ecological responses of 3 wild groundcover plants to traffic stress. Bulletin of Botanical Research 28: 614-617.
Choi H, Rom CR 2011. Effects of ground cover treatments on growth and photosynthesis in young 'Enterprise' apple trees. Journal of the American Pomological Society 65: 147-157.
Christians NE, Ritchie A 2002. Scotts lawns: Your guide to a beautiful yard. Meredith Books, Des Moines. 192 pp.
Clarke OF 2007. Flora of the Santa Ana River and Environs: With References to World Botany. Heyday Books. 495 pp.
Clement CR, DeFrank J 1998. The use of ground covers during the establishment of heart-of-palm plantations in Hawaii. HortScience 33: 814-815.
Cooper-Marcus C, Barnes M 1999. Introduction: Historic and cultural overview. In: Cooper-Marcus C, Barnes M ed. Healing gardens : Therapeutic benefits and design recommendations. John Wiley & Sons, New York. Pp. 1-26.
Copping LG, Hewitt HG 1998. Chemistry and Mode of Action of Crop Protection Agents. Royal Society of Chemistry, Information Services. 145 pp.
Cowie JD, Rijkse VC 1977. Soils of Manawatu County, North Island, New Zealand: Explanatory notes to accompany soil map and extended legend, Part of NZ soil survey report 30 In New Zealand Soil Bureau DoSaIR ed. Wellington, E. C. Keating, Government Printer. Pp. 1-41.
Cox K, Machin RC 2008. Garden Plants for Scotland. Frances Lincoln. 240 pp.

Crain B, White J 2011. Categorizing locally rare plant taxa for conservation status. Biodiversity and Conservation 20: 451-463.
Cregg BM, Schutzki R 2009. Weed control and organic mulches affect physiology and growth of landscape shrubs. HortScience 44: 1419-1424.
Crill PM 1991. Seasonal patterns of methane uptake and carbon dioxide release by a temperate woodland soil. Global Biogeochem. Cycles 5: 319-334.
Crown Zellerbach Corp 1954. Mulching Paper. In Office USP ed. Google Patents. Crown Zellerbach Corporation. United States, Crown Zellerbach Corporation. Pp. 3.
Cruden RW 1974. The adaptive nature of seed germination in *Nemophila menziesii* Aggr. Ecology 55: 1295-1305.
Daehler CC 2003. Performance comparisons of co-occurring native and alien invasive plants: implications for conservation and restoration. Annual Review of Ecology, Evolution, and Systematics 34: 183-211.
Danish S, Ansari MYK 2007. Effect of methyl methane sulphonate on seed germination and seedling growth of *Solanum melongena* L. var. Pusa Kranti. Vegetos 20: 465-467.
Darwent AL, McKenzie JS 1978. Effects of planting date on the growth and development of narrow-leaved hawk's-beard. Canadian Journal of Plant Science 58: 1087-1094.
Davis AS, Hall JC, Jasieniuk M, Locke MA, Luschei EC, Mortensen DA, Riechers DE, Smith RG, Sterling TM, Westwood JH 2009. Weed Science Research and Funding: A Call to Action. Weed Science 57: 442-448.
Davis JM 1994. Comparison of mulches for fresh-market basil production. HortScience 29: 267-268.
Decoteau DR, Kasperbauer MJ, Hunt PG 1989. Mulch surface color affects yield of fresh-market tomatoes. Journal of the American Society for Horticultural Science 114: 216-219.
Demirel N, Cranshaw W 2005. Colonization of cabbage by the western black flea beetle (*Phyllotreta pusilla*) as affected by mulch and time of day. Phytoparasitica 33: 309-313.
Derouet D, Radhakrishnan N, Brosse JC, Boccaccio G 1994. Phosphorus modification of epoxidized liquid natural rubber to improve flame resistance of vulcanized rubbers. Journal of Applied Polymer Science 52: 1309-1316.
Derr JF, Appleton BL 1989. Weed control with landscape fabrics. Journal of Environmental Horticulture 7: 129-133.
DiTomaso JM, Healy EA 2007. Weeds of California and other western states, v.1. ANR Publications, Oakland. 1808 pp.
DiTommaso A, Brainard DC, Webster BR 2005. Seed characteristics of the invasive alien vine *Vincetoxicum rossicum* are affected by site, harvest date, and storage duration. Canadian Journal of Botany 83: 102-110.
Dixon FL, Clay DV 2004. Effect of herbicides applied pre- and post-emergence on forestry weeds grown from seed. Crop Protection 23: 713-721.
Donald CM 1958. The interaction of competition for light and for nutrients. Australian Journal of Agricultural Research 9: 421-435.
Donald CM 1963. Competition among crop and pasture plants. Advances in Agronomy 15: 1-118.
Dou J, Zhou S, Xu Z 2006. Application of three native tropical groundcover plants to lawns and turf in southern Yunnan. Pratacultural Science 23: 93-96.
Drain NW 1968. Ground covers in the Christchurch area. Journal of the New Zealand Royal Institute of Horticulture 1 & 2: 132-137, 163-167, 222-230, 270-273, 316-319, 362-375, 134-138.
Drew MC, Lynch JM 1980. Soil anaerobiosis, microorganisms, and root function. Annual Reviews of Phytopathology 18: 37-66.
Dudas S, Kaufmann F 2010. Effect of mulch on weed growth and physical characteristics of soil (Utjecaj malca na razvoj korova i fizicke osobine tla). Glasnik Zastite Bilja 33: 34-45.
Dudeck AE, Peacock CH 1992. Shade and turfgrass culture. In: Waddington DV, Carrow RN, Shearman RC ed. Turfgrass. Agronomy. American Society of Agronomy, Madison. Pp. 269-284.

Duryea ML, English RJ, Hermansen LA 1999a. A comparison of landscape mulches: chemical, allelopathic, and decomposition properties Journal of Arboriculture 25: 88-96.
Duryea ML, Huffman JB, English RJ, Osbrink W 1999b. Will subterranean termites consume landscape mulches? Journal of Arboriculture 25: 143-150.
Eadie F 2008. 100 Best native plants for New Zealand gardens. Godwit, Auckland. 376 pp.
EcoCover 2007. EcoCover system – summary of findings: 3 university research studies, laboratory analyses, independent field validation. http://www.ecocover.com/pdfs/ecocover-r-and-d.pdf (Accessed 22 October 2012)
Ekstam B, Johannesson R, Milberg P 1999. The effect of light and number of diurnal temperature fluctuations on germination of *Phragmites australis*. Seed Science Research 9: 165-170.
Elliot R 2008. Australian plants: For gardens in the sun. Rosenberg Publishing, Tasmania. 160 pp.
Ellis B 1998. Taylor's guide to growing North America's favorite plants: proven perennials, annuals, flowering trees, shrubs, & vines for every garden. Houghton Mifflin, New York. 342 pp.
Elmore CL 1989. Vegetation management systems in almond orchards. California Agriculture 43: 16-17.
Elmore CL 2000. Weed management in ground covers. University of California, Riverside, Turfgrass and Landscape Management Research Conference and Field Day: 1-2.
Elmore CL, Roncoroni JA, Wade L, Verdegaal PS 1997. Mulch plus herbicides effectively control vineyard weeds. California Agriculture 51: 14-18.
Elwell HA, Stocking MA 1976. Vegetal cover to estimate soil erosion hazard in Rhodesia. Geoderma 15: 61-70.
Eom S, Setter TL, DiTommaso A, Weston LA 2007. Differential growth response to salt stress among selected ornamentals. Journal of Plant Nutrition 30: 1109-1126.
Eom SH, Senesac AF, Tsontakis-Bradley I, Weston LA 2005. Evaluation of herbaceous perennials as weed suppressive groundcovers for use along roadsides or in landscapes. Journal of Environmental Horticulture 23: 198-203.
Evans GJ, Bellinder RR 2009. The potential use of vinegar and a clove oil herbicide for weed control in sweet corn, potato, and onion. Weed Technology 23: 120-128.
Evenari M 1984. Seed physiology: Its history from antiquity to the beginning of the 20th century. The Botanical Review 50: 119-142.
Falk JH, Balling JD 2010. Evolutionary influence on human landscape preference. Environment and Behavior 42: 479-493.
Fenner M 1980. The induction of a light requirement in *Bidens pilosa* seeds by leaf canopy shade. New Phytologist 84: 103-106.
Fennimore SA, Ajwa HA 2011. Totally impermeable film retains fumigants, allowing lower application rates in strawberry. California Agriculture 65: 208-211.
Ferree DC, Warrington IJ 2003. Apples: Botany, Production and Uses. CABI Pub. 660 pp.
Fidalski J, Tormena CA 2007. Pedotransfer functions for the soil water retention and soil resistance to penetration under groundcover management systems in citrus (Funcoes de pedotransferencia para as curvas de retencao de agua e de resistencia do solo a penetracao em sistemas de manejo com plantas de cobertura permanente em citros). Ciencia Rural 37: 1316-1322.
Fidalski J, Tormena CA, Silva APd 2007. Soil physical quality in an orange orchard in Northwestern Parana as affected by groundcover management (Qualidade fisica do solo em pomar de laranjeira no noroeste do Parana com manejo da cobertura permanente na entrelinha). Revista Brasileira de Ciencia do Solo 31: 423-433.
Findlater PA, Carter DJ, Scott WD 1990. A model to predict the effects of prostarte ground cover on wind erosion. Australian Journal of Soil Research 28: 609-622.
Firth DJ, Wilson GPM 1995. Preliminary evaluation of species for use as permanent ground cover in orchards on the north coast of New South Wales. Tropical Grasslands 29: 18-27.
Fish M 1970. Ground cover plants. David & Charles, Newton Abbot. 144 pp.

Flasch Jr RJ 1996. Tree protective mowing template. In ed., United States Patents. Pp. 1.
Flint LH, McAlister ED 1935. Wave lengths of radiation in the visible spectrum inhibiting the germination of light-sensitive lettuce seed. Smithsonian Miscellaneous Collections 94: 1-11.
Flint LH, McAlister ED 1937. Wave lengths of light in the visible spectrum promoting the germination of light-sensitive lettuce seeds. Smithsonian Miscellaneous Collections 96: 1-8.
Foley DJ 1972. Ground covers for easier gardening. Dover Publications, New York. 224 pp.
Fortgens G, Laar HJvd 1989. *Hedera* (winter-hardy ground cover) [*Hedera* (winterharde bodembedekkers)]. Dendroflora: 43-66.
Foster S, Duke JA 2000. A field guide to medicinal plants and herbs of eastern and central North America: Peterson field guide series. Houghton Mifflin Co., New York. 411 pp.
Fujii T 1963. On the anaerobic process involved in the photoperiodically induced germination of *Eragrostis* seed. Plant and Cell Physiology 4: 357-359.
Fujii T 1969. Photocontrol of development of excised *Eragrostis* embryos. Development, Growth & Differentiation 11: 153-163.
Fuller RA, Irvine KN 2010. Interactions between people and nature in urban environments. In: Gaston KJ ed. Urban Ecology. Cambridge University Press, New York. Pp. 134-171.
Gan J, Zhu Y, Wilen C, Pittenger D, Crowley D 2003. Effect of planting covers on herbicide persistence in landscape soils. Environmental Science & Technology 37: 2775-2779.
Gardiner ES, Yeiser JL 1998. Converting stands of low-grade hardwoods to loblolly pine: Stimulating growth and reducing costs through litter retention. Southern Journal of Applied Forestry 22: 148-155.
Gardner DS, Taylor JA 2002. Change over time in quality and cover of various turfgrass species and cultivars maintained in shade. Hort Technology 12: 465-469.
Gardner WA 1921. Effect of light on germination of light-sensitive seeds. Botanical Gazette 71: 249-288.
Gates DE 1991. Trimmer attachment for mowing decks. In ed., United States Patents. Pp. 1.
Geet S, Agrawal HP, Verma V, Williams A, Bisen RK, Sahu AK 2007. Influence of weed management on yield and quality of soybean. Advances in Plant Sciences 20: 641-642.
Genovesi P, Shine C 2004. European Strategy on Invasive Alien Species: Convention on the Conservation of European Wildlife and Habitats (Bern Convention). Council of Europe Press. 64 pp.
Gerhart VJ, Kane R, Glenn EP 2006. Recycling industrial saline wastewater for landscape irrigation in a desert urban area. Journal of Arid Environments 67: 473-486.
Gianessi L 2009. The potential for organic agriculture to feed the world is being oversold. Outlooks on Pest Management 20: 4-5.
Gianessi LP, Reigner NP 2007. The value of herbicides in U.S. Crop production. Weed Technology 21: 559-566.
Glenn JS, Gilliam CH, Edwards JH, Keever GJ, Knight PR 2000. Recycled waste paper mulch reduces available container N. Journal of Environmental Horticulture 18: 188-191.
Gordon GG, Foshee WG, III, Reed ST, Brown JE, Vinson EL, III 2010. The effects of colored plastic mulches and row covers on the growth and yield of okra. Hort Technology 20: 224-233.
Górski T, Górska K 1979. Inhibitory effects of full daylight on the germination of *Lactuca sativa*. Planta 144: 121-124.
Goulet F 1995. Frost heaving of forest tree seedlings: a review. New Forests 9: 67-94.
Gray JL, White RH 1999. Maintaining the new dwarf greens-type bermudagrasses. Golf Course Management 67: 52-55.
Green RJ 2010. Coastal towns in transition: Local perceptions of landscape change. Springer, New York. 174 pp.
Greene DF, Johnson EA 1992. Can the variation in samara mass and terminal velocity on an individual plant affect the distribution of dispersal distances? American Naturalist 139: 825-838.

Greene DF, Johnson EA 1993. Seed mass and dispersal capacity in wind-dispersed diaspores. Oikos 67: 69-74.
Greenly KM, Rakow DA 1995. The effect of wood mulch type and depth on weed and tree growth and certain soil parameters. Journal of Arboriculture 21: 225-232.
Greer L, Dole JM 2003. Aluminum foil, aluminium-painted, plastic, and degradable mulches increase yields and decrease insect-vectored viral diseases of vegetables. Horttechnology 13: 276-284.
Grey-Wilson C 2009. The rock garden plant primer: Easy, small plants for containers, patios, and the open garden. Timber Press, Portland. 232 pp.
Grime JP 1977. Evidence for the existence of three primary strategies in plants and its relevance to ecological and evolutionary theory. The American Naturalist 111: 1169-1194.
Grime JP, Hodgson JG, Hunt R 1988. Comparative plant ecology: A functional approach to common British species. Unwin Hyman, London. 742 pp.
Grist P, Menz K, Thomas 1999. Chapter 14. Rubber: Indonesia: Improving smallholder farming systems in Imperata areas of Southeast Asia: alternatives to shifting cultivation. 161-171 pp.
Grover R 1971. Adsorption of picloram by soil colloids and various other adsorbents. Weed Science 19: 417-418.
Groves RH 1994. Australian vegetation (2nd edition). Cambridge University Press, Melbourne. 562 pp.
Gynn EG, Richards AJ 1985. Acaena novae-zelandiae T. Kirk. Journal of Ecology 73: 1055-1063.
Hadad D, Geresh S, Sivan A 2005. Biodegradation of polyethylene by the thermophilic bacterium Brevibacillus borstelensis. Journal of Applied Microbiology 98: 1093-1100.
Hall JC, Van Eerd LL, Miller SD, Owen MDK, Prather TS, Shaner DL, Singh M, Vaughn KC, Weller SC 2000. Future Research Directions for Weed Science1. Weed Technology 14: 647-658.
Hands DE, Brown RD 2002. Enhancing visual preference of ecological rehabilitation sites. Landscape and Urban Planning 58: 57-70.
Hanrahan I, Schmidt TR, Castillo F, McFerson JR 2011. Reflective ground covers increase yields of target fruit of apple and pear. In: Robinson TL ed. Acta Horticulturae. Pp. 1095-1100.
Hansen S, Trammel H, Dunayer E, Gwaltney S, Farbman D, Khan S 2003. Cocoa bean mulch as a cause of methyxanthine toxicosis in dogs. Journal of Toxicology 41: 720.
Harper JL 1961. Approaches to the study of plant competition. In: Milthorne FL ed. Mechanisms in biological competition. Symposia of the Society for Experimental Biology. Cambridge University Press, London. Pp. 1-39.
Harper JL 1977a. Mixtures of species: I. Space and proportions. In: ed. Population biology of plants. Academic Press, London. Pp. 237-276.
Harper JL 1977b. The limiting resources of the environment. In: ed. Population biology of plants. Academic Press, London. Pp. 305-346.
Harper JL, Clatworthy JN 1963. The comparative biology of closely related species. 6. Analysis of the growth of Trifolium repens and T. fragiferum in pure and mixed populations. Journal of Experimental Botany 14: 172-190.
Harrington KC 1995. Establishment of several ground covers in an orchard. Proceedings New Zealand Plant Protection Conference 48: 68-71.
Harrington KC 2000. Weeds of lawns and sports turf -- identification and control. New Zealand Sports Turf Institute, Palmerston North. 56 pp.
Harrington KC, Grant MR 1993. Herbicide tolerance of potential orchard ground covers. Proceedings Asian-Pacific Weed Conference 14: 256-260.
Harrington KC, Zhang T 1997. Herbicides for controlling weeds in Mercury Bay weed. Proceedings New Zealand Plant Protection Conference 50: 162-466.
Harrington KC, Rahman A 1998. Herbicide tolerance of ground cover species for New Zealand. Plant Protection Quarterly 13: 111-116.
Harrington KC, Bedford TA 2004. Control of weeds by paper mulch in vegetables and trees. New Zealand Plant Protection 57: 37-40.

Harrington KC, He XZ 2010. Determining how soon ground covers can be planted in forests after applying metsulfuron. 17th Australasian weeds conference. New frontiers in New Zealand: together we can beat the weeds. Christchurch, New Zealand, 26-30 September, 2010: 340-343.

Harrington KC, Anderson BJ, Cameron EA 2002. Establishment techniques for dichondra ground cover in orchards. New Zealand Plant Protection 55: 202-206.

Harrington KC, Zhang T, Osborne M, Rahman M 1999. Orchard weed control with *Dichondra micrantha* ground covers. Proceedings of the 12th Australian Weeds Conference: 250-254.

Harrington KC, Hartley MJ, Rahman A, James TK 2005. Long term ground cover options for apple orchards. New Zealand Plant Protection 58: 164-168.

Harrison M 2006. Groundcovers for the South. Pineapple Press. 157 pp.

Hartley MJ, Rahman A, Harrington KC, James TK 2000. Assessing ground covers in a newly planted apple orchard. New Zealand Plant Protection 53: 22-27.

Hartwig NL, Ammon HU 2002. Cover crops and living mulches. Weed Science 50: 688-699.

Haydu J, Way B, Hodges A, Cisar JL, Aldous DE 2008. Economic challenges confronting New Zealand's sports turf industry. Acta Horticulturae 783: 349-359.

Hayes K, Barry S 2008. Are there any consistent predictors of invasion success? Biological Invasions 10: 483-506.

Haynes RJ 1980. Influence of soil management practice on the orchard agro-ecosystem. Agro-Ecosystems 6: 3-32.

Heads MJ 1996. Biogeography, taxonomy and evolution in the pacific genus *Coprosma* (Rubiaceae). Candollea 51: 381-405.

Heger T 2001. A model for interpreting the process of invasion: crucial situations favouring special characteristics of invasive species: Plant invasions: species ecology and ecosystem management. 3-9 pp.

Heger T, Trepl L 2003. Predicting Biological Invasions. Biological Invasions 5: 313-321.

Helfer S 2008. Plant health in private urban gardens. Turkish Journal of Botany 32: 485-488.

Hembry JK, Davies JS 1994. Using mulches for weed control and preventing leaching of nitrogen fertiliser. Acta Horticulturae: 311-316.

Henery ML, Westoby M 2001. Seed mass and seed nutrient content as predictors of seed output variation between species. Oikos 92: 479-490.

Hillier J, Coombes AJ 2007. The Hillier manual of trees and shrubs. David & Charles, Newton Abbot. 512 pp.

Hirshfield M 2006. Planting ground covers. In ed. Fine Gardening. Newton, Conneticut, Taunton Press. Pp. 49-51.

Hodson MJ, Bryant JA 2012. Functional Biology of Plants. John Wiley & Sons. 400 pp.

Hofmann L, Ries RE 1990. An evaluation of sample adequacy for point analysis of ground cover. Journal of Range Management 43: 545-549.

Holm RE 1972. Volatile metabolites controlling germination in buried weed seeds. Plant Physiology 50: 293-297.

Holmes R, Buchanan R 2005. Southeast Home Landscaping. Creative Homeowner. 240 pp.

Holt JS 1987. Factors affecting germination in greehouse-produced seeds of *Oxalis corniculata*, a perennial weed. American Journal of Botany 74: 429-436.

Hoover-Litty H, Hanlin RT 1985. The mycoflora of wood chips to be used as mulch. Mycologia 77: 721-731.

Hopkins G, Goodwin C 2011. Living Architecture: Green roofs and walls. CSIRO Publishing, Collingwood. 296 pp.

Hussain S, Ramzan M, Akhter M, Aslam M 2008. Weed management in direct seeded rice. JAPS, Journal of Animal and Plant Sciences 18: 86-88.

Huston M, Smith T 1987. Plant succession: Life history and competition. The American Naturalist 130: 168-198.

Ingham CS 2009. Himalayan blackberry (*Rubus armenicus*) and English ivy (*Hedera helix*) response to high intensity-short duration goat browsing. Oregon State University. 126 pp.
Ito M, Nagai K 2008. Degradation issues of polymer materials used in railway field. Polymer Degradation and Stability 93: 1723-1735.
Jahnige P 2004. The hidden bounty of the urban forest. In: Elevitch CR ed. The Overstory Book: Cultivating Connections with Trees. Permanent Agriculture Resources, Holualoa. Pp. 291.
Jat RS, Meena HN, Singh AL, Surya JN, Misra JB 2011. Weed management in groundnut (*Arachis hypogaea* L.) in India - a review. Agricultural Reviews 32: 155-171.
Jenni S, Brault D, Stewart KA 2004. Degradable mulch as an alternative for weed control in lettuce produced on organic soils. Acta Horticulturae 638: 111-118.
Jiang L, Ding Y, Meng G 2009. Variations of physiological and biochemical indexes on drought-resistance of five groundcover plants under water stress. Journal of Jiangsu Forestry Science & Technology 36: 6-10.
Jodaugienė D, Pupalienė R, Urbonienė M, Pranckietis V, Pranckietienė I 2006. The impact of different types of organic mulches on weed emergence. Agronomy Research 4: 197-201.
Johns GG 1994. Effect of Arachis pintoi groundcover on performance of bananas in northern New South Wales. Australian Journal of Experimental Agriculture 34: 1197-1204.
Johnson CB 1980. The effect of red light in the high irradiance reaction of phytochrome. Plant, Cell & Environment 3: 45-51.
Johnson DM, Smith WK 2006. Low clouds and cloud immersion enhance photosynthesis in understory species of a southern Appalachian spruce-fir forest (USA). American Journal of Botany 93: 1625-1632.
Johnson E 1952. Killing weed seeds in nursery and greenhouse soils with methyl bromide. Proceedings 4th annu. Calif. Weed Conf., 1952: 71-74 pp.
Johnson GA, Huggins DR 1999. Knowledge-based decision support strategies: linking spatial and temporal components within site-specific weed management. In: Buhler DD ed. Expanding the context of weed management. Hayworth Press, New York. Pp. 77-95.
Johnston IM 1953. Studies in the Boraginaceae, XXV a revaluation of some genera of the Lithospermae. Journal of the Arnold Arboretum 34: 258-299.
Johnston IM 1954. Studies in the Boraginaceae, XXVI. Further revaluations of the genera of the Lithospermae. Journal of the Arnold Arboretum 35: 1-81.
Jordan K, Jones S 2007. Invertebrate diversity in newly established mulch habitats in a midwestern urban landscape. Urban Ecosystems 10: 87-95.
Jordan KK, Jones SC 2002. Invertebrate fauna associated with mulch in urban environments. In: Jones SC, Zhai J, Robinson WH ed. Proceedings of the 4th International Conference on Urban Pests. Pocahontas Press Inc., Blacksburg. Pp. 87-94.
Jordan LS, Jordan JL 1985. Tillage reduction in orchards with cover crops and herbicides. In: Wiese AF ed. Weed control in limited-tillage systems. Monograph series of the weed science society of America. Weed Science Society of America, Champaign. Pp. 127-139.
Kantachot C, Chantaranothai P, Simpson DA 2010. A synopsis of the genus *Persicaria* (Polygonaceae) in Thailand. Thai Forestry Bulletin (Botany) 38: 128-149.
Kaplan R, Kaplan S 1989. The Experience of Nature: A Psychological Perspective. Cambridge University Press. 340 pp.
Karsten HD, Carlassare M 2005. Forage quality of cool season pasture species under two rotational grazing height regimes. 20th International Grassland Congress.
Kelaidis P 1993. Veronicas: Adaptable perennials bloom in vivid blues. In: Fine Gardening ed. Perennials. Taunton Press, Newtown. Pp. 47-50.
Kelly D, Skipworth JP 1984. *Tradescantia fluminensis* in a Manawatu (New Zealand) forest: I. Growth and effects on regeneration. New Zealand Journal of Botany 22: 393-397.
Kendrick RE, Frankland B 1969. The *in vivo* properties of *Amaranthus* phytochrome. Planta 86: 21-32.

Kendrick RE, Spruit CJP 1974. Inverse dark reversion of phytochrome: An explanation. Planta 120: 265-272.

Kendrick RE, Spruit CJP, Frankland B 1969. Phytochrome in seeds of *Amaranthus caudatus*. Planta 88: 293-302.

Kessler JR 2004. Growing and marketing bedding plants. In ed. Alabama Cooperative Extension System. Alabama, Alabama A&M and Auburn Universities. Pp. 1-11.

Kiikkilä O, Derome J, Brügger T, Uhlig C, Fritze H 2002. Copper mobility and toxicity of soil percolation water to bacteria in a metal polluted forest soil. Plant and Soil 238: 273-280.

Kim KU 2001. Trends and expectations for research and technology in the Asia-Pacific region. Weed Biology and Management 1: 20-24.

King TJ 1975. Inhibition of seed germination under leaf canopies in *Arenaria serpyllifolia*, *Veronica arvensis* and *Cerastum holosteoides*. New Phytologist 75: 87-90.

Kirsten K 2001. Gardening with Keith Kirsten. Struik. 256 pp.

Kirsten K 2003. Down to Earth: Garden Plants & Flowers. Struik. 177 pp.

Koller D, Sachs M, Negbil M 1964. Spectral sensitivity of seed germination in *Artemisia monosperma*. Plant and Cell Physiology 5: 79-84.

Kopitke JC, Langford JKR 1952. Weed control in forest nurseries with methyl bromide. Journal of Forestry 50: 208-211.

Korte N, Porembski S 2010. Suitability of different cover crop mixtures and seedlings for a new tree row management in an organic orchard. Gesunde Pflanzen 62: 45-52.

Krech S, McNeill JR, Merchant C 2004. Encyclopedia of World Environmental History: O-Z. Routledge. 1429 pp.

Kristiansen PE, Jessop RS, Sindel BM 2001. Organic weed management survey: methods used by Australian herb and vegetable growers. 10th Australian Agronomy Conference: 1030-1200.

Kwabiah AB 2003. Performance of silage corn (*Zea mays* L.) in a cool climate ecosystem: effects of photodegradable plastic mulch. Canadian Journal of Plant Science 83: 305-312.

Laing RM, Blackwell EW 1964. Plants of New Zealand 7th edition. Whitcombe and Tombs Limited, Christchurch. 500 pp.

Lake JC, Leishman MR 2004. Invasion success of exotic plants in natural ecosystems: the role of disturbance, plant attributes and freedom from herbivores. Biological Conservation 117: 215-226.

Lal R, Wilson GF, Okigbo BN 1978. No-till farming after various grasses and leguminous cover crops in tropical alfisol. I. Crop performance. Field Crops Research 1: 71-84.

Lalande R, Gagnon B, Simard RR 1998. Microbial biomass C and alkaline phosphatase activity in two compost amended soils. Canadian Journal of Soil Science 78: 581-587.

Lalitha M, Thilagam VK, Balakrishnan N, Mostafa M 2010. Effect of plastic mulch on soil properties and crop growth - a review. Agricultural Reviews 31: 145-149.

Lamont WJ, Jr. 1993. Plastic mulches for the production of vegetable crops. Horttechnology 3: 35-39.

Lamont WJ, Jr. 2005. Plastics: Modifying the microclimate for the production of vegetable crops. Horttechnology 15: 477-481.

Larsen L, Harlan SL 2006. Desert dreamscapes: Residential landscape preference and behavior. Landscape and Urban Planning 78: 85-100.

Lea H, Cartwright D 2007. Hamilton city road reserve planting strategy. In Urban Design Section, Design Services Unit ed. Hamilton, Hamilton City Council. Pp.

Leather P, Pygras M, Beale D, Lawrence C 1998. Windows in the workplace: Sunlight, view, and occupational stress. Environment and Behavior 30: 739-762.

LeBaron HM, McFarland JE, Burnside O 2008. The triazine herbicides: 50 years revolutionizing agriculture. Elsevier, San Diego. 584 pp.

Ledgard SF, Steele KW 1992. Biological nitrogen fixation in mixed legume/grass pastures. Plant and Soil 141: 137-153.

Lee WG, Macmillan BH, Partridge TR, Lister R, Lloyd KM 2001. Fruit features in relation to the ecology and distribution of *Acaena* (Rosaceae) species in New Zealand. New Zealand Journal of Ecology 25: 17-27.

Lemaire J, Gardette JL, Lacoste J, Delprat P, Vaillant D 1996. Mechanisms of photooxidation of polyolefins: Prediction of lifetime in weathering conditions. In: Clough RL, Billingham NC, Gillen KT ed. Polymer Durability - Degradation, Stabilization, and Lifetime Prediction. Advances in Chemistry Series. American Chemical Society, Washington DC. Pp. 577-598.

Levy-Yamamori R, Taaffe G 2004. Garden plants of Japan. Timber Press, Portland. 440 pp.

Li Y, Yang L 2009. New developments in sugarcane industry and technologies in China since 1990s. Southwest China Journal of Agricultural Sciences 22: 1469-1476.

Lin YG, Wilson AR, Nzokou P 2011. Combining legume groundcovers and low nitrogen fertilization in a short-rotation Fraser fir (*Abies fraseri*) cropping system: effect on productivity, soil fertility, and nutrient leaching. HortScience 46: 481-486.

Little K, Berg Gvd 1999. The impact of eight different vegetation management treatments on the establishment of Eucalyptus dunnii. ICFR Newsletter: 8-10.

Lloyd KM, Lee WG, Wilson JB 2002. Growth and reproduction of New Zealand *Acaena* (Rosaceae) species in relation to rarity and commonness. Journal of Ecology 26: 149-160.

Loebenstein G, Alper M, Levy S, Palevitch D, Menagem E 1975. Protecting peppers from aphid-borne viruses with aluminum foil or plastic mulch. Phytoparasitica 3: 43-53.

Long CE, Thorne BL, Breisch NL, Douglass LW 2001. Effect of organic and inorganic landscape mulches on subterranean termite (Isoptera: Rhinotermitidae) foraging activity. Environmental Entomology 30: 832-836.

Lonnee D, Rose N, Selinger D, Whitman J 2011. Growing Shrubs and Small Trees in Cold Climates: Revised and Updated Edition. University of Minnesota Press. 448 pp.

Loram A, Warren P, Thompson K, Gaston K 2011. Urban Domestic Gardens: The Effects of Human Interventions on Garden Composition. Environmental Management 48: 808-824.

Loy JB 1991. Solar infrared transmitting, PAR absorbing polyethylene mulch: physical properties and crop response. Proceedings of the National Agricultural Plastics Congress 23: 165-173.

Lukhoba CW, Simmonds MSJ, Paton AJ 2006. *Plectranthus*: A review of ethnobotanical uses. Journal of Ethnopharmacology 103: 1-24.

Lynn DE, Waldren S 2003. Survival of *Ranunculus repens* L. (creeping buttercup) in an amphibious habitat. Annals of Botany 91: 75-84.

Maass JM, Jordan CF, Sarukhan J 1988. Soil erosion and nutrient losses in seasonal tropical agroecosystems under various management techniques. Journal of Applied Ecology 25: 595-607.

Mabberley DJ 2008. Mabberley's Plant-Book: A Portable Dictionary of Plants, Their Classification and Uses. Cambridge University Press. 1021 pp.

MacKenzie DS 1997. Perennial ground covers. Timber Press, Portland. 379 pp.

Malik RK, Green TH, Brown GF, Mays D 2000. Use of cover crops in short rotation hardwood plantations to control erosion. Biomass and Bioenergy 18: 479-487.

Malone CB 1934. History of the Peking summer palaces under the Ch'ing Dynasty Illinois studies of social sciences. University of Illinois, Champaign. pp.

Mancinelli AL, Borthwick HA, Hendricks SB 1966. Phytochrome action in tomato-seed germination. Botanical Gazette 127: 1-5.

Marston RB 1952. Ground cover requirements for summer storm runoff control on aspen sites in northern Utah. Journal of Forestry 50: 303-307.

Martin CA, Ponder HG, Gilliam CH 1991. Evaluation of landscape fabrics in suppressing growth of weed species. Journal of Environmental Horticulture 9: 38-40.

Marvel ME 1952. Cauliflower seedbed fumigation with methyl bromide. Current report, West Virginia Agricultural Experiment Station 2: 9 pp.

Masiunas JB, Eastburn DM, Mwaja VN, Eastman CE 1997. The impact of living and cover crop mulch systems on pests and yields of snap beans and cabbage. Journal of Sustainable Agriculture 9: 61 - 89.

Mathieu N, Jeremy E 2004. Light transmission through colored polyethylene mulches affects weed populations. HortScience 39: 1302-1304.

Matsuoka RH, Kaplan R 2008. People needs in the urban landscape: Analysis of Landscape And Urban Planning contributions. Landscape and Urban Planning 84: 7-19.

Matthews B 1979. Growing Native Plants. A. H. & A. W. Reed, Wellington. 86 pp.

Matthews J 1993. Favourite native plants for the New Zealand home garden. Viking Pacific, Auckland. 64 pp.

McCalla TM 1950. Microorganisms and soil structure. Transactions of the Kansas Academy of Science (1903-) 53: 91-100.

McCalla TM, Haskins FA 1964. Phytotoxic substances from soil microorganisms and crop residues. Bacteriological Reviews 28: 181-207.

McDowell RW, Koopmans GF 2006. Assessing the bioavailability of dissolved organic phosphorus in pasture and cultivated soils treated with different rates of nitrogen fertiliser. Soil Biology and Biochemistry 38: 61-70.

McHenry MT, Wilson BR, Lemon JM, Donnelly DE, Growns IG 2006. Soil and vegetation response to thinning White Cypress Pine (*Callitris glaucophylla*) on the north western slopes of New South Wales, Australia. Plant and Soil 285: 245-255.

McLean GD, Burt JR, Thomas DW, Sproul AN 1982. The use of reflective mulch to reduce the incidence of watermelon mosaic virus in Western Australia. Crop Protection 1: 491-496.

Meena RK, Kolhe SS, Sumeriya HK, Mishra PK 2006. Response of brinjal to various weed management practices. Haryana Journal of Agronomy 22: 181-183.

Melander B, Rasmussen G 2001. Effects of cultural methods and physical weed control on intrarow weed numbers, manual weeding and marketable yield in direct-sown leek and bulb onion. Weed Research (Oxford) 41: 491-508.

Merwin IA, Stiles WC, Es HMv 1994. Orchard groundcover management impacts on soil physical properties. Journal of the American Society for Horticultural Science 119: 216-222.

Metcalf L 1995. The propagation of New Zealand native plants. Godwit Publishing, Auckland. 87 pp.

Metcalf L 2006. Hebes: a guide to species, hybrids, and allied genera. Timber Press, Portland. 260 pp.

Meyer B, Pailler JY, Guignard C, Hoffmann L, Krein A 2011. Concentrations of dissolved herbicides and pharmaceuticals in a small river in Luxembourg. Environmental Monitoring and Assessment 180: 127-146.

Michener D, Sinton N 2002. Taylor's guide to ground covers: more than 400 flowering and foliage ground covers for every garden situation. Houghton Mifflin. 375 pp.

Mika A, Treder W, Buler Z, Rutkowski K 2007. Attempts on improving light relation and apple fruit quality by reflective Mulch. In: Hrotko K ed. Proceedings of the Eighth International Symposium on Canopy, Rootstocks and Environmental Physiology in Orchard Systems. Acta Horticulturae. Pp. 605-610.

Milberg P, Andersson L, Thompson K 2000. Large-seeded species are less dependent on light for germination than small-seeded ones. Seed Science Research 10: 99-104.

Miller PR, Graves WL, Williams WA, Madson BA 1989. Covercrops for California agriculture. University of California Division of Agriculture and Natural Resources, Oakland. 24 pp.

Mirsky SB, Gallandt ER, Mortensen DA, Curran WS, Shumway DL 2010. Reducing the germinable weed seedbank with soil disturbance and cover crops. Weed Research (Oxford) 50: 341-352.

Miyasaka SC, Hollyer JR, Kodani LS 2001. Mulch and compost effects on yield and corm rots of taro. Field Crops Research 71: 101-112.

Mok J-H, Landphair HC, Naderi JR 2006. Landscape improvement impacts on roadside safety in Texas. Landscape and Urban Planning 78: 263-274.

Moles AT, Gruber MAM, Bonser SP 2008. A new framework for predicting invasive plant species. Journal of Ecology 96: 13-17.
Monaco TJ, Weller SC, Ashton FM 2002. Weed science : principles and practices / Thomas J. Monaco, Stephen C. Weller, Floyd M. Ashton. New York : Wiley, c2002 4th ed. pp.
Montague T, Kjelgren RK, Rupp L 2000. Surface energy balance affects gas exchange and growth of two irrigated landscape tree species in an arid climate. Journal of the American Society of Horticultural Science 125.
Moore LB, Irwin JB 1978. The Oxford book of New Zealand plants. Oxford University Press, Wellington. 234 pp.
Mortensen DA, Rauschert ESJ, Nord AN, Jones BP 2009. Forest roads facilitate the spread of invasive plants. Invasive Plant Science and Management 2: 191-199.
MSU Extension 1998. Organic mulches. In ed. Ornamental Plants Plus. East Lansing, Michigan State University. Pp.
Mueller EC, Day TA 2005. The effect of urban ground cover on microclimate, growth and leaf gas exchange of oleander in Phoenix, Arizona. International Journal of Biometeorology 49: 244-255.
Mumtaz T, Khan MR, Hassan MA 2010. Study of environmental biodegradation of LDPE films in soil using optical and scanning electron microscopy. Micron 41: 430-438.
Myles TG 2008. Termite survival on various types of mulch. In Community Design and Development Services BS ed. Guelph, Community Design and Development Services, Building Services. Pp. 1.
Newman EI 1973. Competition and diversity in herbaceous vegetation. Nature 244: 244-310.
Ngouajio M, Ernest J 2005. Changes in the physical, optical, and thermal properties of polyethylene mulches during double cropping. HortScience 40: 94-97.
Niu GH, Rodriguez DS 2006. Relative salt tolerance of selected herbaceous perennials and groundcovers. Scientia Horticulturae 110: 352-358.
Niu GH, Rodriguez DS, Aguiniga L 2007. Growth and landscape performance of ten herbaceous species in response to saline water irrigation. Journal of Environmental Horticulture 25: 204-210.
Noack W 1993. Variety: 'Noaschnee' synonym 'White Noack Groundcover'. Application no. 92/065. Plant Varieties Journal 6: 13-14, 24.
Odenwald NG, Turner JR 2006. Identification, selection, and use of southern plants: For landscape design (4th edition). Claitor's Law Books and Publishing, Baton Rouge. 720 pp.
Oliveira MT, Merwin IA 2001. Soil physical conditions in a New York orchard after eight years under different groundcover management systems. Plant and Soil 234: 233-237.
Olmstead RG, dePamphilis CW, Wolfe AD, Young ND, Elisons WJ, Reeves PA 2001. Disintegration of the Scrophulariaceae. American Journal of Botany 88: 348-361.
Owings A, Bracy R, Chen Y, Rosendale R 2010. New liriope and monkey grass groundcover varieties for Louisiana. Louisiana Agriculture 53: 24.
Page D, Dillon P, Mueller J, Bartkow M 2010. Quantification of herbicide removal in a constructed wetland using passive samplers and composite water quality monitoring. Chemosphere 81: 394-399.
Paine LK, Harrison H 1993. The historical roots of living mulch and related practices. Hort Technology 3: 137-143.
Pamukov K, Schneider MJ 1978. Light inhibition of *Nigella* germination: The dependence of a high irradiance reaction on 720-nm irradiance. Botanical Gazette 139: 56-59.
Pankratov TA, Serkebaeva YM, Kulichevskaya IS, Liesack W, Dedysh SN 2008. Substrate-induced growth and isolation of *Acidobacteria* from acidic *Sphagnum* peat. ISME J 2: 551-560.
Parmeet S, Purshotam S, Singh SS 2008. Production potential and economic analysis of direct wet seeded aromatic rice (*Oryza sativa* L.) Cv. Pusa Basmati 1 as influenced by fertility levels and weed management practices. Oryza 45: 23-26.

Patrick B 2006. Our native muehlenbeckias. Open Space 66: 20-21.
Patterson DT 1998. Suppression of Purple Nutsedge (*Cyperus rotundus*) with polyethylene film mulch. Weed Technology 12: 275-280.
Pellet NE, Heleba DA 1995. Chopped newspaper for weed control in nursery crops. Journal of Environmental Horticulture 13: 77-81.
Penny GM, Neal JC 2003. Light, temperature, seed burial, and mulch effects on mulberry weed (*Fatoua villosa*) seed germination. Weed Technology 17: 213-218.
Perry TO 1989. Tree roots: Facts and fallacies. Arnoldia 49: 3-24.
Pieroni M 1994. Landscaping with Dryandra. Australian Plants 18: 3-10.
Pittenger DR, Shaw DA, Hodel DR, Holt DB 2001. Responses of landscape groundcovers to minimum irrigation. Journal of Environmental Horticulture 19: 78-84.
Pons TL, Schröder HFJM 1986. Significance of temperature fluctuation and oxygen concentration for germination of the rice field weeds *Fimbristylis littoralis* and *Scirpus juncoides*. Oecologia 68: 315-319.
Porteous JD 1996. Environmental aesthetics: Ideas, politics and planning. Routledge, London. 290 pp.
Prichard TL, Sills WM, Asai WK, Hendricks LC, Elmore CL 1989. Orchard water use and soil characteristics. California Agriculture 43: 23-25.
Qin RJ, Gao SD, Ajwa H, Sullivan D, Wang D, Hanson BD 2011. Field evaluation of a new plastic film (vapor safe) to reduce fumigant emissions and improve distribution in soil. Journal of Environmental Quality 40: 1195-1203.
Quigley MF 2003. Reducing weeds in ornamental groundcovers under shade trees through mixed species installation. Horttechnology 13: 85-89.
Quinton JN, Edwards GM, Morgan RPC 1997. The influence of vegetation species and plant properties on runoff and soil erosion: Results from a rainfall simulation study in south east Spain. Soil Use and Management 13: 143-148.
Rahman A, James TK, Cornwell MJ 1996. Influence of lime on activity and persistence of tribenuron and thifensulfuron in soil. Proceedings of the New Zealand Plant Protection Conference 49: 202-206.
Ramakrishna A, Tam HM, Wani SP, Long TD 2006. Effect of mulch on soil temperature, moisture, weed infestation and yield of groundnut in northern Vietnam. Field Crops Research 95: 115-125.
Rathmel JK 1976. Culture and management of bedding plants. In: Mastalerz JW ed. Bedding Plants: a manual on the culture of bedding plants as a greenhouse crop. Pennsylvania Flower Growers. Pennsylvania Pp. 53-59.
Rathmel JK, White JW 1976. Seed germination. In: Mastalerz JW ed. Bedding Plants: a manual on the culture of bedding plants as a greenhouse crop. Pennsylvania Flower Growers, Pennsylvania. Pp. 36-41.
Rauschert ESJ, Mortensen DA, Bjrnstad ON, Nord AN, Peskin N 2010. Slow spread of the aggressive invader, *Microstegium vimineum* (Japanese stiltgrass). Biological Invasions 12: 563-579.
Rejmánek M, Richardson DM 1996. What Attributes Make Some Plant Species More Invasive? Ecology 77: 1655-1661.
Relf PD 1998. People-Plant relationship. In: Simson SP, Straus MC ed. Horticulture as therapy: Principles and practice The Food Products Press, New York. Pp. 21-42.
Rhoads AF, Block TA 2007. The Plants of Pennsylvania: An Illustrated Manual. University of Pennsylvania Press. 1042 pp.
Richardson B, Vanner A, Ray J, Davenhill N, Coker G 1996. Mechanisms of *Pinus radiata* growth suppression by some common forest weed species. New Zealand Journal of Forestry Science 26: 421-437.
Ricotta JA, Masiunas JB 1991. The effects of black plastic mulch and weed control strategies on herb yield. HortScience 26: 539-541.

Robbins P 2007. Lawn people: How grasses, weeds, and chemicals make us who we are. Temple University Press, Philadelphia. 186 pp.
Roberts HA, Bond W, Hewsen RT, Ricketts ME 1977. Weed competition in drilled summer lettuce. Horticultural Reserach 17: 39-45.
Roberts WG 1989. Some plants for dry California conditions. Combined Proceedings - International Plant Propagators' Society 39: 174-177.
Rogers RD, Schumm SA 1991. The effect of sparse vegetative cover on erosion and sediment yield. Journal of Hydrology 123: 19-24.
Rollin P, Malcoste R, Eude D 1970. Le rôle du phytochrome dans la germination des graines de *Nemophila insignis* (L.). Planta 91: 227-234.
Romic D, Romic M, Borosic J, Poljak M 2003. Mulching decreases nitrate leaching in bell pepper (*Capsicum annuum* L.) cultivation. Agricultural Water Management 60: 87-97.
Romic D, Romic M, Borosic J, Tomic F, Klacic Z 1996. Reduction of potential groundwater contamination in the production of vegetables on mulch - lysimetric study. (Bericht uber die 6. Lysimetertagung "Lysimeter im Dienste des Grundwasserschutzes" am 16. und 17). April 1996.: 117-120.
Rose MA, Smith E 1996. Mulching Landscape Plants. In Rose MA ed. Ohio State University Extension Columbus, Ohio State University. Pp.
Ross MA, Harper JL 1972. Occupation of biological space during seedling establishment. Journal of Ecology 60: 77-88.
Ross SM, King JR, Izaurralde RC, O'Donovan JT 2001. Weed suppression by seven clover species. Agronomy Journal 93: 820-827.
Rouse RE, Mullahey JJ 1997. Perennial peanut ground cover in citrus orchard row middles and discussion of potential environmental benefits. Proceedings of the Florida State Horticultural Society 110: 79-82.
Rowley G 2007. *Cotyledon orbiculata* and its cultivars. Cactus and Succulent Journal 79: 148-151.
Roy PK, Hakkarainen M, Varma IK, Albertsson A-C 2011. Degradable Polyethylene: Fantasy or Reality. Environmental Science & Technology 45: 4217-4227.
Roy PK, Titus S, Surekha P, Tulsi E, Deshmukh C, Rajagopal C 2008. Degradation of abiotically aged LDPE films containing pro-oxidant by bacterial consortium. Polymer Degradation and Stability 93: 1917-1922.
Ruiz-Avila RJ, Klemm VV 1996. Management of *Hydrocotyle ranunculoides* L.f., an aquatic invasive weed of urban waterways in Western Australia. Hydrobiologia 340: 187-190.
Runham SR, Town SJ, Fitzpatrick JC 2000. Evaluation over four seasons of a paper mulch used for weed control in vegetables. Acta Horticulturae 513: 193-201.
Sacamano CM, Feldman WR 1984. The Boyce Thompson Southwestern Arboretum groundcover evaluation and introduction project. Desert Plants 6: 67-69.
Salim R, Abu El-Halawa R 2002. Efficiency of dry plant leaves (mulch) for removal of lead, cadmium and copper from aqueous solutions. Process Safety and Environmental Protection 80: 270-276.
Sanders RA 1986. Urban vegetation impacts on the hydrology of Dayton, Ohio. Urban Ecology 9: 361-376.
Sarrantonio M, Gallandt E 2003. The role of cover crops in North American cropping systems. Journal of Crop Protection 8: 53-74.
Schmid WG 2005. Timber Press pocket guide to shade perennials. Timber Press, Portland. 252 pp.
Schonbeck MW 1999. Weed suppression and labor costs associated with organic, plastic, and paper mulches in small-scale vegetable production. Journal of Sustainable Agriculture 13: 13 - 33.
Schrock D 2004. Ortho home gardener's problem solver. Meredith Books, Des Moines. 624 pp.
Schroth G, Zech W, Heimann G 1992. Mulch decomposition under agroforestry conditions in a sub-humid tropical savanna processes and influence of perennial plants. Plant and Soil 147: 1-11.

Scopel AL, Ballare CL, Sanchez RA 1991. Induction of extreme light sensitivity in buried weed seeds and its role in the perception of soil cultivations. Plant, Cell & Environment 14: 501-508.

Shiraishi S, Watanabe I, Kuno K, Fujii Y 2002. Allelopathic activity of leaching from dry leaves and exudate from roots of ground cover plants assayed on agar. Weed Biology and Management 2: 133-142.

Shogren RL 1999. Paper coated with polymerised vegetable oils for use as mulch as biodegradable mulch. In United States Patent Office ed. Google Patents. USA, Secretary of Agriculture, USA. Pp.

Shogren RL, David M 2006. Biodegradable paper/polymerised vegetable oil mulches for tomato and pepper production. Journal of Applied Horticulture 8: 12-14.

Shooshtarian S, Salehi H 2012. Physiological and ecological investigation on adoption of some groundcover plants as turfgrass alternatives in arid landscape region of Kish Island during cool season. African Journal of Agricultural Research 7: 546-554.

Silvertown J 1980. Leaf-canopy-induced seed dormancy in a grassland flora. New Phytologist 85: 109-118.

Silvy NJ 2012. The wildlife techniques manual: Volume 1: Research : Management. Johns Hopkins University Press, Baltimore. 1136 pp.

Simpson AGW 1992. Growing lawns including lawn alternatives and ground covers. Kangaroo Press. 144 pp.

Singer JW, Nusser SM, Alf CJ 2007. Are cover crops being used in the US corn belt? Journal of Soil and Water Conservation 62: 353-356.

Singh G 2004. Plant Systematics: An Integrated Approach. Science Publishers. 561 pp.

Six J, Paustian K, Elliott ET, Combrink C 2000. Soil Structure and Organic Matter I. Distribution of Aggregate-Size Classes and Aggregate-Associated Carbon. Soil Sci. Soc. Am. J. 64: 681-689.

Skroch WA, Powell MA, Bilderback TE, Henry PH 1992. Mulches: Durability, aesthetic value, weed control and temp. Journal of Environmental Horticulture 10: 43-45.

Smith-Dodsworth JC 1991. New Zealand native shrubs and climbers. David Bateman, Auckland. 104 pp.

Smith DR, Gilliam CH, Edwards JH, Eakes DJ, Williams JD 1997. Recycled waste paper as a landscape mulch. Journal of Environmental Horticulture 15: 191-196.

Smith DR, Gilliam CH, Edwards JH, Olive JW, Eakes DJ, Williams JD 1998. Recycled waste paper as a non-chemical alternative for weed control in container production. Journal of Environmental Horticulture 16: 69-75.

Smith LJ, Skroch WA 1995. Turf herbicide injury to landscape trees as influenced by mulch. Journal of Environmental Horticulture 13: 60-63.

Snapp SS, Swinton SM, Labarta R, Mutch D, Black JR, Leep R, Nyiraneza J, O'Neil K 2005. Evaluating cover crops for benefits, costs and performance within cropping system niches. Agronomy Journal 97: 322-332.

Sotir R, Gray D 1989. Fill slope repair using soil bioengineering systems. Public Works 120.

Spencer R, Pearson S 2002. Horticultural flora of south eastern Australia. UNSW Press, Sydney. 656 pp.

Spillman WJ 1923. Application of the law of diminishing returns to some fertilizer and feed data. Journal of Farm Economics 5: 36-52.

Spruit CJP, Mancinelli AL 1969. Phytochrome in cucumber seeds. Planta 88: 303-310.

Standish RJ, Robertson AW, Williams PA 2001. The impact of an invasive weed *Tradescantia fluminensis* on native forest regeneration. Journal of Applied Ecology 38: 1253-1263.

Starr G 1988. Dalea - a genus of horticulturally promising legumes for desert landscapes. Desert Plants 9: 3-5, 28-31.

Steward LG, Sydnor TD, Bishop B 2003. The ease of ignition of 13 landscape mulches. Journal of Arboriculture 29: 317-321.

Stinchcombe GR, Stott KG 1983. A comparison of herbicide-controlled orchard ground cover management systems on the vigour and yield of apples. Journal of Horticultural Science 58: 477-489.
Sullivan WC 1994. Perceptions of the rural-urban fringe: citizen preferences for natural and developed settings. Landscape and Urban Planning 29: 85-101.
Sullivan WC, Lovell ST 2006. Improving the visual quality of commercial development at the rural–urban fringe. Landscape and Urban Planning 77: 152-166.
Sun Z, Dong L, Gao D 2009. The study of four native wild groundcovers. In: Johnston M, Dragovic MJO, Criley RA ed. Acta Horticulturae. Pp. 365-373.
Sykes WR, Edgar E, Webb CJ, Garnock-Jones PJ, Allan HH, Moore LB, Healy AJ 1988. Flora of New Zealand: Naturalised pteridophytes, gymnosperms, dicotyledons. V.R. Ward, Govt. Printer. 1365 pp.
Taha H, Douglas S, Haney J 1997. Mesoscale meteorological and air quality impacts of increased urban albedo and vegetation. Energy and Buildings 25: 169-177.
Tahir I, Gustavsson KE 2010. Improving quality and storability of apples by a combination of aluminum reflective mulch, summer pruning and controlled nitrogen fertilization. In: Erkan MAU ed. Acta Horticulturae. Pp. 245-250.
Tarara JM 2000. Microclimate modification with plastic mulch. HortScience 35: 169-180.
Taylor GM 1961. A key to the *Coprosmas* of New Zealand - Part 1. Tuatara 9: 31-64.
Taylorson RB, Borthwick HA 1969. Light filtration by foliar canopies: Significance for light-controlled weed seed germination. Weed Science 17: 48-51.
Tenenbaum F 2003. Taylor's encyclopedia of garden plants. Houghton Mifflin, New York. 447 pp.
Tenenbaum F, Buchanan R, Holmes R 2001. Taylor's master guide to gardening. Houghton Mifflin. 624 pp.
TerAvest D, Smith JL, Carpenter-Boggs L, Granatstein D, Hoagland L, Reganold JP 2011. Soil carbon pools, nitrogen supply, and tree performance under several groundcovers and compost rates in a newly planted apple orchard. HortScience 46: 1687-1694.
Thomas DC, Weigend M, Hillger HH 2008. Phylogeny and systematics of *Lithodora* (Boraginaceae Lithospermeae) and its affinities to the monotypic genera *Mairetis, Halacsya* and *Paramoltkia* based on ITS1 and trnLUAA-sequence data and morphology. Taxon 57: 79-97.
Thomas GS 1977. Plants for ground-cover. J. M. Dent & Sons, London. 282 pp.
Thompson K, Grime JP 1983. A comparative study of germination responses to diurnally-fluctuating temperatures. Journal of Applied Ecology 20: 141-156.
Thompson RC, Olsen Y, Mitchell RP, Davis A, Rowland SJ, John AWG, McGonigle D, Russell AE 2004. Lost at sea: Where is all the plastic? Science 304: 838.
Thompson W 2006. Gardeners seek agapanthus reprieve. In ed. The New Zealand Herald. Auckland, APN News and Media. Pp. 5.
Tixier P, Lavigne C, Alvarez S, Gauquier A, Blanchard M, Ripoche A, Achard R 2011. Model evaluation of cover crops, application to eleven species for banana cropping systems. European Journal of Agronomy 34: 53-61.
Tomback DF, Linhart YB 1990. The evolution of bird-dispersed pines. Ecological Economics 4: 185-219.
Toole G 2004. Essential A2 Biology for OCR. Nelson Thomas, Cheltenham. 176 pp.
Toole VK 1973. Effects of light, temperature and their interactions on the germination of seeds. Seed Science and Technology 1: 339-396.
Toole VK, Borthwick HA 1968. The photoreaction controlling seed germination in *Eragrostis curvula*. Plant and Cell Physiology 9: 125-136.
Trexler J 1993. The purposeful lawn In: Marinelli J ed. The natural lawn & alternatives. Brooklyn Botanic Garden, Brooklyn. Pp. 8-11.
Trowsdale SA, Simcock R 2011. Urban stormwater treatment using bioretention. Journal of Hydrology 397: 167-174.

Turgeon AJ 2008. Turfgrass management. Pearson Education, Upper Saddle River. 436 pp.
Tveit M, Ode Å, Fry G 2006. Key concepts in a framework for analysing visual landscape character. Landscape Research 31: 229-255.
Ulrich RS 1999. Effects of gardens on health outcomes: theory and research. In: Cooper-Marcus C, Barnes M ed. Healing gardens : Therapeutic benefits and design recommendations. John Wiley & Sons, New York. Pp. 27-86.
Univer T, Pork K, Univer N 2009. Living grass mulches in strawberry cultivation. Agronomy Research 7: 532-535.
Upadhyaya MK, Blackshaw RE 2007. Non-chemical weed management: principles, concepts and technology. CABI, Reading. 239 pp.
Urems I, Calskan ME, Uludag A, Calskan S 2009. Weed management in early-season potato production in the Mediterranean conditions of Turkey. Bulgarian Journal of Agricultural Science 15: 423-434.
Ustuner T, Ustuner M 2011. Investigation on different mulch materials and chemical control for controlling weeds in apple orchard in Turkey. Scientific Research and Essays 6: 3979-3985.
Vallauri DR, Aronson J, Barbero M 2002. An analysis of forest restoration 120 years after reforestation on badlands in the southwestern alps. Restoration Ecology 10: 16-26.
van der Spuy U 1976. Gardening with groundcovers. A. H. & A. W. Reed, Wellington. 112 pp.
Van Toor RF, Till CM, James DE, Teulon DAJ 2004. Evaluation of UV reflective mulches for protection against thrips (*Thrips tabaci*) in onion (*Allium cepa*) crops. In: Zydenbos SM ed. New Zealand Plant Protection, Vol 57. New Zealand Plant Protection-Series. Pp. 209-213.
Vengris J, Torello WA 1982. Lawns: Basic factors, construction and maintenance of fine turf areas. Thomson Publications, Fresno. 195 pp.
Vleeshouwers LM, Bouwmeester HJ, Karssen CM 1995. Redefining seed dormancy: An attempt to integrate physiology and ecology. Journal of Ecology 83: 1031-1037.
Wang H, Lopez-Pujol J, Meyerson LA, Qiu J, Wang X, Ouyang Z 2011. Biological invasions in rapidly urbanizing areas: a case study of Beijing, China. Biodiversity and Conservation 20: 2483-2509.
Wang J, Chen Y 2008. Effect of microencapsulation and 4A zeolite on the properties of intumescent flame-retardant natural rubber composites. Journal of Fire Sciences 26: 153-171.
Wang PW, Chen JY 1990. Studies on breeding new cultivars of ground-cover chrysanthemum. Acta Horticulturae Sinica 17: 223-228.
Wardle P 1991. Vegetation of New Zealand. Cambridge University Press, Cambridge. 672 pp.
Watt MS, Whitehead D, Mason EG, Richardson B, Kimberley MO 2003a. The influence of weed competition for light and water on growth and dry matter partitioning of young *Pinus radiata*, at a dryland site. Forest Ecology and Management 183: 363-376.
Watt MS, Clinton PW, Whitehead D, Richardson B, Mason EG, Leckie AC 2003b. Above-ground biomass accumulation and nitrogen fixation of broom (*Cytisus scoparius* L.) growing with juvenile Pinus radiata on a dryland site. Forest Ecology and Management 184: 93-104.
Wesson G, Wareing PF 1969a. The role of light in the germination of naturally occurring populations of buried weed seeds. Journal of Experimental Botany 20: 402-413.
Wesson G, Wareing PF 1969b. The induction of light sensitivity in weed seeds by burial. Journal of Experimental Botany 20: 414-425.
Wibawa W, Mohd Ghazali M, Mohamad RB, Abdul Shukor J, Dzolkhifli O 2010. Efficacy and cost-effectiveness of three broad-spectrum herbicides to control weeds in immature oil palm plantation. Pertanika Journal of Tropical Agricultural Science 33: 233-241.
Wichman SR, Wright SD, Cameron EK, Keeling DJ, Gardner RC 2002. Elevated genetic heterogeneity and Pleistocene climatic instability: inferences from nrDNA in New Zealand Coprosma (Rubiaceae). Journal of Biogeography 29: 943-954.
Wiecko G 2006. Fundamentals of Tropical Turf Management. CABI, Cambridge. 208 pp.
William RD 1990. Selecting weeds as a winter living mulch in vineyards. Pacific Northwest Living Mulch News 6: 7.

Williams ED 1983. Effects of temperature fluctuation, red and far-red light and nitrate on seed germination of five grasses. Journal of Applied Ecology 20: 923-935.

Williams P, Thompson W 2006. Agapanthus joins planned hit-list for national ban. In ed. The New Zealand Herald. Auckland, APN News and Media. Pp. 3.

Williams WT 1988. Lawn mower stabilizing devices for use in mowing steep terrain. In ed., United States Patents. Pp.

Williamson JF 1964a. Lawns and ground covers. Lane Book Co., Menlo Park. 112 pp.

Williamson JF 1964b. Lawns and ground covers. In Clark DE ed. Menlo Park, California, Lane Magazine & Book Company. Pp. 112.

Wilson PC, Whitwell T, Riley MB 1995. Effects of ground cover and formulation on herbicides in runoff water from miniature nursery sites. Weed Science 43: 671-677.

Yang Y, Xiao B, Tian Z, Wu Y 2009. Application of groundcover plants to landscape building in the middle part of Shaanxi Province. Journal of Southwest Forestry University 29: 67-71, 94.

Yaniv Z, Mancinelli AL 1968. Phytochrome and seed germination. IV. Action of light sources with different spectral energy distribution on the germination of tomato seeds. Plant Physiology 43: 117-120.

Yelverton DFH, Gannon TW 2010. Integrated vegetation management along roadsides in the south-eastern United States. 17th Australasian Weeds Conference: 1-13.

Yildiz A, Benlioglu S, Boz O, Benlioglu K 2010. Use of different plastics for soil solarization in strawberry growth and time-temperature relationships for the control of *Macrophomina phaseolina* and weeds. Phytoparasitica 38: 463-473.

Yu Q, Friesen LJS, Zhang X, Powles SB 2004. Tolerance to acetolactate synthase and acetyl-coenzyme A carboxylase inhibiting herbicides in *Vulpia bromoides* is conferred by two co-existing resistance mechanisms. Pesticide Biochemistry and Physiology 78: 21-30.

Zheng W, Xu X, Zhao K, Chen L 2009. *Lysimachia christinae* 'Zixin': a new groundcover plant. HortScience 44: 474-475.

Zimdahl RL 2002. The evolution of weed science - an ethical perspective. Proceedings of the 13th Australian Weeds Conference: 436-440.

Zollinger N, Kjelgren R, Cerny-Koenig T, Kopp K, Koenig R 2006. Drought responses of six ornamental herbaceous perennials. Scientia Horticulturae 109: 267-274.

Zribi W, Faci JM, Aragues R 2011. Mulching effects on moisture, temperature, structure and salinity of agricultural soils (Efectos del acolchado sobre la humedad, temperatura, estructura y salinidad de suelos agricolas). Itea 107: 148-162.