# EFFECT OF ROOTZONE COMPOSITION AND CULTIVATION/AERATION TREATMENT ON THE PERFORMANCE OF GOLF GREENS UNDER NEW ZEALAND CONDITIONS

A thesis submitted in partial fulfilment
of the requirements for the degree of
Doctor of Philosophy in Turfgrass Science
at Massey University
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**2004**

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# DECLARATION

This is to certify that the research carried out for my Doctoral thesis entitled "EFFECT OF ROOTZONE COMPOSITION AND CULTIVATION/AERATION TREATMENT ON THE PERFORMANCE OF GOLF GREENS UNDER NEW ZEALAND CONDITIONS" in the Institute of Natural Resources, Massey University, Palmerston North, New Zealand is my own work and that the thesis material has not been used in part or in whole for any other qualification.

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# DECLARATION

This is to certify that the research carried out in the Doctoral thesis entitled "EFFECT OF ROOTZONE COMPOSITION AND CULTIVATION/AERATION TREATMENT ON THE PERFORMANCE OF GOLF GREENS UNDER NEW ZEALAND CONDITIONS" was done by Cunqi Liu in the Institute of Natural Resources, Massey University, Palmerston North, New Zealand. The thesis material has not been used in part or in whole for any other qualification, and I confirm that the candidate has pursed the course of study in accordance with the requirements of the Massey University regulations.

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# CERTIFICATE OF REGULATORY COMPLANCE

This is to certify that the research carried out for the Doctoral thesis entitled EFFECT OF ROOTZONE COMPOSITION AND CULTIVATION/AERATION TREATMENT ON THE PERFORMANCE OF GOLF GREENS UNDER NEW ZEALAND CONDITIONS in the Institute of Natural Resources at Massey University, New Zealand:

(a) is the original work of the candidate, except as indicated by appropriate attribution in the text and/or in the acknowledgements;

(b) that the text, excluding appendices/annexes, does not exceed 100,000 words;

(c) all the ethical requirements applicable to this study have been complied with as required by Massey University, other organisations and/or committees (the New Zealand Sports Turf Institute), which had a particular association with this study, and relevant legislation.

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## ABSTRACT

The performance of golf greens in terms of rootzone physical properties, sward characteristics and playing quality is highly dependent upon the original rootzone composition and subsequent management. Such performance also continuously changes with time under usage. A study to this performance was conducted from April 1998 to January 2003 at the research site of the New Zealand Sports Turf Institute. This thesis reports results of both the field measurements made of rootzone physical properties, sward characteristics and playing quality of five alternative golf green rootzones during the first five years after sowing, and of the simulation modeling of their performance predicted for the first 30 years after sowing. Rootzone treatments were partially amended sand rootzone, soil rootzone, pure sand rootzone, fully amended sand rootzone, and partially amended sand + zeolite rootzone. A split-plot design was superimposed on the rootzone treatments consisting of twice-yearly cultivation/aeration treatments (control, HydroJect, scarification and Verti-drain).

Results showed that performance of golf greens could be objectively, quantitatively and comprehensively assessed and monitored over the long-term at the rootzone level by using an Integrated Rate Methodology (IRM) model through computing the Comprehensive Golf Green Performance Index ($CGGP_I$).

The performance of golf greens showed a gradual improvement during the first two years after sowing. It then deteriorated progressively over the remainder of the 30 years predicted for all rootzone and cultivation/aeration treatments. This general trend was reflected mainly by a gradual decrease with time in water infiltration rate, oxygen diffusion rate, air-filled porosity and deep rooting. Also, there was a gradual increase in green speed, surface hardness, root mass and organic matter content near the surface profiles. By the $14^{th}$ and $27^{th}$ year after sowing, the IRM model predicted that the

$CGGP_I$ for all the three amended sand rootzones and the pure sand rootzone were below the minimum acceptable threshold.

The key factor that caused the general deterioration in green performance of all the sand-based rootzones appeared to be excess accumulation of organic matter in the surface of the profiles.

Whilst there were marked differences in the performance of golf greens between the rootzone types, it was only the conventional soil rootzone that consistently performed unacceptably. Quantitative benefits of upgrading from a soil-based to a sand-based rootzone were evident in terms of improved infiltration rate, increased oxygen diffusion rate and macroporosity, reduced organic matter accumulation near the surface, better root growth and distribution, more stable turfgrass sward, lower weed cover and less fluctuation with seasons in surface hardness.

Among the four sand-based rootzones, the pure sand rootzone had the highest incidence of dry patch disorder, poorest turf visual quality, greatest changes over time in the relative balance of *Festuca* and *Agrostis*, and largest fluctuation with seasons in surface hardness. However, it contained the best root growth distribution. After the fifth year from sowing, the green performance of the pure sand rootzone remained significantly better than the three amended sand rootzones.

There was negligible difference in the performance of golf greens between the three amended sand rootzones on all measured or predicted occasions. The supposed benefits of burying a zeolite-amended sand layer at 100-200 mm depth, ostensibly for encouraging deep rooting, were not apparent under the experimental conditions used, possibly because the experimental plots were never managed under nutrient or moisture stress conditions.

Beneficial effects of twice-yearly cultivation/aeration treatments on rootzone physical properties, sward characteristics and playing quality were evident, although these effects were extremely short-lived. Verti-drain treatment with hollow tines tended to be most effective in controlling surface organic matter accumulation and the resultant rootzone physical deterioration. In contrast, the scarification treatment gave variable response, reducing root mass, hence organic matter accumulation, near the surface on the one hand, but on the other decreasing infiltration rate and turfgrass cover.

HydroJect treatment, although tending to induce a higher incidence of disease and pest damage, appeared particularly effective in minimizing the occurrence of dry patch disorder on sand-based rootzones when used in conjunction with a proprietary wetting agent. None of the cultivation/aeration treatments could effectively halt the general deterioration with time in the performance of golf greens under the twice-yearly treatment frequency used. It was concluded that:

(a) The performance of sand-based rootzones for golf greens will be limited in the long term by excess accumulation of organic matter near the surface of the profile;

(b) Cultivation/aeration treatments will need to commence immediately after full turf establishment and should be carried out more than twice per year on golf greens under New Zealand conditions;

(c) HydroJect treatment, when used in conjunction with wetting agent application, is an effective management tool for prevention of dry patch disorder on sand-based golf greens; while scarification should not be used in isolation of other physical cultivation;

(d) Upgrading from a conventional soil rootzone to a high-grade, sand-based rootzone will greatly improve golf green performance;

(e) The practice of constructing only the top 100 mm of the sand rootzone with organic-amended sand is an alternative method that can be used successfully for putting green construction instead of the fully amended, standard USGA-type profile; the pure sand rootzone system is also an appropriate alternative for rootzone construction of golf greens, provided the initial establishment can be managed successfully;

(f) The integrated rate modeling approach is potentially an effective decision-making tool for rootzone upgrading, surface preparation planning, performance assessment and monitoring, professional consultancy, and seasonal management of golf greens.

**KEYWORDS**: Comprehensive Golf Green Performance Index ($CGGP_I$), compost, golf green construction, HydroJect, Integrated Rate Methodology (IRM) model, playing quality, pure sand, rootzone physical properties, sward characteristics, scarification, Verti-drain and zeolite.

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# STRUCTURE OF THESIS

All chapters in this thesis, except Chapter One (Introduction), Two (Review of the Literature), Three (Materials and Methods), Eight (General Discussion) and Nine (Conclusions), are based on a series of papers that have been published or submitted for publication. The two papers in Chapter Seven (model section), which have been submitted for publication, are presented here as scientific papers but in thesis format. These two submitted papers are saved in the supplied disc in the appendix. The references relevant to individual chapters are at the end of each chapter. All the materials and methods used in this research are integrated into one chapter (Chapter Three) due to the similarity. The results are discussed in detail in each experimental chapter and integrated into a general discussion in Chapter Eight. The main findings from the research in this thesis are summarized separately in Chapter Nine.

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# 1. INTRODUCTION

## 1.1 INTRODUCTION

Golf turf is a leading sector of the sports turf industry (Robinson 1980; Way 2001; Beard 2002). It not only provides playing surfaces for the game, a major worldwide outdoor leisure activity, but also plays an important role in the conservation of urban environments and natural resources (Beard & Green 1994; Beard 2002).

The most critical component of a golf course is its golf greens (Beard 2002). Approximately 75% of shots played in a round of golf take place onto or within the greens (Lodge & Baker 1991; Beard 2002). The performance of golf greens in terms of rootzone physical properties, sward characteristics and playing quality has a profound influence on the playing enjoyment of players, as well as their final score for a round of golf (Baker 1994). It is the most important factor by which players judge the overall performance of a golf course (Barr 1993; Baker 1994; Power 2004).

The performance of golf greens is highly dependent on the original rootzone composition and subsequent management (Baker & Richards 1991, 1993; Lodge & Lawson 1993; Adams & Gibbs 1994; Baker *et al.* 1999a, b, c). One of the most significant achievements in golf green rootzone development has been the use of sand as the basic growing medium, which allows a high intensity of play often under harsh weather conditions. This growing medium typically overlies a gravel drainage layer to form the well-documented suspended or perched water table system (Gibbs *et al.* 2000). The best-known published example of such a drainage system is the United States Golf Association (USGA) recommendations for putting green construction, which uses fully (organic) amended sand for the rootzone (USGA 1993, 2004). However, in many parts of the world, including New Zealand, it is rare to find *bona fide* golf greens built to the USGA recommendations. The reasons for this include the cost and difficulty in obtaining a rootzone mix that conforms exactly to USGA requirements, and the long-term preference by golf superintendents in many countries to use pure sand instead of the fully amended sand due to simplicity of the construction method (Snow 1992; Gibbs *et al.* 2000).

Recently, there has been an increasing interest in New Zealand in use of the inorganic amendment zeolite as an alternative to the USGA-specified organic amendment (Yang *et al.* 1998; Myer *et al.* 2003). Concurrently, there has been a general Australasian recommendation that only the top 100-150 mm of USGA-type profile warrants organic amendment as opposed to the whole rootzone depth (Gibbs *et al.* 1997, 2000, 2001). These two modified USGA rootzones plus the pure sand rootzone have been developing in parallel with the recent worldwide surge in research work investigating improvements in the USGA-type golf green construction (Callahan *et al.* 1997 a, b; Bigelow *et al.* 2000, 2001; Baker & Binns 2001a, b; Waltz *et al.* 2003). However, to date, these alternative rootzone systems have remained largely un-validated scientifically despite their increasing use. It is difficult to gauge whether the increased resources needed to build these types of golf greens (i.e. the two modified USGA profiles plus the pure sand rootzone) are fully justified in terms of improvements in their performance, ease of maintenance and cost-effectiveness (Gibbs *et al.* 2000, 2001).

An added complication is that golf greens are highly dynamic, and their performance changes continuously over time with subsequent management and usage (Murphy *et al.* 1993a, b; Habeck & Christians 2000; Curtis & Pulis; 2001; O'Brien & Hartwiger 2003). Sand constructions, even a *genuine* USGA-type construction, do not necessarily guarantee long-term satisfactory performance (Gibbs *et al.* 2001). The shift of rooting depth with time towards the upper portion of the profile (hence the accumulation of organic matter in the surface), is considered the principal problem experienced on all types of sand-based golf greens (Carrow 1995, 2004a, b, c). Organic matter inter-packs with sand particles and fills pores, resulting in decreased water infiltration rate, reduced oxygen diffusion, shallow rooting and poor playing quality (Adams 1981; Carrow 1995; O'Brien & Hartwiger 2003). If the organic matter (dead or living) accumulates beyond a reasonable level, physical benefits of sand are diminished and the performance of golf greens deteriorates quickly (Habeck & Christians 2000; O'Brien & Hartwiger 2003).

With the introduction and increased availability of innovative physical cultivation equipment in New Zealand during the last decade or so (e.g. HydroJect and novel coring/aeration type equipment), there is potentially more opportunity than before to manipulate organic matter accumulation, root growth and the resultant deterioration of golf green performance (Gibbs *et al.* 2000, 2001). According to previous studies (Carrow 1995; O'Brien & Hartwiger 2003), such equipment should be beneficial on greens in all regions of the world. However, to date, research investigating the effect of physical cultivation equipment on organic matter accumulation and root growth, and the resultant deterioration of golf green performance has been limited in the cool, humid zones typical of New Zealand (Carrow 1995; Gibbs *et al.* 2000, 2001).

Therefore, the general aim of this study was to monitor long-term green performance of five alternative rootzone systems (i.e. two modified USGA rootzones, pure sand rootzone, the standard USGA rootzone and a conventional soil rootzone) managed under four alternative cultivation/aeration treatments (i.e. control, HydroJect, scarification and Verti-drain) with particular respect to achieving the following objectives:

(a) To determine the key factors limiting the performance of golf greens and causing their general deterioration over time in terms of soil physical properties, sward characteristics and playing quality.

(b) To predict the long-term general trend of golf green performance for the five alternative rootzone systems managed under the four alternative cultivation/aeration treatments.

(c) To determine the relative effectiveness of the three alternative cultivation/aeration treatments (i.e. HydroJect, scarification and Verti-drain) in manipulating the organic accumulation in the surface profile and general deterioration of green performance under New Zealand conditions.

(d) To assess advantages and disadvantages between the five alternative rootzone systems, particularly between the standard USGA rootzone and the three alternative sand-based rootzones.

(e) To develop an appropriate methodology that could give a quantitative, objective and comprehensive prediction of the long-term performance of golf greens in terms of soil physical properties, sward characteristics and playing quality.

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# 2. REVIEW OF THE LITERATURE

## 2.1 INTRODUCTION

The performance of golf greens is greatly controlled by the profile construction type, rootzone composition and subsequent management (McAuliffe *et al.* 1993; Baker *et al.* 1999a, b, c; Habeck & Christians 2000). It can be assessed comprehensively according to rootzone physical properties, sward characteristics and surface playing quality (Barr 1993; Moore 1998; McAuliffe 2001, 2003; Power 2004). Numerous studies regarding effects of rootzone composition (Adams *et al.* 1971; Lodge & Baker 1993; Baker *et al.* 1999a, b, c; Richardson & Karcher 2001) and cultivation/aeration management techniques (McAuliffe *et al.* 1993; Murphy *et al.* 1993a; Murphy & Rieke 1994; Bunnell *et al.* 2001) on the rootzone physical properties, sward characteristics and playing quality of golf greens have been presented since 1970. Critical reviews on the history, practice and current development of golf green rootzone constructions have also been published (Hummel 1993). A number of rootzone systems (Adams *et al.* 1971; USGA 1993; Callahan *et al.* 1997 a, b; Gibbs *et al.* 1997; Bigelow *et al.* 2000; Baker & Binns 2001a, b), and maintenance techniques and equipment (Carrow 1989, 1992; Rieke & Murphy 1989; Murphy *et al.* 1993a; Murphy & Rieke 1994) have been developed and utilized worldwide over the last half-century, which have greatly helped increase the green carrying capacity and playing quality. Many performance criteria have been developed overseas as authoritative guidelines for the construction, maintenance and preparation of golf greens (USGA 1993, 2004; Hind *et al.* 1995).

Research journal papers about effects of rootzone composition and cultivation/aeration treatment on golf green performance and the application of mathematical models in performance analysis of ecosystems in agricultural science (in, for example, *Journal of Turfgrass Science, Agronomy Journal, International Turfgrass Society Research Journal, Golf Course Management, USGA Green Section Record, New Zealand Turf Management Journal, Agricultural Systems,* and *Ecological Modeling*) published in recent decades (1980-2004) are reviewed here. As the literature on these topics is voluminous, only parts of the papers, which are here as representative papers, will be cited in this review.

# 2.2 EFFECT OF ROOTZONE COMPOSITION AND CULTIVATION/AERATION TREATMENT ON ROOTZONE PHYSICAL PROPERTIES OF GOLF GREENS

## 2.2.1 Background and overview

The suitability of a soil for plant growth is highly dependent on its physical properties (Gibbs 1986). For sports turf, rootzone physical properties are of particular importance. They not only refer to the transmission capacity of a rootzone, but also directly contribute to turf playability (e.g. surface firmness and resilience) (Baker & Canaway 1990). An ideal golf green rootzone should have physical properties that permit continuous use with minimum maintenance. Key properties include infiltration rates high enough to absorb heavy rainfall, adequate water holding capacity, adequate aeration and resistance to compaction, as well as minimum deterioration (Brown & Duble 1975; Neylan & Robinson 1997).

Rootzone physical properties are greatly controlled by rootzone composition and subsequent maintenance. Although there are plenty of successful examples of soil-based golf greens under appropriate management, sand-based golf greens have many advantages over conventional soil-based golf greens because they are technically able to confer desirable rootzone physical properties even under high usage and adverse weather conditions (Gibbs *et al.* 1997; Baker *et al.* 1997a, 1999a). Most modern methods of putting green construction utilize a sand-based rootzone (Hummel 1993; Gibbs *et al.* 1997; Baker *et al.* 1999a). A representative example of this system is the fully amended, USGA-type sand-based profile (Hummel 1993; USGA 1993, 2004; Gibbs *et al.* 1997). The USGA-type fully amended sand method of golf green rootzone construction has revolutionized the quality of sports turf surfaces during the last 45 years (Gibbs *et al.* 1997). However, in many countries of the world, including New Zealand, there has been a long-term preference by golf superintendents to use pure sands for golf green construction instead of the fully amended sands. This preference can be put down to a variety of factors including construction cost and difficulty in obtaining a rootzone mix that conforms with USGA requirements (Gibbs *et al.* 2000). Pure sand rootzones, although easy to construct, are more demanding in terms of their nutritional and irrigation management compared with amended sands, and if usage is heavy, there can be problems with surface instability (Baker & Richards 1995). In particular, it is very difficult to achieve uniform turfgrass establishment on pure sand rootzones (Snow 1992; Baker *et al.* 1997b). Recently, much research has been conducted worldwide to investigate improvements in the USGA golf green recommendations (Callahan *et al.* 1997 a, b; Bigelow *et al.* 2000, 2001; Baker & Binns 2001a, b; Waltz *et al.* 2003). In Australia and New Zealand, modified USGA profiles have been recommended for golf green construction (i.e. only the top 100-150 mm of profile is amended by organic amendment with or without an underlying zeolite amended layer) (Gibbs *et al.* 1997; Yang *et al.* 1998; Myer *et al.* 2003). However, these partially amended sand rootzone systems are largely unvalidated under field conditions, despite their increasing use.

Rootzone physical properties are not only greatly controlled by the original rootzone composition, but they are also continuously changing with use. Poor rootzone physical properties caused by deterioration over time are a common issue in the management of all types of golf greens (Baker *et al.* 1999a; Murphy *et al.* 1993b). The deterioration can be rapid on both soil-based and sand-based rootzones, but the deterioration rate, mechanism and subsequent results are quite different among different types of rootzones and highly dependent on rootzone composition (Schmidt 1980; Baker *et al.* 1997a, 1999a). For sand-based rootzones, the occlusion of macropores by accumulation of organic matter in the green surface is of particular importance in this process (Adams 1981; Canaway & Bennett 1986; Murphy *et al.* 1993b; Carrow 1995, 2004). Regular application of some form of cultivation/aeration treatment is considered a solution for the control of surface organic matter accumulation (Carrow 1992; Murphy 1990; Murphy & Rieke 1994; Murphy *et al.* 1993a; Shim & Carrow 1997).

The major changes caused by physical deterioration include reduced air-filled porosity, oxygen diffusion rate and hydraulic conductivity (Schmidt 1980; Agnew & Carrow 1985), increased rootzone bulk density, strength and water retention (O'Neil & Carrow 1983; Sills & Carrow 1983) and altered pore size distribution (Carrow 1980; Gibbs & Baker 1989). These effects are more serious in the upper layer (50-100 mm) of the rootzone (Baker 1988). All these physical changes will eventually result in poor visual and playing quality, less carbohydrate reserves, lower shoot density, a weed dominated sward, the excessive accumulation of thatch in the surface layer and reduced deep rooting (O'Neil & Carrow 1983; Agnew & Carrow 1985; Wiecko *et al.* 1993). For golf greens, most researchers have identified that infiltration rate, rootzone porosity, oxygen diffusion rate, moisture retention and organic matter content are the major factors controlling rootzone physical properties and the ability of the rootzone to provide adequate playing conditions (Baker & Richards 1993; USGA 1993; Murphy & Field 1996; Baker *et al.* 1997a, 1999a).

Under field conditions, the most relevant measurement of rootzone drainage capacity of golf greens is to measure water infiltration rate (Hind *et al.* 1995). In most instances, infiltration rate should be the primary criterion for evaluating rootzone physical properties of golf greens because it is of most importance to the player (Schmidt 1980; Baker 1988). Water infiltration rate, which is affected by the state of the immediate surface as well as by the hydraulic conductivity of the rooting media below (Daniells 1977), can be easily determined by the 'Ring Method' (Taylor *et al.* 1991). For golf greens, the single ring (large size) method can be used for measurement of infiltration rate because rootzone conditions of sports turf are generally uniform across the surface, compaction of the top layer is usually the most limiting layer for water infiltration, and lateral flow will have little impact on water transmission (Taylor *et al.* 1991).

There are two physical attributes that soils should possess to help plant growth remain successful. (1). Sufficient macropores to allow satisfactory drainage, aeration and unimpeded root extension. (2). Sufficient mesopores and micropores to resist gravitational drainage, but wide enough to release water to plant roots (Gibbs 1986; Vavrek 1992; Thien 1994). Rootzone porosity and pore size distribution are also important properties for assessing the physical performance of golf greens, both of which can be measured on a tension table (Carter 1993; Stewart *et al.* 2001). Air-filled porosity at -3, -4, -5 kPa moisture potentials belongs to the macropore group (Murphy & Field 1996). For golf greens, emphasis is commonly placed on these macropores (Baker & Richards 1993; Murphy & Field 1996; Baker *et al.* 1999a).

The measurement of macroporosity is an indirect measure of a rootzone aeration status because functional ability of rootzone pores for gas exchange and fluid flow is dependent on both their size and nature modified by the degree of pore continuity, tortuosity and stability (Gibbs 1986; Murphy & Field 1996). A more realistic approach to determine aeration status is to measure oxygen diffusion rate because of its close relationship with turfgrass growth (O'Neil & Carrow 1983; Murphy & Field 1996). Oxygen diffusion rate is a measure of oxygen supply to a point sink in the rootzone, commonly measured by platinum microelectrode method in the field (O'Neil & Carrow 1983).

Water retention capacity of rootzone, particularly for a sand-based rootzone, has a large influence on turfgrass growth and playing quality of sports turf (Snow 1992; Baker & Binns 2001a). It is largely dependent on rootzone compaction, composition and profile structure. In particular, organic matter content has a remarkable influence on the water retention capacity of sand-based rootzones (Baker 1984; McCoy 1992).

Bulk density was used as an important parameter for assessing putting green rootzone mixes before 1993 by the USGA (Hummel 1993). Based on several studies, bulk density measurement was dropped from the USGA recommendations in 1993 (Hummel 1993) because it was not a sensitive factor in predicting green performance (Waddington *et al.* 1974; Hummel 1993). However, bulk density is still considered as one of the important factors in rootzone physical studies because of its large effect on rootzone strength as well as its usefulness in defining rootzone relative compaction (Van Wijk 1980; Carter 1993; Murphy & Field 1996).

## 2.2.2 Effect of rootzone composition on rootzone physical properties of golf greens

### *2.2.2.1 Water infiltration rate (IR)*

The accepted water infiltration rate for golf greens to cope with most periods of intensive rainfall is ≥ 25 mm $h^{-1}$ in the USA (Waddington *et al.* 1974), and ≥ 20 mm $h^{-1}$ in the UK (Hind *et al.* 1995). Adams (1981) suggested that ideal field infiltration rates should approach 20 mm $h^{-1}$ to cope with expected rainfall events during the football season. A value of 10 mm $h^{-1}$ has always been regarded as the minimum for areas of good quality turf by many researchers (Gibbs & Baker 1989; Hind *et al.* 1995; Baker *et al.* 1997a).

Many studies have shown that infiltration rate increases greatly as the proportion of sand in golf green rootzones increases. This effect on infiltration rate is more evident under wear (Adams *et al.* 1993; Baker & Richards 1993; Lodge & Baker 1993). The most striking feature of infiltration rate is its fast decline over time, which takes place following the onset of wear on all types of golf green rootzones, leading to unacceptable water infiltration rate on soil-based and some low-grade mixed rootzones (Baker & Richards 1993; Lodge & Baker 1993; Baker *et al.* 1997a, 1999a). However, sand-dominant rootzones for golf greens are unlikely to reach a level of infiltration that results in regular water ponding (Baker & Richards 1993; Lodge & Baker 1993; Baker *et al.* 1997a, 1999a).

Studies have shown that surface capping (organic matter) and sealing (fine particles) are the key factors causing drainage deterioration on golf greens (Lodge & Baker 1993; Neylan & Robinson 1997; O'Brien & Hartwiger 2003). Adams (1981) calculated that the placement of a 5 mm deep fine textured crust ($K_{sat}$ = 0.001 mm $h^{-1}$) on a sand construction would reduce its apparent permeability from 44 mm $h^{-1}$ to 0.7 mm $h^{-1}$. Other researchers (Canaway & Bennett 1986; Baker & Hacker 1988; Carrow 1992, 2004a, b, c; Murphy *et al.* 1993b; Habeck & Christians 2000; Curtis & Pulis 2001) reported similar results under sports turf conditions. It is, therefore, important to initiate an early program of topdressing and cultivation to maintain infiltration rate on sports turf (Neylan & Robinson 1997).

### 2.2.2.2 Oxygen diffusion rate (ODR)

Compared with crops, turfgrasses have a wider tolerance range for oxygen availability (O'Neil & Carrow 1983; Murphy & Field 1996). Various ODR levels critical for turfgrass root growth have been reported (O'Neil & Carrow 1983; Van Wijk 1980). ODR values of $20\text{-}40 \times 10^{-8}$ g $cm^{-2}$ $min^{-1}$ have been regarded as the acceptable range for the growth of most turfgrasses (Stolzy & Letey 1964; Mclntyre 1970; Van Wijk 1980; O'Neil & Carrow 1983; Agnew & Carrow 1985; Murphy & Field 1996).

Studies have demonstrated a close relationship between ODR and air-filled porosity and bulk density (Murphy & Field 1996), and have shown the best agreement to be a fourth-degree exponential equation between soil porosity and gas diffusion (Thien 1994). Therefore, if rootzone compaction reduces air-filled pores to half their original values, gases will then diffuse through the soil 16 times slower than before the compaction (Thien 1994).

Rootzone moisture plays a key role in controlling the rate of exchange of $O_2$ (Carter 1993). Oxygen diffuses 64-104 times more quickly through air than through water or water film (Thien 1994). Smaller pores resulting from soil compaction are more likely to be blocked by water films, so a small reduction in pore size may greatly diminish the movement of gas through it (Murphy & Field 1996). A reduction in ODR with the profile depth is generally observed (Van Wijk 1980), which is caused mainly by a gradual increase in moisture content down the profile. In contrast, the ODR in the upper 50 mm is considerably lower than ODR at greater depths. This decrease is mainly due to blocking of the surface soil pores by roots and organic materials (Van Wijk 1980).

### *2.2.2.3 Rootzone porosity*

The USGA (1993, 2004) recommended that laboratory compacted materials for golf green rootzones should have a total porosity ($T_P$) of 35-55% and an air-filled porosity ($F_a$) at –3 kPa moisture potential of 15-30%. Under field conditions, Radko (1974) suggested the minimum limit of 15% for $F_a$ in sand culture. This is in contrast to the limit of 10% that several researchers had decreed as the minimum acceptable threshold for any turf medium, soil or sand-based (Adams *et al* 1971a; Gibbs & Baker 1989; Baker 1995). Experience in agricultural systems suggests that when the $F_a$ is less than 5%, poor soil structure will severely limit plant growth (Gibbs & Baker 1989). Therefore, in this thesis these three values can be primarily considered as minimum preferable (15%), minimum acceptable (10%) and minimum critical (5%) values respectively, with a top limit of 30%. These four values provide a series of threshold ranges against which rootzone performance can be judged.

Total porosity is a relatively invariant and constant factor (Carter 1993). Studies have shown that the sand-dominated rootzones have lower total porosity but higher air-filled porosity compared with soil-based rootzones. Neither of the two types of rootzones indicated serious total porosity problems at the 0-50 mm rootzone depth in most cases (Hind *et al.* 1995; Neylan & Robinson 1997). Rootzone compaction and plant root growth converts macropores into mesopores and micropores (Carrow 1995). This change may reduce total porosity only slightly, but its greatest impact is to shift the function of the surface rootzone layer from aeration to water storage by reducing the percentage of macropores (Vavrek 1992; Thien 1994; Baker 1995).

Air-filled porosity is greatly affected by rootzone composition, and quickly deteriorates with time (Schmidt 1980; Baker & Canaway 1990; Williams *et al.* 1992; Adams *et al.* 1993) though the decline rate is less than for water infiltration (Schmidt 1980). For example, air-filled porosity is generally greater with increased amounts of sand in the rootzone (Schmidt 1980; Baker & Canaway 1990). After only one season of wear, air-filled porosity has been shown to decrease below acceptable values in both sand-based and soil-based rootzones, leading to poor aeration and root growth (Williams *et al.* 1992; Adams *et al.* 1993; Hind *et al.* 1995).

Studies have suggested that blockage of air-filled porosity by roots and organic matter under compaction is the principal reason leading to poor aeration status of the surface profile (Adams & Saxon 1979; Lodge & Baker 1993; Carrow 1995; Neylan & Robinson 1997).

### *2.2.2.4 Water retention (WR)*

The recommended acceptable water content range for golf greens is 15-25% at –3 kPa for volumetric water content (VWC) (USGA 1993, 2004) and 12-18% at -4 kPa for gravimetric water content (GWC) (Baker & Richards 1993).

Water retention in the rootzone is generally higher on finer textured sands with higher contents of organic matter than on coarse sands with lower contents of organic matter (e.g. medium fine sands > mixed medium > coarse sands) (Baker & Canaway 1990; Baker *et al.* 1997a; Bigelow *et al.* 2001). However, studies showed that rootzone layers of distinctly different properties could dramatically affect rootzone water relations (Baker & Binns 2001a; Bigelow *et al* 2001). Taylor *et al* (1993, 1994) demonstrated the dual function of the blinding layer in controlling water drainage and retention in rootzones. The gravimetric moisture content in the rootzone was greatest where there was no blinding layer, intermediate with a coarse (1-5 mm) blinding layer and lowest with fine (0.25-2.0 mm) blinding layer (Taylor *et al.* 1993, 1994).

### *2.2.2.5 Organic matter content (OMC)*

The use of sand-dominated rootzones to increase drainage potential of golf greens over the past 20-30 years inevitably means that moisture and nutrient holding capacity are reduced (Baker 1984; Snow 1992; Joo *et al.* 2001). The current trend has been to add some form of organic/inorganic amendments into a specified sand to provide physical and chemical buffering capacities of a sand-based rootzone, improving water and nutrition retention, grass growth (e.g. the establishment) (Schmidt 1980; McCoy 1992b; Joo *et al.* 2001) and playing quality (e.g. enhance the surface stability and resilience) (Hurdzan 1987; McCoy 1992). However, inappropriate addition of organic matter into sand may cause many problems (e.g. an anaerobic soil development of black layer in the profile) (Gibbs 1992a).

If the added organic matter content into a sand-dominated rootzone is too high, a similar level of compaction will cause a more severe decrease in rootzone transmission abilities compared with pure sand because of the inter-packing action among sand and organic matter particles (Van Wijk 1980). The maximum incorporation rate (by weight) of organic matter in pure sand should be 3-3.5% (McCoy 1992). The recommendations of the USGA (1993) listed a target organic matter content for sand green rootzones of 1-5% by weight (ideally 2% - 4%), but after one year of testing, adjusted this range to between 0.7-3% by weight (Hummel 1994).

Similarly, subsequent accumulation of organic matter in greens' rootzones following establishment also should be sustained below 3-5% (w/w) (Murphy *et al.* 1993b; Habeck & Christians 2000; Curtis & Pulis 2001; Carrow 2004a, b, c). Adams and Saxon (1979) considered that organic matter begins to dictate rootzone physical properties when it exceeds about 12% by weight in the rootzone. About 5% by weight in the top 50 mm depth should be the objective (Adams 1986). Rapid accumulation of organic matter in the surface profile (0-50 mm) is considered as the principal problem in management of sand-based golf greens (Carrow 1995, 2004 a, b, c; Hind *et al.* 1995; Baker *et al.* 1999a; Habeck & Christians 2000; Curtis & Pulis 2001).

Besides incorporation ratio, the nature of organic amendment also has large effects on rootzone physical performance (Paul *et al.* 1970). Amendments like peat and manure decompose over time, and the decomposed products easily inter-pack within sand particles in a compacted sand-dominated rootzone (Petrovic *et al.* 1997), leading to poor rootzone transmission rates (Skirde 1974; Karlsson 1988). Compost is also commonly used as an organic amendment in golf green construction because of its availability and many benefits (Wilkinson 1994). Compared with other sources of organic materials, compost usually displays a consistent increase in conductivity with increasing rate of addition into sands (McCoy 1992). In contrast, Davis *et al.* (1970) reported that added composted bark into medium sands decreased saturated conductivity of the sands, but had little effect on the air-filled porosity or plant available water.

In recent years, various inorganic amendments (e.g. clinoptilolite zeolite and perlite) have received considerable interest from the turf industry (Hummel 1993; Joo *et al.* 2001). These products have similar physical characteristics to sand and are claimed to be slow to break down (Joo *et al.* 2001). Petrovic (1990, 1993), and Neylan and Robinson (1997) found that amending sand with clinoptilolite zeolite (5-10% by weight, particle size between 0.1-1 mm) could provide an ideal environment for golf greens. The amendment resulted in a high resistance to compaction; rapid infiltration rate; increased establishment rate (as effective as peat in improving establishment) and shoot growth; adequate aeration for deep rooting; increased cation exchange capacity, nitrogen and phosphorus accumulation; protection of the rootzone from excessive nitrate and potassium leaching; and conservation of water through a better moisture holding capacity. Similar results have been achieved by others (Ferguson *et al.* 1986). In New Zealand, Yang *et al.* (1998) found that amending medium-coarse sands with zeolite (6%, w/w) had beneficial effects on both rootzone physical and chemical properties, but no beneficial effect could be justified with a similar proportion of zeolite was added to fine sand. Myer *et al.* (2003) concluded that medium-coarse sands amended with zeolite (10%, v/v) were able to buffer against nutrient and moisture stress for up to two weeks.

The potential problem for zeolite is the uncertainty of the long-term stability of its crystalline structure in the rootzone (Petrovic 1993). Quantitative information on the effects of zeolite on root growth is also limited.

### 2.2.2.6 Bulk density ($D_b$)

The former USGA specifications for golf green rootzone constructions gave a very wide acceptable range for $D_b$ (1.2-1.6 t $m^{-3}$) (Hummel 1993). A *critical* $D_b$ should be definable for a particular soil, above which plant vigor will decrease. For medium to fine-textured soils, a $D_b$ of 1.5-1.6 t $m^{-3}$ is critical for root growth of most plant species (Rimmer 1979). For most mineral soils, the *critical* $D_b$ is $\geq$ 90% of the *reference* $D_b$ compared with the *optimum* $D_b$ that is generally $\leq$ 87% of the *reference* $D_b$ (Soane 1990). The *reference* $D_b$ is basically a maximum value, which usually can be obtained under a static pressure of 200 kPa (Hakansson 1990).

In New Zealand, Murphy and Field (1996) found that at a relative compaction (a given $D_b \div$ *reference* $D_b$) of 90% there was a sharp break in species dominance on sandy loam racetracks. Below 90% desirable deep-rooted perennial ryegrass dominated. However, above 90% shallow-rooted meadowgrass species (*Poa trivialis and P. annua*) were dominant. A relative compaction of around 90% is a critical upper limit above which the vigor of most turfgrasses is severely restricted (Murphy & Field 1996).

Thien (1994) found that sandy soils have the highest uncompacted bulk densities and change the least when subjected to compaction. Clayey soils have the lowest uncompacted bulk densities and will change the most as a result of compaction (Thien 1994). For sand-clay mix rootzones, the $D_b$ value increases considerably with clay content. At and over 13% clay content, the $D_b$ hardly increases any further. The filling up of the intergranular spaces with fine particles may cause the initial larger increase in $D_b$ under rootzone compaction (Thien 1994).

Organic matter content is a major factor affecting bulk density. For some rootzones, organic matter has a completely dominating effect on bulk density and measurement of organic matter content can be used to predict bulk density (Adams 1973). Lower $D_b$ values in the upper layer (0-25 mm) of sports turf rootzones can be explained by higher organic matter content and much more structured root mass (Van Wijk 1980).

Greater rates of change in $D_b$ under rootzone compaction action are associated with intermediate water contents (moist range) (Carter 1993). This means that moist soils will compact more than dry or wet soils (Karlsson 1988). However, proper turf management requires maintaining soil water content in the moist range (i.e. at field capacity) (Adams & Gibbs 1994; Thien 1994).

### 2.2.3 Effect of cultivation/aeration treatment on rootzone physical properties of golf greens

Cultivation/aeration is briefly defined as mechanically disturbing the rootzone or thatch layer by punching or slicing various types and depths of holes or fissures into turf surface to improve overall rootzone quality and turfgrass performance without destroying the turf (Bunnell & McCarty 2001). The use of cultivation/aeration practices on sports turf has received significant attention for the past 25-30 years (Rieke &

Murphy 1989; Wrigley 1998a). Golf greens established on sand-based rootzones also require regular cultivation/aeration treatment, preferably combined with sand topdressing to minimize the negative effects of organic matter accumulation on rootzone physical properties (Canaway *et al.* 1986). Improvements in rootzone compaction, water infiltration, oxygen diffusion rate, rooting depth, thatch reduction, and overall green quality are potential benefits from various cultivation/aeration methods (Bunnell & McCarty 2001). Studies on cultivation/aeration equipment introduced in recent years for golf green management are briefly reviewed in the following section.

#### *2.2.3.1 HydroJect (HJ)*

HydroJect (high pressure water injection cultivation) is a recently developed technique (introduced in 1990), which uses short bursts of high-velocity, high-pressure (e.g. 5,000 psi) water injection to cultivate soil to various depths (Murphy & Rieke 1994). It is designed primarily for use on putting greens as mid-season cultivation equipment, and leaves the green surface virtually undisturbed, and entry holes that are nearly invisible shortly after treatment (Murphy 1990).

The HydroJect appears to alter rootzone physical properties deep in the profile, and has been shown to be equal or superior to hollow tine cultivation in reducing bulk density and increasing porosity and saturated hydraulic conductivity in the surface layer (Vavrek 1992; Murphy & Rieke 1994). Murphy and Rieke (1994) showed that it could increase total porosity in the 76-152 mm layer, and provide a significant reduction in rootzone strength in 70-100 mm layer (three treatments per year). A study conducted on fine sandy loam golf greens under New Zealand conditions showed that HydroJecting resulted in alleviation of compaction and an improvement in infiltration rates two weeks after cultivation, though this effect had disappeared after eight months (McAuliffe *et al.* 1993). In contrast, other studies have found that HydroJecting, with very little subsurface fracture and surface disruption, has no significant effect on surface hardness, rootzone aeration and infiltration rate (Bunnell *et al.* 2001; Bunnell & McCarty 2001).

### 2.2.3.2 Scarification (S)

The aim of scarification is to produce a sward with an erect growing habit, to control flat weeds, and particularly to limit the accumulation of excess organic matter (thatch) in the surface of sports turf (Karlsson 1988). On coarser turf it may suffice to carry out scarification once or twice a year, while a fine turf requires one to four scarifications per month (Perris 1984, cited in Karlsson 1988).

Canaway *et al.* (1986) found that pre-season scarification (on a sand rootzone) did not increase water infiltration rate, either at the time, or during the subsequent months. Limited published information is currently available on the effect of scarification on other rootzone physical properties.

### 2.3.3.3 Verti-drain (VD)

The Verti-drain was developed in the Netherlands in the late 1970's, introduced to Britain in 1982 and into the USA in 1987. Verti-draining is now in widespread use on sports turf throughout the UK, Europe, North America, Australia and New Zealand (Way 1991). The Verti-drain is a power-driven unit using solid or hollow tines (12-25 mm in diameter) able to penetrate the rootzone to a depth of 300-400 mm. It is primarily designed to address deep-seated compaction (e.g. cultivation hard pan) and to improve rootzone drainage. The tines penetrate, pivot and withdraw, which allows for greater loosening action deeper in the profile with relatively little turf or rootzone surface disruption (Carrow 1992; O'Brien 1994; Baker *et al.* 1999).

Studies have shown contradictory effects of Verti-draining in reducing bulk density, rootzone strength and penetration resistance, and in increasing macroporosity and infiltration rate of sports turf. The effects have usually been short-lived and largely dependent on rootzone moisture content when the cultivation was carried out (Baker *et al.* 1999; Bunnell & McCarty 2001). For example, several studies showed that Verti-draining conferred little improvement in infiltration rate (Shim & Carrow 1997) and oxygen diffusion rate (Bunnell & McCarty 2001). In contrast, other studies showed that Verti-draining, with deep penetration and loosening action in the profile, increased infiltration rate and macroporosity, decreased bulk density and penetration resistance, and the effect lasted from two weeks to ten months (Carrow 1992; Lee & Rieke 1993; McAuliffe *et al.* 1993; Shim & Carrow 1997).

The Verti-drain can also be used on golf greens as a deep cultivation technique. However, research data to demonstrate the magnitude and duration of the effectiveness of Verti-draining in reducing rootzone strength or increasing water percolation on golf greens is relatively limited (Shim & Carrow 1997).

### 2.2.4 Summary

Rootzone composition has a large influence on rootzone physical properties of golf greens. Most improvement in rootzone physical properties of golf greens has come about by improving rootzone composition, especially by utilizing sand as a basic construction medium. Many rootzone physical criteria have been developed as authoritative guidelines for golf green construction and maintenance. However, it appears that there is relatively limited published information currently available on: (a) the relative advantages and disadvantages between a standard USGA profile and the current alternatives for golf green rootzone constructions (e.g. partially amended sand rootzones either with or without a zeolite amended sand layer; pure sand rootzone) in terms of the overall rootzone physical performance and the physical deterioration under long-term field conditions; (b) effects of rootzone composition on oxygen diffusion rate.

Cultivation and aeration have both positive and negative effects on rootzone physical properties though these effects are usually short-lived. Previous studies on effects of cultivation/aeration treatments on rootzone physical properties have mainly been conducted on winter game pitches constructed with soil-based, or sand-soil mixed rootzones. Results of earlier studies are often contradictory. There is relatively little published comparative information on the effectiveness of physical cultivation/aeration equipment (e.g. HydroJect, Verti-drain and scarification) on the control of the rootzone physical deterioration of golf greens constructed with sand-based rootzones in the cool, humid zones typical of New Zealand.

# 2.3 EFFECT OF ROOTZONE COMPOSITION AND CULTIVATION/AERATION TREATMENT ON SWARD CHARACTERISTICS OF GOLF GREENS

## 2.3.1 Introduction

Species composition, turf cover, root distribution, dry patch severity and sward density/uniformity are factors that can be used to assess turf sward characteristics. These characteristics are greatly controlled by rootzone composition and subsequent management and usage (e.g. wear intensity), and they have a large influence on a green's visual attractiveness and playing quality (Lodge & Lawson 1993; Baker *et al.* 1995, 1997b). For example, poor rootzone physical conditions will lead to poor visual quality and turfgrass growth, which is reflected in lower carbohydrate reserves, lower shoot density, an annual poa-dominated sward, excessive accumulation of root mass in the surface and reduced deep rooting (O'Neil & Carrow 1983; Agnew & Carrow 1985; Rieke & Murphy 1989; Wiecko *et al.* 1993). Some cultivation/aeration treatments can improve turfgrass growth by reducing rootzone compaction, thatch or waterlogging (Beard 1973; Murphy *et al.* 1993a).

In New Zealand and UK, most golf greens are established with a fescue/bent mixture, i.e. a traditional 80/20 of *Festuca/Agrostis* sward (Baker *et al.* 1997b). The relative proportion of the two species in a sward will change depending on rootzone composition, resultant soil physical/chemical properties (e.g. pH, soil water and nutrient conditions) and maintenance practices (Lodge *et al.* 1991; Baker *et al.* 1995, 1997b; Lawson 2000). Establishment and subsequent maintenance of such a sward is a delicately balanced process and it is a continuous struggle to achieve the optimum balance between the two sown turfgrasses (Lodge *et al.* 1990).

Turf cover will affect the visual and playing quality of golf greens. It is also an attribute of surface stability of sand-based rootzones (Adams *et al.* 1985; Gibbs *et al.* 1989). Good quality for golf greens requires maximizing the coverage of turfgrasses and minimizing the bare-ground and, therefore invasion of weeds (e.g. annual poa, moss and some flat weeds).

Root mass and distribution is very important for the rate of uptake and amount of water and nutrients absorbed, for synthesis and transportation of certain regulators and for sinkage of carbohydrates within turfgrasses (Carrow 1989). A prerequisite for a sports turf to perform well is the requirement for deep and healthy root systems to explore a rootzone volume large enough to supply sufficient growth. In many cases, the below-ground component forms a greater proportion of turf phytomass and provides resources by which turf can recover from excessive wear, close mowing and harsh weather conditions (Parr *et al.* 1984). For sports turf, roots also contribute to the surface stability, resilience and shear strength (Van Wijk 1980; Adams *et al.* 1985; Gibbs *et al.* 1989). It appears that the effect of rootzone composition and cultivation/aeration treatment on root growth of golf green turf has received very little attention in the literature (Hannaford & Baker 2000). An exception is the recent study in the UK by Hannaford and Baker (2000), which examined the effect of sand and amendment type, and their mixed rate on root development under golf green conditions.

Dry patch, commonly termed localized dry spot (LDS), may be defined as an irregular turf area appearing to be drought stressed through lack of available water (Wallis & McAuliffe 1988; Tucker *et al.* 1990; York & Baldwin 1992). It is mainly due to water-repellent organic matter (a product of fungal activity and/or organic matter breakdown) coatings being deposited onto sand grains (Wallis & McAuliffe 1988; Tucker *et al.* 1990; York & Baldwin 1992). Dry patch, which can greatly reduce turfgrass root growth, turf visual quality and playability, is a widespread problem in the management of sand-based golf greens in UK and New Zealand (Wallis & McAuliffe 1988; York & Baldwin 1992; York 1993). In the USA, it is considered as an advanced stage of summer bentgrass decline (Karnok & Tucker 2001). Hallett *et al.* (2001) reported that water repellency tended to be persistent once established because few native microorganisms were able to degrade hydrophobic organic matter in rootzones.

## 2.3.2 Species composition and turf cover

Studies have shown that although rootzone composition can have no significant effect on species composition on newly constructed golf greens, it can greatly affect establishment and disease resistance. For example, seedling establishment is often noticeably worse on pure sand rootzones. The severity of take-all patch disease, which infects only *Agrostis*, has been shown to be worse on amended sand rootzones than on pure sand rootzones, with disease incidence negligible on soil-based rootzones (Baker *et al.* 1997b). There is little published information on the primary catalyst for inducing take-all disease on the amended sand and pure-sand rootzones.

For old golf greens ($\geq$ 5 years), species composition has been closely related to the rootzone type. Baker *et al.* (1995) showed there was a general trend for increased *Festuca* content as the sand content, macroporosity increased and as clay content and retention capacity of nutrients and moisture in rootzones decreased. The highest proportion of *Festuca* was found on pure-sand rootzones, whilst the lowest was recorded on soil-based rootzones. However, a reverse pattern was reported for *Agrostis* (Lodge *et al.* 1991; Baker *et al.* 1995, 1997b). This is because the fertility requirements for *Festuca* are lower than for *Agrostis*, and *Festuca* is better adapted to drier conditions (Adams 1975; Baker *et al.* 1997b). Influences of rootzone composition, soil pH and organic matter content on availability of nutrients and water have been proposed as major factors controlling species composition of fine turf (Lodge & Lawson 1993).

*Poa annua*, a dominant turf weed on golf greens, is often associated with problems of disease susceptibility, drought stress, thatch formation (Gibeault 1965; Beard *et al.* 1978; Peel 1982; Baldwin 1993; Baker *et al.* 1997b), and poor visual and playing quality (Canaway & Baker 1992; Baker *et al.* 1997b). The effect of rootzone composition on *P. annua* is similar to that of rootzone composition on the *Agrostis*, but opposite to that on the *Festuca*. Lodge *et al.* (1991), and Lodge and Lawson (1993) showed that the ingress of *P. annua* into a *Festuca/Agrostis* sward occurred mainly on soil-based rootzones and that higher nitrogen and lime input enhanced the rate of ingress.

Species composition also changes with age and usage of golf green. In UK studies, the proportion of *Agrostis* and *P. annua* continued to increase whilst *Festuca* declined with age and wear in both sand and soil-based rootzones. The rate of this change was enhanced by nitrogen application (Lodge *et al.* 1990; Baker 1991; Baker *et al.* 1995; Baker *et al.* 1997b, 1999b). Baker *et al.* (1997b, 1999b) considered that a higher proportion of *Festuca* in the traditional UK seed mixture (80:20 of *Festuca:Agrostis*, w/w) might produce a sward with too much *Festuca*, and in the long run would inevitably lead to severe ingress of *P. annua* in the sward under wear on sand-dominated rootzones. This implies that a lower ratio of *Festuca* in the seed mixture may be more appropriate when used on sand-dominated golf greens. Lodge and Lawson (1993) found that (a) on pure sand rootzones, the cover of *Festuca* showed an overall decline over time while the cover of *Agrostis* generally increased and *P. annua* remained relatively low; (b) on a USGA profile, *P. annua* remained virtually absent throughout the trial period, and *Agrostis* increased markedly as *Festuca* declined; (c) on soil-based rootzones, the cover of *Festuca* (initially low) and *Agrostis* (initially high) continued to decline over time, and *P. annua* content greatly increased.

Lodge and Lawson (1993) also found that on pure sand rootzones, the decline in turf cover over time took place chiefly at the expense of *Festuca*, while on USGA and soil-based rootzones, the turf cover remained relatively constant. Baker *et al*. (1997a) found that after 25 years most of the sand-dominated greens had live grass cover of < 80%. Thus, the 80% can be regarded as the minimum acceptable turf cover of golf greens in this thesis.

Cultivation/aeration can be injurious to turf quality (Engel & Alderfer 1967; Bunnell & McCarty 2001), but others indicate cultivation/aeration benefits turf quality in the long-run (Murphy *et al*. 1993a). Bunnell and McCarty (2002) reported that Verti-draining reduced visual turf quality for 2-3 weeks following treatment, but the less aggressive techniques such as HydroJecting resulted in excellent turf quality. Little published information is available on the effect of cultivation/aeration treatment on species composition and turf cover of golf greens.

### 2.3.3 Root development

Hannaford and Baker (2000) found that sand particle size (e.g. medium and medium-coarse sand) and organic amendment type (e.g. topsoil, fensoil and peat) of rootzones had large effects on rooting depth in sand-dominated golf greens, but amendment-mixing rate had no significant effect on root development. For example, rooting was deepest in peat-amended sand-based rootzones, intermediate in fensoil-amended and shallowest in topsoil-amended, and the medium-coarse sand rootzones generally had a deeper rooting than the medium sands (Hannaford & Baker 2000). This implies that deep rooting is associated mainly with the level of macroporosity of the rootzones. Ferguson *et al*. (1986) reported that amended sand with zeolite (5-10% by volume) might increase both root growth and turf quality.

A layered structure of a rootzone also affects root development in the profile. Leboucher (1989) showed that plant roots were usually not able to progress normally and regularly if the substrate of the rootzone was composed of several layers with different textures. For example, if different rootzone layers had been compacted to different extents, or the texture between rootzone layers was quite different, root growth of turfgrasses showed a sudden change at the surface between two layers. Plant roots tend to grow in a more superficial layer, richer in nutrients, moisture and air.

Under sports turf conditions, most of roots are found in the upper 0-50 mm of the profile (Lemaire & Bourgoin 1981; Canaway 1984). There is a regular decrease in root density from the surface down the profile (Van Wijk 1980). For example, under sports field conditions with a sand-soil mixed rootzone, about 84% to 99% (Van Wijk 1980) of root mass is distributed in the upper 50 mm. It is proposed that this phenomenon is caused mainly by close and frequent cutting as well as by poor oxygen supply and saturated soil water conditions lower in the profile (Van Wijk 1980).

Several studies have shown that root biomass progressively increases with turf age (Canaway 1984), and that rooting depth reduces with time in sand culture (McAuliffe & Wells 1988; Carrow 1995). This phenomenon has important implications for sports turf management because excessive accumulation of roots in the surface layer (0-50 mm) not only limits turfgrass capacity for water and nutrient uptake from lower in the profile, but it also may give rise directly to an accumulation of thatch (Agnew 1993; Couillard *et al.* 1997).

Regular surface scarifying can minimize thatch accumulation (Field & Murphy 1991). However, White and Dickens (1984) found that for a sandy loam golf green planted with Bermudagrass (*Cynodon dactylon* L. *Pars*), biweekly vertical mowing provided no more thatch control than the twice-yearly application.

Murphy and Rieke (1994) found that regular HydroJecting maintained a lower mass of thatch, possibly because enough soil being moved into the thatch layer with water injection, thus creating an improved environment for thatch decomposition. HydroJecting leads to less loss of crown tissue and encourages deeper root penetration of turfgrasses, e.g., root number below the 200 mm depth is increased by HydroJecting (applied 2-3 times per year) (Vavrek 1992; Murphy & Rieke 1994). In contrast to hollow tine cultivation, HydroJecting did not reduce surface root weight density

(Murphy & Rieke 1994). Bishop (1990) recommended it should be used in conjunction with the traditional aerification programs.

Carrow (1992) found that Verti-draining (using solid tines) increased root growth at the 300-600 mm rootzone depth, but decreased root mass at 0-300 mm. This was probably because Verti-draining decreased the adventitious rooting in the surface 25-50 mm. The implication for this is that vigorous Verti-draining should be timed just prior to periods of maximum root growth whenever possible. However, another study (Carrow & Shim 1997) showed that Verti-draining (four times per year) often decreased root length density at the 200-600 mm depth because of mechanical injury to existing roots, but root efficiency (mm water uptake per cm root) in the zone increased because of greater root viability of the remaining roots in response to lower rootzone strength. McAuliffe *et al.* (1993) found that HydroJecting and Verti-draining (once per year) had no significant influence on root mass in the 50-100 mm depth throughout the eight-month experiment period.

## 2.3.4 Dry patch severity

Tucker *et al.* (1990) found there was no relationship evident between normal management practices (e.g. fertilizers and pesticides application) and the severity of dry patch disorder, or any difference between localized dry spots and adjacent healthy areas in rootzone chemical properties. However, sandy rootzones have been found to be most prone to severe repellency because sand particles have a relatively low 'specific surface area', and are more readily coated by the organic materials (Wallis & McAuliffe 1988). Baker *et al.* (1999a) found that the worst affected rootzones by dry patch consisted of medium-coarse sand typically containing peat and soil amendment at mixing ratios of 90:10 and 80:20 compared with medium sand containing soil amendment at higher mixing ratio of 70:30. Dry patch becomes most pronounced when soil becomes dry over the hot summer (Wallis *et al.* 1989a, b). Water repellency has been found to decline with increasing soil water content (Wallis & McAuliffe 1988). Therefore, more frequent irrigation of affected areas is helpful in temporarily alleviating dry patch (Paul & Henry 1973).

Wetting agent treatment of dry patch is the most effective and commonly used practice on golf greens despite its cost (Wallis & McAuliffe 1988; Wallis *et al.* 1989b; Karnok

& Tucker 2001). For example, a single application of wetting agent on water repellent sand-based golf greens established with creeping bentgrass greatly improved the colour, visual quality and root length (Karnok & Tucker 2001) as well as increased infiltration rate and rootzone moisture content (Morgan *et al.* 1966; Leinauer *et al.* 2001). Research has shown that rootzone hydrophobicity can be more severe in the top 30-50 mm of a profile, and in some cases the upper 80-100 mm of rootzone can be water repellent (Wallis *et al.* 1989b; Tucker *et al.* 1990; Baker *et al.* 1999a). Therefore, a surface water flush (with wetting agent) alone is not enough for dry patch control. The humic and/or fluidic acid coating of the sand particles has been shown to cause hydrophobic soil associated with localized dry spots (Roberts & Carbon 1972; Miller & Wilkinson 1977). So, an application of 0.1 *M* NaOH sufficient to saturate the upper 50 mm of soil, followed by a water flush of one pore volume, could significantly reduce the hydrophobicity if repeated three or more times (Karnok *et al.* 1993).

Soil fungi are the component of the microbial community that also causes water repellency (Hallett *et al.* 2001). In recent years, long-term strategies based on manipulating the microbial community in rootzones have suggested that bio-control may be a potential tool against water repellency. Research in this area is based mainly on additions of specific microorganisms to rootzones that are able to degrade hydrophobic organic materials (Roper 1994). Another study has tested the application of slow-release fertilizers to rootzones in order to stimulate indigenous microorganisms that are able to degrade hydrophobic substances (Franco *et al.* 2000). Whilst both approaches have been shown to offer potential control against water repellency in laboratory studies, at present neither has been proven effective under field conditions (Hallett *et al.* 2001).

Studies have shown that the HydroJecting is effective in minimizing the incidence of dry patch disorder when used in conjunction with a proprietary wetting agent (Murphy & Rieke 1994; Karcher *et al.* 1996, 2001) though quantitative information is still limited for golf greens. Moreover, little published information is currently available on the relationship between dry patch severity and other cultivation/aeration treatments on golf greens.

## 2.3.5 Summary

Studies have shown that pure sand rootzone is generally associated with difficulty in initial establishment, susceptibility to certain diseases and incidence of dry patch disorder. These disadvantages can be improved by amending sand with organic amendments or by appropriate management. For example, HydroJecting when used in conjunction with a proprietary wetting agent, may minimize the dry patch disorder. In contrast, the soil-based rootzone tends to be associated with shallow root distribution and a weed (e.g. *P. annua*) dominated sward. These issues are very difficult to correct through management practices under golf green conditions.

The relative balance of the two sown turfgrasses *Festuca* and *Agrostis* is greatly influenced by rootzone composition of golf greens. The availability of soil water and nutrients is considered the main factor determining this balance. The gradual decrease of *Festuca* with time and usage (i.e. wear) on sand-dominated rootzones will lead to weed invasion and poor stability of the green surface.

However, little published information is available on (a) the relative advantages and disadvantages of the standard USGA profile, the pure sand rootzone, and the proposed partially amended sand rootzones in terms of root development and other sward characteristics; (b) effects of cultivation/aeration treatment on species composition, turf cover, visual quality and dry patch disorder under golf green conditions; (c) authoritative guidelines for evaluating sward characteristics in terms of root distribution, relative balance of the sown turfgrasses, dry patch severity and turf quality index. In particular, it appears that the effect of rootzone composition on root growth has received very little attention in golf green research. Findings on the effects of cultivation/aeration (e.g. Verti-drain and HydroJect) on root development are often contradictory. Quantitative information on effects of zeolite amendment on root development within sand-based rootzones is limited.

## 2.4 EFFECT OF ROOTZONE COMPOSITION AND CULTIVATION/AERATION TREATMENT ON PLAYING QUALITY OF GOLF GREENS

### 2.4.1 Introduction

The playing quality of golf greens can be measured to provide a direct empirical assessment of golf green performance. Objective measures, standards and specifications are then formulated for the construction, maintenance and surface preparation of golf greens (Canaway & Baker 1993).

Playing quality is essentially an abstract concept based on player perception of how a surface 'plays'. However, certain objective measures can be made on playing surfaces, which correlate with player perception. Playing quality for any sport turf can normally be subdivided into a number of components. For golf greens, the player/surface interaction is not important, only the ball/surface interaction is critical (Baker 1994). Ball response for any given shot, with its specific velocity, spin and approach angle, is influenced by ball/surface friction, and the hardness of the green surface in terms of the amount of deformation that occurs and the contact time between the ball and the turf (Haake 1991b; Baker & Richards 1991; Lodge 1992). Two of the most important components of the playing quality of golf greens are ball roll properties and ball impact properties (Canaway & Baker 1993; Baker1994).

Ball roll resistance determines ball roll properties. Ball rolling resistance is considered as a force acting at the point of contact between the ball and the surface whose direction is opposite to that of motion, and thus causes a deceleration of the ball as it moves across the surface. It is usually expressed indirectly in terms of ball deceleration or the distance rolled by the ball. On golf greens, ball roll properties are commonly expressed as ball roll distance (i.e. green speed) (Baker 1994). In the last 40 years, increasing emphasis has been placed on the speed of golf greens (Engel 1984; Baker 1994). Various methods and equipment have been devised for evaluating the green speed (Beard 1973). However, the Stimpmeter, released by the USGA in 1978, has become the most widely used tool for its assessment (Radko 1977, 1978, 1980). A correction method developed by Brede (1991) is often used if the slope of green along the path of ball roll is > 6°, or the difference between the averages of the two series of rolls differs by more than 20% (Baker *et al.* 1997a).

The processes of ball impact on a surface are complex and are governed primarily by ball rebound resilience (the energy returned to the ball after impact), the surface hardness (the amount of deflection for a given force), the amount of spin which is retained after impact through ball/surface friction and the shot played (the ball approach angle, velocity and the original backspin) (Baker 1994). Most of the published work on ball impact properties has been restricted to the last two decades (Baker 1994). One of the commonly used methods for determining ball impact properties of golf greens is through measuring the green surface hardness.

Measurements of surface hardness depend mainly on the assumption that values of impact forces, deceleration and deformation are highly dependent on the drop mass, drop height and the hardness of the surface dropped on (Baker & Canaway 1993). By dropping missiles from a constant height and using a constant mass, different surface hardness readings can be compared (Rogers & Waddington 1991). A wide range of techniques has been developed for hardness measurements on turf surfaces (Baker & Canaway 1993). The Clegg Impact Soil Tester (CIT) introduced by Clegg (1976) is the most widely used method for determining natural turf hardness characteristics (Lush 1985; Baker & Canaway 1993). Units are recorded in CIV's (*Clegg Impact Value*) and converted to $g_{max}$ (peak deceleration) using the equation [$g_{max}$ = 10(CIV)] (Bunnell & McCarty 2001). The 2.25 kg hammer was originally developed to simulate the impact energy of a person running or falling, while the 0.5 kg hammer was developed to simulate ball bounce on the surface and is considered more sensitive than 2.25 kg hammer for determining variations in sward characteristics (e.g. cutting height and turf cover) (Rogers & Waddington 1989, 1992, 1993). Thus, the 0.5 kg hammer can be considered suitable for the study of effects of sward characteristics, while the 2.25 kg hammer can be considered suitable for the study of effects of rootzone composition and aeration treatment on playing quality of golf greens.

### 2.4.2 Ball roll distance (green speed)

Several studies have been carried out to evaluate effects of rootzone composition and sward characteristics on green speed. Studies have shown that green speed can be related to a wide range of turf characteristics such as species composition and cultivar type (Canaway & Baker 1992), fertilizer input (Colclough 1989; Lodge & Baker 1991), cutting height (Engel *et al.* 1980) and topdressing (Radko 1980). Findings included: (a) The type of amendments added into sand rootzones was the most important rootzone factor in affecting ball roll distance, with significantly higher values typically recorded for peat and soil amended rootzones (Baker *et al.* 1999c). (b) Effects of sand type, mixing ratio of amendment/sand and rootzone type were not significant (Rieke *et al.* 1996; Baker *et al.* 1999c).

The ratio of sand to soil, or the type of sand, had little effect on green speed except during wet seasons when rolling distance was greater on high-grade sand-dominated rootzones than on soil-based and other mixture rootzones according to Baker and Richards (1991). In contrast, Lodge and Baker (1991) reported that pure sand constructions produced consistent and the fastest putting surfaces, whereas soil constructions produced the slowest surfaces throughout the year. Canaway and Baker (1992) found that surface rootzone moisture content decreased green speed, and that there was a negative correlation between moisture content and green speed.

Species composition have been shown to have a large effect on green speed, with *Festuca* providing the fastest surface, *P. annua* consistently producing the slowest and *Agrostis* being intermediate (Canaway & Baker 1992). The green speed category for regular membership play in the USA (Radko 1980; Canaway & Baker 1992) is given in Table 2-1, and the proposed playing quality limits in the UK (Baker *et al.* 1996; Baker 1998) are given in Table 2-2.

Cutting height, like rolling, is a very important factor in controlling green speed, and has been shown to be inversely related to ball roll distance ($r > 0.9$) (Engel *et al.* 1980; Rogers & Waddington 1989; Canaway & Baker 1992; Richards & Baker 1992). Close mowing contributes to faster greens (Busy & Boyer 1997).

Rolling that decreases sward height has been shown to significantly increase green speed by 11% within 24 hours and 6% within 48 hours compared with non-rolled greens (Rieke *et al.* 1996; Mooney & Baker 2000; Nikolai *et al.* 2001). HydroJecting can increase putting green speed immediately following the treatment by way of decreasing surface irregularities (Murphy & Rieke 1994; Karcher *et al.* 1996, 2001).

### 2.4.3 Green surface hardness

Rootzone composition has been shown to have greater effects on surface hardness than on green speed (Baker *et al.* 1999c). Research has shown that hardness values are more consistent on sand-dominated rootzones, whereas the rootzones with a high soil component tend to be soft in wet and hard in dry soil conditions (Baker & Richards 1991; Lodge & Baker 1991). Baker *et al.* (1999c) showed that surface hardness was greater for a low ratio (10:90) peat/sand rootzone than for a high ratio (20:80 or 30:70) rootzone. In contrast, other studies found that the effects of the type of sand, rootzone or amendment on surface hardness were not significant (Baker *et al.* 1996; Neylan & Robinson 1997; Richardson & Karcher 2001).

**Table 2-1 USGA classification of green speed for regular membership and tournament play** (Adapted from Radko 1980)

| Level | Category | Distance rolled (m) |
|---|---|---|
| **Regular membership play** | Fast | 2.59 |
| | Medium fast | 2.29 |
| | Medium | 1.98 |
| | Medium slow | 1.68 |
| | Slow | 1.37 |
| **Tournament play** | Fast | 3.20 |
| | Medium-fast | 2.90 |
| | Medium | 2.59 |
| | Medium-slow | 2.29 |
| | Slow | 1.98 |

**Table 2-2 Proposed limits for interpreting the playing quality of golf greens under British conditions** (Adapted from Baker *et al.* 1996; Baker 1998)

| Parameter | Test method | Normal range | Accepted range |
|---|---|---|---|
| **Green speed (m)** | Stimpmeter | 1.6-2.8 | 1.5-3.0 |
| **Hardness (gravities)** | Clegg Impact Soil Tester 0.5 kg hammer dropped from 0.3 m | 70-100 | 55-120 |
| **Stopping distance (m)** | "Five iron" simulation (Angle 53°, velocity 22.7 m $s^{-2}$, backspin 750 rad $s^{-1}$) | 0.5-5.0 | -0.5-8.0 |
| **Stopping distance (m)** | "Nine iron" simulation (Angle 53°, velocity 18.8 m $s^{-1}$, backspin 880 rad $s^{-1}$) | 0.0-2.0 | -1.0-3.5 |
| **Surface evenness (mm)** | Profile gauge | ≤ 1.0 | ≤ 1.25 |

Baker *et al.* (1997a) found that surface hardness decreased with the progression of wear and time. Five years following establishment, hardness values (by 0.5 kg hammer) were all below the suggested UK limit of 55 gravities on both peat and fensoil amended sand golf greens (Baker *et al.* 1996).

Low hardness values have been obtained from sports turf (i.e. athletic fields) with a high moisture content, dense grass cover, presence of thatch and low soil bulk density, while higher values have been obtained from dry, high bulk density and compacted rootzones with less turf cover (Rogers & Waddington 1991). Rootzone moisture content, which was shown to be negatively correlated with the hardness value ($r^2$ = 0.92), was considered the key factor causing this large variation in surface hardness of sports turf (i.e. athletic fields and lawn tennis courts) (Rogers & Waddington 1989; Newell & Wood 2000). Neylan and Robinson (1997) reported that although the highest Clegg reading was sometimes recorded immediately after heavy rolling (on golf greens), manipulation of rootzone moisture content was more important than rolling in providing a harder surface (on lawn tennis courts) (Newell & Wood 2000). Newell and Wood (2000) found a 5.5 gravities decline in surface hardness for every 1% increase in moisture content for lawn tennis courts. Lodge (1992) found that increased irrigation rate produced harder surfaces on pure sand rootzones, but softer surfaces on the USGA and soil-based rootzones. Gibbs *et al.* (1993) shown that the negative correlation between the hardness values and rootzone moisture content became weak as the sand content increased in a sand-soil mixed rootzone of soccer pitch.

At low rootzone moisture content, factors such as rootzone compaction and sward characteristics become more important in affecting surface hardness of sports turf (i.e. athletic field) (Rogers & Waddington 1992). Newell and Wood (2000) observed significant effects of turfgrass species or cultivars on surface hardness of lawn tennis courts. Effects of cutting height and root mass on the surface hardness of an athletic field have also been found to be minimal (Rogers & Waddington 1989). However, quantitative information on these aspects is very limited for golf greens.

Lodge and Baker (1991) found that the correlation between surface hardness and ball roll distance or between surface hardness and post-impact roll distance was very weak. Rootzone moisture content correlated better with surface hardness measured by the 0.5 kg hammer than by 2.25 kg. Rogers and Waddington (1991) found that correlation between surface hardness and bulk density was not as great as that between surface hardness and rootzone moisture content or between surface hardness and turf cover.

Bunnell and McCarty (2001) reported that Verti-draining reduced surface hardness 30 days following treatment, and attributed to its greater degree of surface disruption and core removal as well as greater subsurface fracture. However, HydroJecting had no effect either 15 days or 30 days following treatment.

## 2.4.4 Summary

Much research has been carried out to study the effects of rootzone composition, sward characteristics and maintenance practices (e.g. cutting and rolling) on the playing quality of sports turf. Some authoritative guidelines have been published overseas specifically for golf greens.

With respect to green speed, cutting height and rolling are the controlling factors. Close cutting and heavy rolling produces a faster green. Species composition can also change green speed significantly. Differences in green speed caused by rootzone composition are less than those caused by sward characteristics. Amendments added in a sand-dominated rootzone are the only rootzone factor that can affect green speed. Effects of other rootzone factors (e.g. type of rootzone/sand, mixing ratio of sand/soil or amendment/sand) are generally not significant though findings are not consistent among researchers.

In contrast, rootzone composition (i.e. rootzone type and ratio of amendment/sand) has a larger influence on surface hardness than sward characteristics. The effect of sward characteristics on surface hardness can be detected only under low rootzone moisture conditions, though published results are somewhat contradictory. Generally, sand-based rootzones can produce a consistent, hard and fast green throughout the year. In contrast, soil-based rootzones tend to produce a soft and slow green under wet rootzone conditions, and a hard and fast green under dry rootzone conditions. Moisture content in the upper portion of profiles may be the controlling factor, and it is more important than heavy rolling. Previous studies have shown little effect of cutting height on surface hardness.

There is a close correlation between surface hardness and rootzone moisture content. However, no close correlation has been found either between green speed and surface hardness, or between green speed and rootzone moisture content.

Most earlier studies on the effects of rootzone composition and sward characteristics on playing quality are focused on winter game pitches, published information in this area is relatively limited on golf greens. In particular, limited quantitative information is available on: (a) the relative difference in playing quality performance between the USGA profile, partially amended sand rootzones and pure sand rootzone; and (b) effects of the proposed cultivation/aeration treatment on playing quality of golf greens.

## 2.5 A DYNAMIC MATHEMATICAL MODEL FOR COMPREHENSIVE ASSESSMENT AND MONITORING OF THE LONG-TERM PERFORMANCE OF GOLF GREENS

### 2.5.1 Introduction

Since the 1960s, numerous system analysis models for grasslands, forests and crops have been developed and incorporated with goal-oriented management approaches to agricultural practices (Wu *et al.* 1996). For example, some of the representative models in these fields are generalized additive models (GAMs) (Thomas & Neil 1991), a combined plant growth simulation model (GOSSYMCOMAX) (Reddy, *et al.* 1995), CROPGRO crop growth model (Boote *et al.* 1996), CENTURY soil organic matter model (Gijsman *et al.* 1996), agricultural land management alternatives with numerical assessment criteria model (ALMANAC) (Kiniry *et al.* 1996), sorghum forage yield simulating model (SORKAM) (Fritz *et al.* 1997), and a dynamic simulation model of the soil-plant-atmosphere system (GAPS) (Rossiter & Riha 1999). However, little published information is currently available on development of system analysis models in turf science.

All models listed above can be generally divided into additive, multiplicative and mixed models. Crop models are very successful for simulating crop production processes and predicting crop or forage yields under different ecological environment and management practices. They all require a quantitative dependent variable (e.g. crop yields) for successful modeling, and are not very suitable for analyzing complicated ecosystems. For example, additive models have limited applications in ecosystem modeling because factors in an ecosystem are often correlated with each other. The performance of the latter two types of models becomes unsatisfactory as the number of factors increase, because the system performance index is a product of numbers all less than one (Wu *et al.* 1994). In particular, a fundamental weakness in these crop models is that they use strictly quantitative approaches to describe systems that are highly tangled and only qualitatively understood (Wu *et al.* 1996). This problem is especially acute in developing a model for dynamically monitoring golf green performance because of a lack of a quantitative dependent variable, both additive and multiplicative effects of factors, severe disturbance from the usage and maintenance activities and the complexity of the system. Such a combined effect of natural factors and human influences cannot be modeled in a strictly scientific approach.

A resource integration approach, which is based on the integrated rate methodology (IRM), was originally developed for predicting the effective relative growth rate from a potential relative growth rate by integrating multiple environmental factors into a number between zero and one (Sharpe *et al.* 1987, cited in Li *et al.* 1990; Dawes & Hatton 1993; Wu *et al.* 1994). The mathematical foundation of IRM can be viewed as a generalization of Michaelis-Menten Kinetics for multiple substrates (Wu *et al.* 1994). Model inputs must be numerical, but qualitative scores or indices may be used as well as continuous variables. By sacrificing numerical precision for some factors, it is still possible to derive a comprehensive model to simulate overall system performance. After appropriate modification, this modeling method can be developed successfully for multi-factor modeling to simulate any complicated agroecological system (Wu *et al.* 1996), such as pastoral and sports turf ecosystems.

## 2.5.2 The general approach of integrated rate methodology (IRM)

The general approach for resource integration is to relate different inputs to a production process or rate calculation in a reciprocal relationship (Wu *et al.* 1994) (Equ. 2-1). The IRM equation can be derived by the three different mathematical approaches according to the nature of the studied systems: i.e. Continuous-time Markov (CTM) mathematics (Wu *et al.* 1994); Generalized Michaelis-Mention mathematics (Wu *et al.* 1994) and Parallel Resistance mathematics (Wu *et al.* 1994). The general form of the IRM model can be expressed as:

$$A = A_o \left[\sum_{i=1}^{n} w_i \div \sum_{i=1}^{n} (w_i \div x_i)\right] \qquad (2\text{-}1)$$

Where:

$x_i$ = normalized (i.e. scaled from 0 to 1) input variables. Realistic values for the $x_i$ inputs are not necessarily extended across the entire range 0 to 1. For instance, the range for the effect of maintenance could be set between 0.3 and 0.7;

$A$ = the calculated output variable;

$A_o$ = the maximum or potential value for variable $A$;

$w_i$ = the weighting factors that reflect the relative sensitivity of resource $i$ with respect to the output $A$. In absence of relevant information, $w_i$ value is sometimes set as 1;

$n$ = the total number of resources.

Variable normalization is analogous to a fuzzy membership function (Wu *et al.* 1996). Each measured value of an input variable is transformed into the normalized value (scaled between 0 and 1) by taking the ratio of the measured value to its corresponding optimal value (i.e. $x_i/x_{max}$). The merit of adopting a reciprocal relationship of harmonic means (Equ. 2-1) is that it provides a saturation response exhibited by many ecological systems (Wu *et al.* 1996). Resource integration equations ordinarily implement a hypothetical 'effect' of an input variable on an ecological system instead of using the actually measured value of an input variable. For example, we use the effect of rootzone drainage capacity on turf performance as an input rather then the measured amount of infiltration rate. Therefore, these effects (i.e. normalized factor values) can be modeled directly under given factor weightings. Equation (2-1) by itself is only a static computation. The output of a subsystem, however, often provides basic values for next step modeling or provides process rates in other subsystems of a simulation model. Linking these outputs or sub-models forms the mechanistic basis for a dynamic model. Model simulations involve the iterative calculation of process rates and output, as in most other modeling methods (Wu *et al.* 1994; 1996).

The resource integration approach allows simulations at an early stage of model development, rather then needing to wait for the set up of a complete database. This is because conceptual-level expressions can be implemented in a numerical form using normalized or discrete variables to characterize processes or inputs that are poorly or only conceptually understood (Wu *et al.* 1996). For example, little quantitative information is to be expected about the quality of maintenance for a new or untried turf management alternative in most cases. To implement this management alternative into a simulation model early, a normalized index ranging from 0 to 1, with 1 indicating 'optimal', is assigned to reflect hypothetical effects of the management alternative (Wu *et al.* 1996). Such indices can also represent inputs such as root mass and distribution, species composition or seasons, which are difficult to implement mechanistically in quantitative models.

Resource integration models thus incorporate theoretical, heuristic, and empirical modeling techniques. The mathematics involved is simple and easy to manipulate, facilitating the study of highly complex, loosely structured and dynamic ecological systems (Wu *et al.* 1996). The parameters assigned to such a model have great flexibility, because theoretical or conceptual inputs that carry imprecise as well as precise information can be used (Wu *et al.* 1994, 1996). The unique contribution of this methodology to ecological modeling theory is that it can be used to analyze various responses by adjusting the relative significance of system variables when an investigated system lacks a quantitative dependent variable (Wu *et al.* 1996). The relative significance of system variables can be easily determined through calculating factor weightings based on the 'half-saturation' and 'saturation' values in terms of factor responses to the system performance. The integration of system factors from various sources unites, making the resource integration modeling approach applicable to a wide range of disciplines, particularly problems centered in human influences and management (Wu *et al.* 1994, 1996). As many of ecological, agricultural and socioeconomic factors involved in an ecosystem are as yet poorly understood, or merely qualitative in nature, it is therefore perceived that the primary purpose of the integrated resource approach is as a decision-making tool (Wu *et al.* 1996). It is hoped that it will further provide a useful tool for developing a cost-effective and an adaptive management solution in practice (Wu *et al.* 1996).

### 2.5.3 Summary

The IRM modeling method was primarily developed for the multi-factor agroecosystems as a decision-making tool. It has very good resource integrating and trend predicting capacity. So, it has the potential to be used as an effective system analysis tool to provide a comprehensive evaluation and a method for monitoring the long-term performance of golf greens. It appears that relatively little research has been conducted on this aspect in sports turf according to published information.

## 2.6 SUMMARY AND CONCLUSIONS

A survey of the literature shows that much research has been carried out on the effects of rootzone composition and cultivation/aeration treatment on golf green performance during the last 10-20 years. It is difficult to draw conclusions from all these findings. Nevertheless, from the above review, some general trends include:

1. Many rootzone physical and playing quality criteria have been developed as authoritative guidelines for golf green construction, maintenance, surface preparation, and performance assessment. However, little published information is available on the definition of quality criteria of sward characteristics, which is an important component in assessing golf green performance.

2. There have been many studies that have investigated effects of sand type, sand proportion and various amendment materials on the performance of sand/soil and amended sand rootzones under laboratory or greenhouse conditions, where plant growth and wear has been limited. Recent research has focused on how rootzone physical and playing quality properties of soil and sand-based greens behave in the field under compaction and wear with different fertilizer and irrigation regimes, to better understand their precise management requirements.

   The above studies have shown: (a) Sand-based rootzones have many advantages over traditional soil-based rootzones for golf greens. However, sand constructions also have disadvantages and their long-term success cannot be guaranteed. For example, rapid accumulation of organic matter and plant roots with time in the upper profile is a common issue in golf green management, which will lead to fast physical deterioration, greatly altering their original rootzone physical properties and thereby decreasing overall green performances. Quantitative information on how to effectively solve this problem appears limited. (b) Relative advantages and disadvantages in terms of rootzone physical properties, sward characteristics and playing quality in the long-term between the standard USGA profile and various modified rootzones are not clear under field conditions.

3. Much research has been carried out to investigate effects of cultivation/aeration treatment (HydroJect, Verti-drain and scarification) on rootzone physical properties.

Various studies have shown not only short-lived, but also positive and negative effects of cultivation/aeration treatment on rootzone physical properties and the results are often contradictory. This discrepancy may be due to many reasons, including different application frequency and timing of cultivation/aeration treatments in different studies. This area deserves further study. Moreover, published information is very limited on the effects of cultivation/aeration treatment on sward characteristics and playing quality of golf greens constructed with sand-based rootzones in the cool, humid zones typical of New Zealand.

4. The integrated rate methodology (IRM) uses a system analysis approach to integrate multi-faceted components into a dynamic mathematical model through strict system factor linkage. Such a system analysis model has the potential to offer comprehensive assessment and dynamic monitoring of the long-term performance of a highly complicated turf ecosystem. It appears that little research has been conducted on this aspect in the sports turf industry compared with a large amount of development in ecological modeling in other branches of agricultural science.

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# 3. MATERIALS AND METHODS



**Fig. 3-1 Experimental plots**

## 3.1 EXPERIMENTAL DESIGN

Trial plots were constructed in March 1997 at the research site of the New Zealand Sports Turf Institute (NZSTI), Palmerston North, New Zealand (mean annual rainfall 1000 mm, mean daily temperature 13.2°C, mean annual soil temperature at 100 mm depth 12.6°C, average of eight frost days per year, zero snowfall) (Fig. 3-1; Appendix Figs. 3-1, 3-2). Profile design consisted of a suspended water table with a 250 mm deep rootzone overlaying a 100 mm deep angular gravel drainage layer. Gravel contained 88% and 12% of particles in the 4.0-8.0 mm and 2.0-4.0 mm size ranges respectively, so avoiding the need for a blinding layer (USGA 1993). Depth of the rootzone was determined from the moisture release characteristics of the sand that was used to construct four of the five rootzones, as opposed to the USGA-specified depth of 300 mm (Gibbs *et al.* 1997).

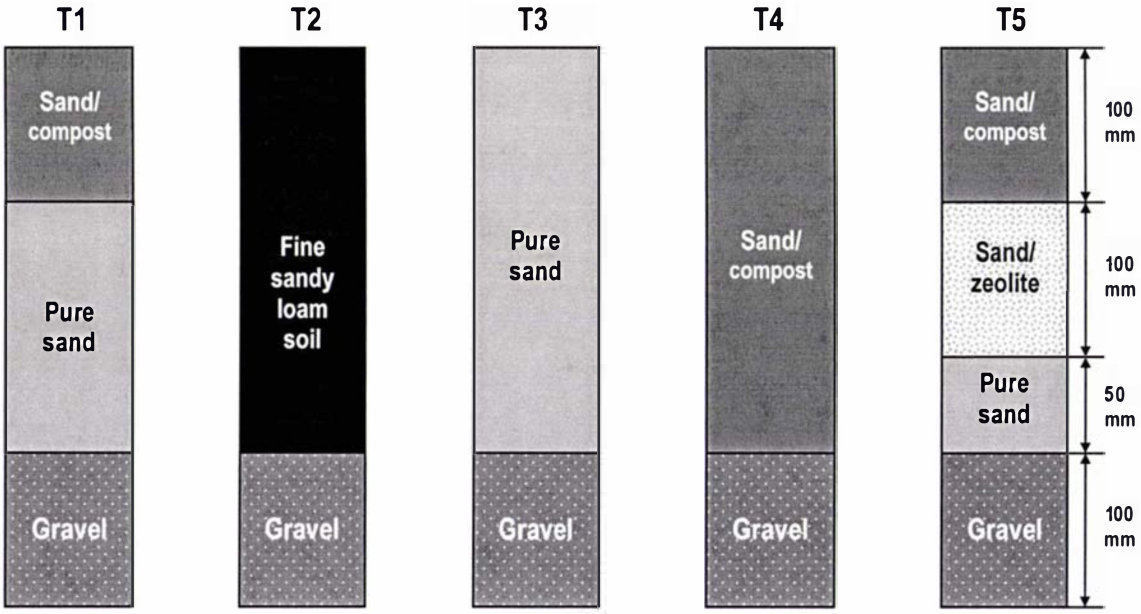


**Fig. 3-2 Rootzone design**

The trial layout was three randomized blocks with each block containing five randomly arranged plots (each 7.2 m by 3.2 m) of different rootzone treatments. The five rootzones were partially amended (compost) medium-coarse sand (T1), fine sandy loam soil (T2), medium-coarse pure sand (T3), fully amended medium-coarse sand (T4) and partially amended medium-coarse sand + zeolite (T5) (Fig. 3-2). T4 was a near-standard USGA rootzone using an approved compost instead of peat as the organic amendment (and a 250 mm deep rootzone as mentioned above, T1 and T5 were modifications of a standard USGA rootzone, T3 and T2 were a typical pure sand rootzone and the soil rootzone respectively. Each treatment was separated by a 250 mm depth of high-grade polythene sheeting to prevent capillary transfer of water between plots. Selected characteristics of the various rootzone media used in the five profiles are given in Table 3-1. Mixing rates of sand to compost and sand to zeolite were 6:1 and 9:1 (v/v) respectively. Sand and compost were mixed offsite, but sand and zeolite were mixed uniformly on-site by hand. A split-plot design was superimposed on rootzone treatments using selected cultivation/aeration sub-treatments applied twice per year in spring/early summer and autumn, based on typical turf management practices for New Zealand golf courses. The four cultivation/aeration treatments were the control (C), HydroJect (HJ), scarification (S) and Verti-drain (VD) (Table 3-2). HJ had no removal of soil plugs and organic matter, but resulted in deep redistribution of soil porosity; scarification was used for surface organic matter removal only, and VD was followed by deep compaction relief plus organic matter removal through soil exchange. The cultivation/aeration sub-plots were 1.8 m by 3.2 m in size.

## 3.2 ESTABLISHMENT AND MAINTENANCE

Experimental plots were sown on 27 March 1997 with a mixture of colonial bentgrass (*Agrostis capillaris* L. cv. 'Egmont') @ 2.5 g $m^{-2}$, New Zealand 'browntop' bentgrass (*A. capillaris/A. castellana* Boiss. & Reut.) @ 2.5 g $m^{-2}$, and Chewing's fescue (*Festuca nigrescens* Lam. ssp. *commutata* cv. 'Enjoy') @ 15 g $m^{-2}$. The ratio of each turfgrass species in the mixture is determined by real seed numbers per gram dry seeds. The objective during 1997 was to achieve uniform establishment on all plots, an objective that required some variation in establishment technique (Gibbs *et al.* 2000). From December 1997 all plots were maintained uniformly to a standard representing a golf green putting quality for recreational play under New Zealand conditions irrespective of rootzone type or cultivation/aeration treatment (Table 3-3).

**Table 3-1 Selected physical and chemical characteristics of rootzone media**

| Item | | Diameter (mm) | Local soil‡ | Pure sand | Sand/ compost | Compost | Zeolite |
|---|---|---|---|---|---|---|---|
| Category | Fine gravel | 2-4 | 0.0 | 0.6 | 0.9 | - | 0.0 |
| | Very coarse sand | 1-2 | 0.0 | 4.2 | 4.2 | - | 23.6 |
| | Coarse sand | 0.5-1.0 | 0.1 | 27.8 | 27.3 | - | 56.4 |
| | Medium sand | 0.25-0.50 | 0.5 | 58.8 | 54.7 | - | 14.7 |
| | Fine sand | 0.15-0.25 | 7.4 | 8.0 | 8.0 | - | 1.1 |
| | Very fine sand | 0.05-0.15 | 40.2 | 0.4 | 1.2 | - | 0.7 |
| | Silt | 0.002-0.05 | 46.1 | 0.1 | 1.8 | - | 1.7 |
| | Clay | <0.002 | 5.7 | 0.1 | 1.9 | - | 1.8 |
| Characteristics | Organic matter (%, w/w) | | 3.3 | 0.0 | 2.1 | 36.0 | - |
| | $K_{sat}$ (mm $h^{-1}$)† | | - | 975 | 226 | - | - |
| | Total porosity (%, v/v) | | - | 42.4 | 41.8 | - | - |
| | Water-filled porosity at -3 kPa (%, v/v)† | | - | 10.2 | 16.2 | - | - |
| | Air-filled porosity at -3 kPa (%, v/v)† | | - | 32.2 | 25.6 | - | - |
| | Bulk density (t $m^{-3}$)† | | - | 1.53 | 1.50 | 0.52 | 0.83 |
| | CEC ($NH_4$ acetate extract) (cmol $kg^{-1}$) | | 11.0 | 0.5 | 10.0 | - | 108 |
| | pH (in water) | | 5.4 | 7.2 | 7.6 | 8.5 | - |

*Sampled from stockpiles of material immediately prior to construction of plots*

† *Prepared according to USGA laboratory recommendations (ASTM F1815, 1997)*

‡ *Manawatu fine sandy loam*

## Table 3-2 Cultivation/aeration treatments*

| *Treatment* | *Description* |
|---|---|
| **Scarification (S)** | Carried out in Feb. 1998, Nov. 1998, Mar. 1999, Dec. 1999, Apr. 2000, Oct. 2000, Mar. 2001, Sep. 2001, Mar. 2002 and Oct. 2002 using a Protea scarifier (Model No. SVG 500). Cultivation depth was 10-15 mm with a blade width of 3 mm and blade spacing 30 mm. Two diagonal passes per application. |
| **Verti-drain (Deep tine cultivation, VD)** | Carried out in Mar. 1998 (hollow tines), Nov. 1998 (solid tines), Mar. 1999 (hollow tines), Dec. 1999 (solid tines), Mar. 2000 (solid tines), Oct. 2000 (hollow tines), Mar. 2001 (solid tines), Sep. 2001 (hollow tines), Mar. 2002 (solid tines) and Oct. 2002 (hollow tines) using a Verti-Drain 75 (Model No. 105.145). The diameter for both hollow and solid tines was 18 mm. Cultivation depth was 100 mm for hollow tines and 150 mm for solid tines. The tine spacing was approximately 120 mm × 120 mm for all applications. |
| **HydroJect (High pressure water injection cultivation, HJ)** | Applied in Feb. 1998, Nov. 1998, Mar. 1999, Dec. 1999, Apr. 2000, Sep. 2000, Mar. 2001, Oct. 2001, Mar. 2002 and Oct. 2002. The treatments were performed with a Toro HydroJect 3000 with 11 nozzles (orifice of 1.5 mm inside diameter) spaced 75 mm apart. Each application incorporated 'WettaSoil' (polypropylene glycol and nonyl phenolethoxylate) @ 20 $\ell$ $ha^{-1}$. The depth of holes varied from 100-200 mm. Two passes per application. |
| **Control (C)** | No cultivation/aeration treatment applied. |

* ***After each cultivation/aeration treatment, all plots including the plots of the control treatment were topdressed with corresponding rootzone materials @ 2 $\ell$ $m^{-2}$.***

## 3.3 SAMPLING PROTOCOL

Each sub-plot was split in half (each 1.8 m by 1.6 m). One half was used for making destructive measurements by using a sampling grid to prevent sampling over the same point twice. Destructive measurements included soil porosity, bulk density, root distribution, rootzone moisture and organic matter content. The other half was used for making non-destructive measurements, including water infiltration rate, oxygen diffusion rate, surface hardness, green speed, species composition, dry patch severity and overall visual quality (Tables 3-4, 3-5).

## 3.4 GUIDELINES USED FOR ASSESSMENT OF GOLF GREEN PERFORMANCE

Upper and lower limits of acceptability for each rootzone physical property, sward characteristic and playing quality measured, currently in use overseas (e.g. USA and UK) as authoritative guidelines for golf green construction and management, were reviewed and adjusted according to New Zealand golf management practices. Details of the adopted and adjusted guidelines for each measured component of golf green performance are summarized in Table 3-6.

## 3.5 STATISTICAL ANALYSIS

Analysis of variance (ANOVA) of data and tests for significance of differences in ball impact and the disease incidence between treatments used the Split-plot option of the General Linear Model (GLM) procedures of the Statistical Analysis System (SAS Institute 1990a). The analysis of variance (MANOVA) of data and the tests for significance of differences between treatments for the other turf performance components (e.g. rootzone physical properties, sward characteristics and playing quality), which were measured repeatedly over the first five years after sowing or predicted at half year steps over a 30 year period after sowing, used the Repeated Measure option of the GLM procedure of the SAS (SAS Institute 1990a; 1997). For each predicting year, two periods of the predicted data were pooled together and used as two replicates for the analysis of variance (MANOVA) of data and the tests for significance of differences between treatments. Significant differences ($P \leq 0.05$)

between rootzone types, cultivation/aeration treatments and for rootzone × cultivation/aeration interaction effects was tested using the Fisher's LSD method. However, significance of the change with time for each performance component between measurement occasions was determined using the Duncan's Multiple Range Test (LSR) (Ott 1977). The Module for Linear Regression of the SAS system (SAS Institute 1990b) was used to calculate the factor weightings of the Integrated Rate Methodology (IRM) model.

**Table 3-3 Details of trial management**

| *Maintenance* | *Description* |
|---|---|
| **Mowing** | All plots were mown three times per week at a height of 7 mm during 1998, 6 mm during 1999, 5 mm during 2000 and 4 mm thereafter irrespective of season. |
| **Irrigation** | Applied using a pop-up system, using pure sand plots as the benchmark for determining watering requirements (up to 35 mm per week in peak summer months). |
| **Fertilization** | The amount and type of fertilizers applied each year was based on results of a regular soil test for P, K and Mg. Annual total (kg ha$^{-1}$) was:<br>N P K Mg S<br>1998* 313 31 208 17 401<br>1999** 340 42 122 29 333<br>2000*** 148 18 137 15 206<br>2001**** 238 0 147 15 136<br>2002***** 315 0 147 15 85 |
| **Wear** | Compaction wear was applied using a pedestrian 1.0 t cricket roller on 7 Apr., 17 Aug., 1 Sep. and 3 Nov. in 1998 (double pass on each occasion). Wear intensity was increased to weekly wear applications of a ride-on 1.5 t cricket roller (5 passes per wear application) from Jun. 1999 to Dec. 2002. Wear was not carried out under frosty or saturated ground conditions. |
| **Pesticides/ wetting agents** | Insecticides: diflubenzuron @ 50 g ha$^{-1}$ (7 Apr. 1998, 15 Jan. 1999; 12 May 1999; 4 Jan. 2001 and 26 Apr. 2002); endosulfan @ 1.5 ℓ ha$^{-1}$ (17 Apr. 1998 and 15 Sep. 1998); chlorpyrifos @ 1.5 ℓ ha$^{-1}$ (1 Aug. 1998, 18 Jan.1999; 11 Jun. 1999; 22 May 2000; 23 Jun. 2000; 2 Mar. 2001; 7 Jun. 2002), were applied mainly for control porina moth (*Wiseana* spp.), sod worm and earthworms.<br><br>Fungicides: propiconazole @ 1.5 ℓ ha$^{-1}$ (8 Jun. 1998; 19 Feb. 2000 and 14 Apr. 2000); terbuconazole @ 750 g ha$^{-1}$ (29 Sep. 1998 and 12 May 1999); beta-methoxy-acrylates @ 1.8 ℓ ha$^{-1}$ (5 Nov. 1998 and 14 Jan. 1999); chlorothalonil @ 10 ℓ ha$^{-1}$ (19 Sep. 1999; 19 Feb. 2000; 14 Apr. 2000; 6 Dec. 2000; 15 Jan. 2001; 9 Feb. 2001; 2 Mar. 2001; 9 May 2001; 5 Dec. 2001; 19 Dec. 2001; 7 Jan. 2002; 4 Apr. 2002 and 24 Apr. 2002); azoxystribin @ 1.2 kg ha$^{-1}$ (4 Apr. 2002) were applied to control fairy ring, take-all patch and dollar spot diseases.<br><br>Herbicides: picloram/2,4-D @ 1.5 ℓ ha$^{-1}$ (22 Sep. 1998); clopyralid + mecoprop + Ioxynil + bromoxynil @ 1.0 ℓ ha$^{-1}$ (4 Jan. 2001); mecoprop + ioxynil + bromoxynil @ 1.5 ℓ ha$^{-1}$ (8 Apr. 2002), were applied to control chickweed (*Stellaria* spp.), clover (*Trifolium* spp.), hydrocotyle (*Hydrocotyle* spp.) and onehunga weed (*Soliva* spp.).<br><br>Wetting agents: polypropylene glycol and nonyl phenolethoxylate @ 10 ℓ ha$^{-1}$ (15 Jan. 1999; 6 Oct. 2000; 1 Nov. 2000; 29 Nov. 2000; 3 Dec. 2000; 4 Jan. 2001; 24 Jan. 2001; 2 Mar. 2001; 28 Mar. 2001; 3 Oct. 2001; 19 Nov. 2001; 7 Jan. 2002 and 18 Nov. 2002); polyether modified polysiloxane @ 0.8 ℓ ha$^{-1}$ (19 Sep. 1999; 18 Oct. 1999; 18 Nov. 1999; 30 Nov. 1999 and 6 Sep. 2000), were applied uniformly on all plots. |

* *as 15 liquid applications of ammonium sulphate, potassium sulphate, magnesium sulphate and diammonium phosphate plus an additional application of 110 kg ha$^{-1}$ controlled release Scotts Triaform (31 : 1 : 8 + trace elements) on 4 March 1998.*

** *as 11 liquid applications of the same fertilizers plus an additional solid application of 250 kg ha$^{-1}$ controlled release Scotts Contec (19 : 0.8 : 12 + trace elements) in early October.*

*** *as 13 liquid applications of ammonium sulphate, potassium sulphate and magnesium sulphate.*

**** *as 11 liquid applications of ammonium sulphate (or urea), potassium sulphate and magnesium sulphate.*

***** *as 13 liquid applications of urea, potassium sulphate and magnesium sulphate.*

**Table 3-4 Sampling protocol for measurement of rootzone physical properties**

| *Measurement* | *Description* |
|---|---|
| **Water infiltration rate (IR)** | Measured using a single ring (150 mm deep and 300 mm diam.) inserted to a depth of 50 mm in each sub-plot, then filled with water and maintained with a head of 50 mm for approximately 60 minutes before recording the time taken for the water level to drop 20 mm. Values were standardized to 10°C (Lodge & Baker 1993) and transformed through $\log_{10}(x + 1)$ before performing statistical analysis (Taylor *et al.* 1991). During dry periods of the year, all plots were irrigated to field capacity prior to measurements taking place. Measurements were carried out in Apr. 1998, Nov. 1998, Apr. 1999, Jun. 1999, Dec. 1999, May 2000, Dec. 2000, Apr. 2001, May 2001, Jul. 2001, Sep. 2001, Nov. 2001, Jun. 2002 and Dec. 2002. |
| **Oxygen diffusion rate (ODR)** | Measured using a Jenson Oxygen Diffusion Ratemeter. Ten microelectrodes of 4 mm exposed platinum wire were inserted to two different rootzone depths of 50 mm and 175 mm. The inserted microelectrodes were maintained in the field for 24 hours before recording readings. All readings were normalized to a field capacity (100 mb) of moisture content (Carter 1993). Measurements were made in Apr. 1998, Oct. 1998, Jul. 1999, Dec.1999, May 2000 and Nov. 2001 for the 50 mm depth and in Jul. 1999, Dec. 1999, May 2000 and Nov. 2001 for the 175 mm depth. Two cores (22 mm diam.) were also taken simultaneously from two soil depth (0-50 mm and 150-200 mm) in each sub-plot for measuring gravimetric moisture content on each sampling date. |
| **Water retention** | In Apr. 1998, May 1999, Jul. 2000, May 2001 and Jul. 2002, one undisturbed core (54 mm diam.) was sampled to 105 mm in each sub-plot and cut at 35 mm increments. A nylon cloth with a hole size of 90 μm was placed on to the base of each sectioned core and held tightly in position with a rubber band. Cores were saturated overnight before being placed on a sand tension table and successively equilibrated over 24-48 hours at moisture potentials of -3, -4 and -5 kPa. Cores were then oven-dried at 105°C for 24 hours and weighed. Air-filled porosity and volumetric soil moisture content were calculated using equations recommended by ASTM F1815 (1997). |
| **Organic matter content (OMC)** | Two cores (22 mm diam.) were taken from five depths (0-25, 25-50, 50-100, 100-150 and 150-200 mm) in each sub-plot. Surface samples were trimmed to remove above ground plant material, and fresh samples from the same depth were bulked in the each sub-plot and oven-dried at 105°C for 24 hours and organic matter content (OMC, % by weight) was determined after dry combustion at 440°C for eight hours. Measurements were made in Apr. 1998, Apr. 1999, May 2000, Apr. 2001 and Jun. 2002. |
| **Moisture content** | Gravimetric moisture content of the whole profile was determined by oven-drying the fresh samples taken for the measurement of organic matter content at 105°C for 24 hours. Moreover, surface moisture content was also measured by taking two cores (22 mm diam) from the 0-50 mm depth in each sub-plot at the time of each green speed, surface hardness and holding power measurement. Samples from each sub-plot were bulked and oven-dried for 24 hours at 105°C. Water loss was calculated as a percentage of the weight of oven-dry materials. |

## Table 3-5 Protocol for measurement of playing quality and sward characteristics

| *Measurement* | *Description* |
|---|---|
| **Ball roll distance (green speed)** | Ball roll distance was measured using a USGA Stimpmeter (Radko 1980). Three readings were taken in each of two opposite directions per sub-plot. Where readings in opposing directions differed by more than 20%, the correction suggested by Brede (1991) was used in the calculation of results. Measurements were carried out in Apr. 1998, Nov. 1998, Jun. 1999, Jan. 2000, May 2000, Dec. 2000, Apr. 2001, Dec. 2001, Jul. 2002 and Dec. 2002. |
| **Surface hardness** | A Clegg Impact Soil Tester was used to measure surface hardness (Clegg 1976). Two weights were used: 0.5 kg and 2.25 kg. The hammer of 0.5 kg weight was dropped from a height of 300 mm using four consecutive drops on the same location. Readings from the first and fourth drops were recorded. The hammer of 2.25 kg weight was dropped from a height of 450 mm and only a single drop made per location. The mean reading from a total of five locations per sub-plot was used (expressed in gravities). Measurements were made in Apr. 1998, Nov. 1998, Apr. 1999, Jun. 1999, Nov. 1999, May 2000, Oct. 2000, Jun. 2001, Nov. 2001, Jul. 2002 and Dec. 2002. |
| **Root mass and root distribution** | Two cores (54 mm diam.) were taken from five depths (0-50, 50-100, 100-150, 150-200 and 200-250 mm) in each sub-plot. Surface samples were trimmed to remove above ground plant material. Samples from each depth were washed on a sieve (250µm) to extract roots and then dried at 75°C for 24 hours to determine dry root weight. Measurements were made in Apr. 1998, Nov. 1998, Apr. 1999, Jan. 2000, May 2000, Dec. 2000, May 2001, Dec. 2001, Jul. 2002 and Jan. 2003. No separation was made of living and dead roots. |
| **Species composition** | Species composition was determined using an optical first-hit point analysis technique (Zhou 1993). One hundred points were taken per sub-plot in 20 randomly placed five-point quadrat ($5 \times 20 = 100$). The amount of each live plant species and bare-ground was calculated as a percentage of the occurrence in the total points. Data were normalized by using the arcsin transformation before performing statistic analysis (SAS Institute 1990a). Measurements were carried out in Sep. 1999, Nov. 2000, Sep. 2001 and Sep. 2002. |
| **Visual turf quality** | Visual turf quality was expressed for each sub-plot in terms of turf uniformity, density and the incidence of dry patch disorder, disease and pest damages. For each parameter of turf uniformity and density, a scale of 0-9 was used where 0 represented very poor density or uniformity and 9 represented very good density or uniformity. Measurements were made in Sep. 2000, Sep. 2001 and Sep. 2002. For each parameter of dry patch disorder, disease and pest incidence, a 0-5 visual scale was used (0 = no damage, 5 = most severe damage). Disease and pest incidence was assessed only when a disease or insect pest was well established on the plots for a given period. Dry patch was scored weekly on each sub-plot over each summer (from 10 Jan. 2000 to 28 Apr. 2000, from 6 Nov. 2000 to 10 Apr. 2001, from 1 Jan. 2002 to 25 Apr. 2002 and from 25 Nov. 2002 to 5 Mar. 2003). The result for each treatment was presented as an average for each month. |

**Table 3-6 Adopted and adjusted guidelines for performance assessment of golf greens**

| *Component of golf green performance* | *Preferred range* | |
|---|---|---|
| | *Authoritative guidelines (if available)* | *Adjusted guidelines** |
| **Water infiltration rate (mm $h^{-1}$) measured by single ring method** | ≥ 20 mm $h^{-1}$ in UK (Hind *et al.* 1995) or ≥ 25 mm $h^{-1}$ in USA (Waddington *et al.* 1974) | 20-100 |
| **Oxygen diffusion rate (× $10^{-8}$ g $cm^{-2}$ $min^{-1}$) measured by a Jenson Oxygen Diffusion Ratemeter** | 20-40 (O'Neil & Carrow 1983) | 20-40 |
| **Air-filled porosity (%,v/v) at -3kPa in the 35-70 mm depth** | 15-30 (Hind *et al.* 1995; Hummel 1994; USGA 2004) for laboratory-compacted materials | 10-30 |
| **Water-filled porosity (%, v/v) at -3kPa in the 35-70 mm depth** | 15-25 (Hummel 1994; USGA 2004) for laboratory-compacted materials | 20-35 |
| **Total porosity (%,v/v) in the 35-70 mm depth** | 35-55 (USGA 1993, 2004) for laboratory-compacted materials | 35-55 |
| **Organic matter content (%, w/w) in the surface 25 mm of the profile** | 1-4 (USGA 1993) for original rootzone materials | ≤ 8 |
| **Organic matter content (%, w/w) in the 25-50 mm depth** | 1-4 (USGA 1993) for original rootzone materials | ≤ 4 |
| **Organic matter content (%, w/w) in the surface 35 mm of the profile** | 1-4 (USGA 1993) for original rootzone materials | ≤ 6 |
| **Organic matter content (%, w/w) at the 35-70 mm depth** | 1-4 (USGA 1993) for original rootzone materials | ≤ 3 |
| **Bulk density (t $m^{3}$) in the 35-70 mm depth** | 1.2-1.6 (USGA 1989, cited in Hummel 1993) for laboratory-compacted materials | 1.2-1.6 |
| **Dry root-mass percentage at the 50-250 mm depth in the total profile** | Not available | ≥ 3.5% |
| **Visual dry patch severity scores (0-5)** | Not available | 0-2 |
| **Visual turf quality scores (uniformity + density) (0-9)** | Not available | 7-9 |
| **Total turfgrass cover (%)** | > 80 (Baker *et al.* 1997) | > 85 |
| **Relative balance index of two sown species of browntop/Chewing's fescue** | Not available | 0.03-0.40 |
| **Surface hardness (10 × gravity) measured by a Clegg Impact Soil Tester (0.5 kg CIT hammer, single drop at a height of 300 mm)** | 55-120 (Baker *et al.* 1996) | 80-140 |
| **Ball roll distance (m) measured by a Stimpmeter** | 1.5-3.0 in UK (Baker *et al.* 1996) or 1.37-2.59 in USA (Radko 1980) | 1.5-3.0 |

- Adjusted based on results of the present study and expert validation (Gibbs, *pers. comm.*)

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# 4. EFFECT OF ROOTZONE COMPOSITION AND CULTIVATION/AERATION TREATMENT ON ROOTZONE PHYSICAL PROPERTIES OF GOLF GREENS

## 4.1 ABSTRACT

This chapter reports the monitoring of golf green performance during the first five years after sowing as measured by rootzone physical properties of five alternative golf green rootzones under New Zealand conditions. Rootzone treatments were partially amended sand rootzone, soil rootzone, pure sand rootzone, full amended sand rootzone and partially amended sand + zeolite rootzone. A split-plot design was superimposed on the rootzone treatments consisting of twice-yearly cultivation/aeration treatments (control, HydroJect, scarification and Verti-drain).

Results showed that the soil rootzone possessed physical properties consistently below minimum acceptable values. Advantages of the sand-based rootzones over the soil-based rootzone were significant in terms of improved infiltration rate, reduced rate of organic matter accumulation, and increased macroporosity and oxygen diffusion rate. However, there was a measurable deterioration over time in rootzone physical properties for all rootzones, particularly for the sand-based rootzones and particularly during the first three years after sowing. By the third year after sowing, the porosity in the upper portion of profiles was also considered limiting to greens' performance for the sand-based rootzones.

There was a negligible difference in overall physical performance between the three amended sand rootzones on all measurement occasions, and no evidence of a physical disadvantage of omitting organic amendment in the pure sand rootzone three years after sowing.

The Verti-drain treatment was generally associated with increased water infiltration rate and macroporosity, and reduced organic matter accumulation near the surface. However, beneficial effects of a single Verti-drain operation on rootzone physical properties (e.g. infiltration rate) lasted only approximately two months. Effects of the HydroJect treatment on rootzone physical properties were not apparent. In contrast, the scarification treatment showed that whilst it was effective in significantly reducing organic matter accumulation near the surface, it also caused a significant reduction in water infiltration rate. None of the cultivation/aeration treatments could halt the general physical deterioration over time under the twice-yearly frequency of the treatment.

It was concluded that: (a) the New Zealand practice of constructing only the top 100 mm of the sand rootzone with organic-amended sand was of no physical disadvantage compared with a fully amended USGA-type rootzone; (b) the pure sand rootzone system was not of any long-term physical disadvantage compared with the amended sand rootzones; (c) the twice-yearly frequency of the cultivation/aeration treatments appeared inadequate for golf greens; and (d) scarification should not be used in isolation of other physical cultivation.

**KEYWORDS**: Compost, HydroJect, infiltration rate, organic matter control, oxygen diffusion rate, scarification, soil porosity, Verti-drain and zeolite.

## 4.2 INTRODUCTION

The physical properties of a golf green rootzone are highly dependent upon the original rootzone composition and subsequent management. They have a large influence on the turfgrass growth and the playing quality of golf greens (Baker & Canaway 1990; Vavrek 1992; Thien 1994).

The effects of rootzone composition and cultivation/aeration treatment on the rootzone physical properties of golf greens has been much researched in the last 50 years (Lunt 1956; Swartz & Kardos 1963; Madison 1969a; Adams *et al.* 1971; Brown & Duble 1975; Davis 1980; O'Neil & Carrow 1983; Baker & Richard 1993; Baker *et al.* 1999). However, to date, little information is available in the literature on the relative advantages and disadvantages, in terms of rootzone physical properties, of the standard USGA profile and its various modifications of the USGA specifications under field conditions. Research investigating the effect of the physical cultivation equipment (e.g. HydroJect, scarification and Verti-drain) on control of surface organic matter accumulation, which is considered as the principal factor causing the performance deterioration of sand-based golf greens, has been limited in the cool, humid zones typical of New Zealand (Carrow 1995, 2004a, b, c; Hind *et al.* 1995; Baker *et al.* 1999; Habeck & Christians 2000; Curtis & Pulis 2001).

The aim of this field trial was to monitor the overall physical performance of five alternative rootzone systems (two modified USGA rootzones, pure sand rootzone, the standard USGA rootzone and a conventional soil rootzone) managed under three alternative cultivation/aeration treatments (HydroJect, scarification and Verti-drain) by regular measurement of water infiltration rate, oxygen diffusion rate, water and air retention, organic matter content and bulk density during the first five years after sowing.

## 4.3 MATERIALS AND METHODS

For details of the trial design, methods and statistical analysis, refer to the Chapter three in this thesis.

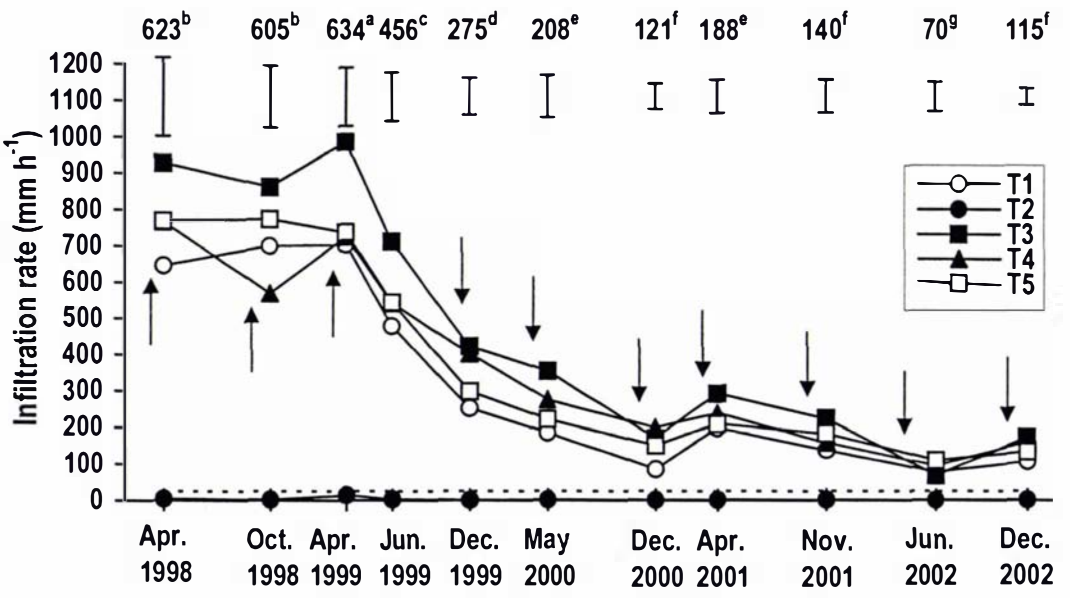
## 4.4 RESULTS

Whilst significant differences between individual rootzone and cultivation/aeration treatments were commonly found, at no stage in this trial were any significant interaction effects found between rootzone and cultivation/aeration treatments.

### 4.4.1 Water infiltration rate (IR)

There was an overall progressive decline in infiltration rate during the five years of the trial for all rootzone and cultivation/aeration treatments, particularly for the four sand-based rootzones and particularly after the period when more intensive wear began to be applied in early 1999 (Fig. 4-1). For example, between the period from April 1999 to December 2000, infiltration rate averaged over all rootzones decreased from 634 mm $h^{-1}$ to 121 mm $h^{-1}$, with significant decreases measured between all measurement occasions. However, there were no significant decreases in averaged infiltration rate between most of the measurement occasions after December 2000. After this time, decreases in infiltration rate had leveled off for all rootzone and cultivation/aeration treatments though wear intensity remained the same.

There were some significant influences of rootzone type on infiltration rate (Fig. 4-1). Infiltration rate tended to be faster on the pure sand rootzone than on the three amended sand rootzones during the first three years of the trial (from April 1998 to December 2000) and this result was significant in April 1999. After December 2000, infiltration rates of the four sand-based rootzones appeared to have merged, and no significant differences in infiltration rate were measured between the pure sand and the three amended sand rootzones. There were also no significant differences in infiltration rate between the three amended sand rootzones on all measurement occasions. Consistent and significant differences in infiltration rate were measured only between the sand-based rootzones



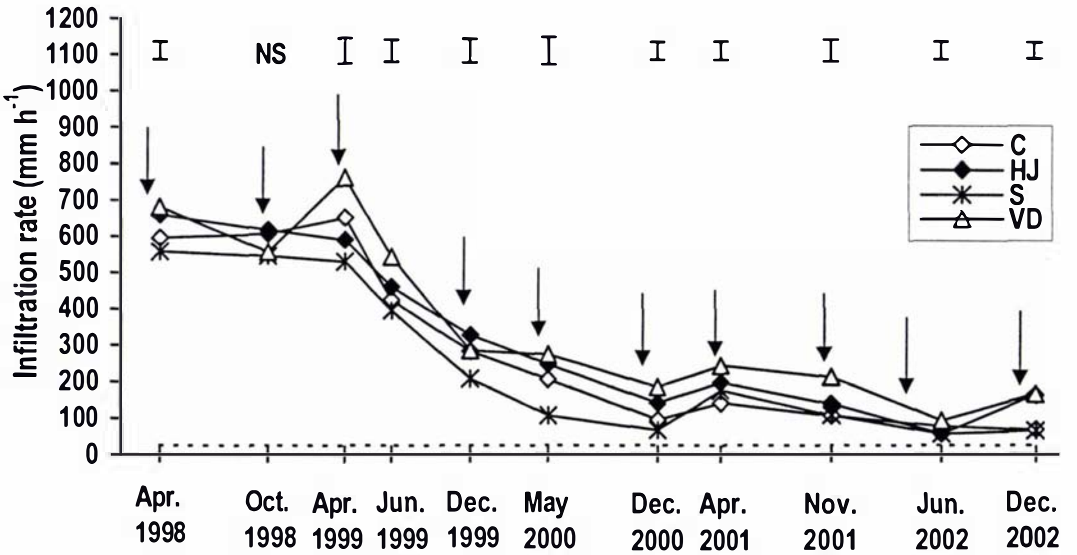




**Fig. 4-1 Changes in infiltration rate over the long-term in relation to each rootzone type and cultivation/aeration treatment**

*NS---not significantly different at the 0.05 level of probability. Error bars represent the LSD values for each group of treatments on each period of measurement. Arrows show the application time of cultivation/aeration treatment. The dotted line represents a value of 20 mm h$^{-1}$, the recommended minimum value for UK golf green turf (Hind et al. 1995). Top row of numbers represents infiltration rate (mm h$^{-1}$) averaged over all rootzone treatments on each measurement occasion, and the means with the same letters in the upper right hand are not significant at the 0.05 level of probability. T1---Partially amended sand rootzone; T2---Soil rootzone; T3---Pure sand rootzone; T4---Fully amended sand rootzone; T5---Partially amended sand + zeolite rootzone. C---Control; HJ---HydroJect; S---Scarification; VD---Verti-drain.*

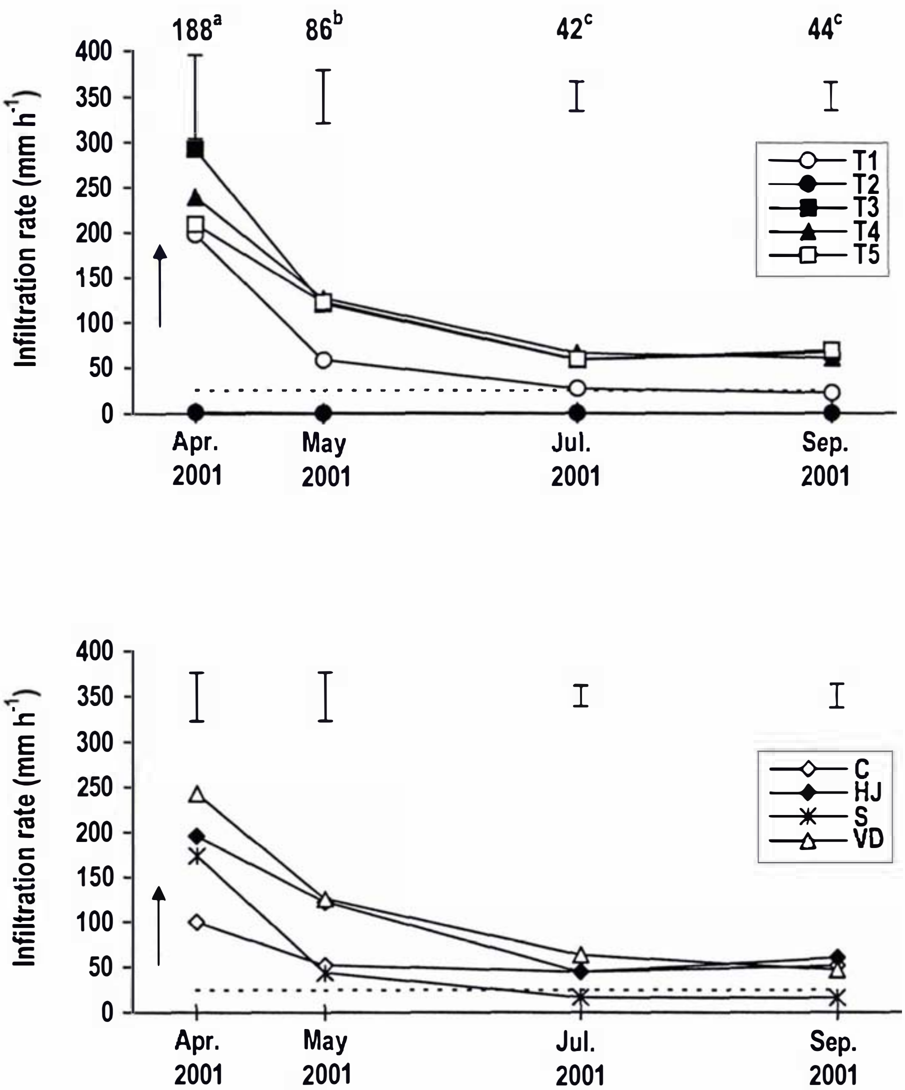



**Fig. 4-2 Changes in infiltration rate over the short-term after cultivation in relation to each rootzone type and cultivation/aeration treatment**

*Error bars represent the LSD values for each group of treatments on each period of measurement. Arrows show the application time of the cultivation/aeration treatment. The dotted line represents a value of 20 mm $h^{-1}$, the recommended minimum value for the UK golf green turf (Hind et al. 1995). Top row of numbers represents infiltration rate (mm $h^{-1}$) averaged over all rootzone treatments on each measurement occasion, and the means with the same letters in the upper right hand are not significant at the 0.05 level of probability. T1---Partially amended sand rootzone; T2---Soil rootzone; T3---Pure sand rootzone; T4---Fully amended sand rootzone; T5---Partially amended sand + zeolite rootzone. C---Control; HJ---HydroJect; S---Scarification; VD---Verti-drain.*

and the soil rootzone. For example, infiltration rates of the soil rootzone always remained below the 20 mm $h^{-1}$ critical threshold throughout the whole measurement period (14 mm $h^{-1}$ in April 1999 declined to 1 mm $h^{-1}$ in December 2002). In contrast, infiltration rates of the four sand-based rootzones always remained well above the threshold during the same period despite an overall average decline from 788 to 144 mm $h^{-1}$ (Fig. 4-1).

Some increases in infiltration rate were significant on occasions after cultivation/aeration treatments, particularly from Verti-drain treatment in April 1999 and December 2002 (Fig. 4-1). For example, Verti-drain treatment tended to result in faster infiltration rate than the control and other cultivation/aeration treatments, and this result was significant on five out of the eleven measurement occasions. In contrast, scarification treatment resulted in slower infiltration rate compared with the control, HydroJect and Verti-drain treatments, and this result was significant in December 1999 and May 2000.

In addition to long-term measurements, effects of cultivation/aeration treatments on infiltration rate were also monitored intensively over the short-term from April 2001 to September 2001. During this period, significant increases in infiltration rate often associated with cultivation/aeration treatment seemed to have disappeared about two months after the application of the treatments on all the four sand-based rootzones (Fig. 4-2).

## 4.4.2 Oxygen diffusion rate (ODR)

### *4.4.2.1 50 mm rootzone depth*

Oxygen diffusion rate (ODR) showed a large fluctuation with time and/or season at the 50 mm rootzone depth (Fig. 4-3). An increase in ODR was evident in the mid-summer period after cultivation/aeration treatments in December 1999, but a similar result was not observed after other treatment occasions. In spite of this, there was a general decrease in ODR at the 0-50 mm depth for all rootzone and cultivation/aeration treatments to near or below the $20 \times 10^{-8}$ g $cm^{-2}$ $min^{-1}$ threshold during the measurement period (Fig. 4-3). For example, by November 2001, ODR values averaged over all rootzones decreased from $66 \times 10^{-8}$ g $cm^{-2}$ $min^{-1}$ in April 1998 to 22 ×

$10^{-8}$ g cm$^{-2}$ min$^{-1}$, with significant decreases measured between the majority of the measurement occasions.

A pattern in the effect of rootzone type on ODR was evident throughout the five years of the trial. There was a noticeable trend for the soil and pure sand rootzones to give consistently lower ODR readings than the three amended sand rootzones. On most occasions this result was significant (Oct. 1998, July 1999, May 2000 and Nov. 2001). For example, ODR values of the soil and pure sand rootzones were below the critical threshold by November 2001. In contrast, values of the three amended sand rootzones always remained above the threshold throughout the duration of the trial, but there was no significant difference in ODR values between the three amended sand rootzones on all measurement occasions.

No consistent and significant effects of cultivation/aeration treatments on ODR were measured at the 50 mm depth during the first three years following establishment. However, a pattern emerged by the fourth year (Nov. 2001) where the three cultivation/aeration treatments resulted in significantly higher ODR values than the control treatment (Fig. 4-3).

### *4.4.2.2 175 mm rootzone depth*

It was difficult to distinguish a trend in changes of ODR value with the profile depth for any of the rootzone and cultivation/aeration treatments (Fig. 4-3). However, similar to the 50 mm depth, there was an overall decline with time in ODR at the 175 mm depth for all rootzone and cultivation/aeration treatments, particularly for the sand-based rootzones and particularly over the first three years of measurement. For example, between the period from July 1999 to May 2000, ODR values averaged over all rootzones decreased from $50 \times 10^{-8}$ g cm$^{-2}$ min$^{-1}$ to $33 \times 10^{-8}$ g cm$^{-2}$ min$^{-1}$ and with a significant decrease measured on each measurement occasion. After May 2000, decreases in average ODR appeared to have stabilized, with no significant changes measured between the last two measurement occasions (Fig. 4-3).

By November 2001, the ODR values were grouped statistically into three classes among sand-based rootzones: the fully amended sand rootzone (highest), the two partially amended sand rootzones (intermediate), and the pure sand rootzone (lowest).

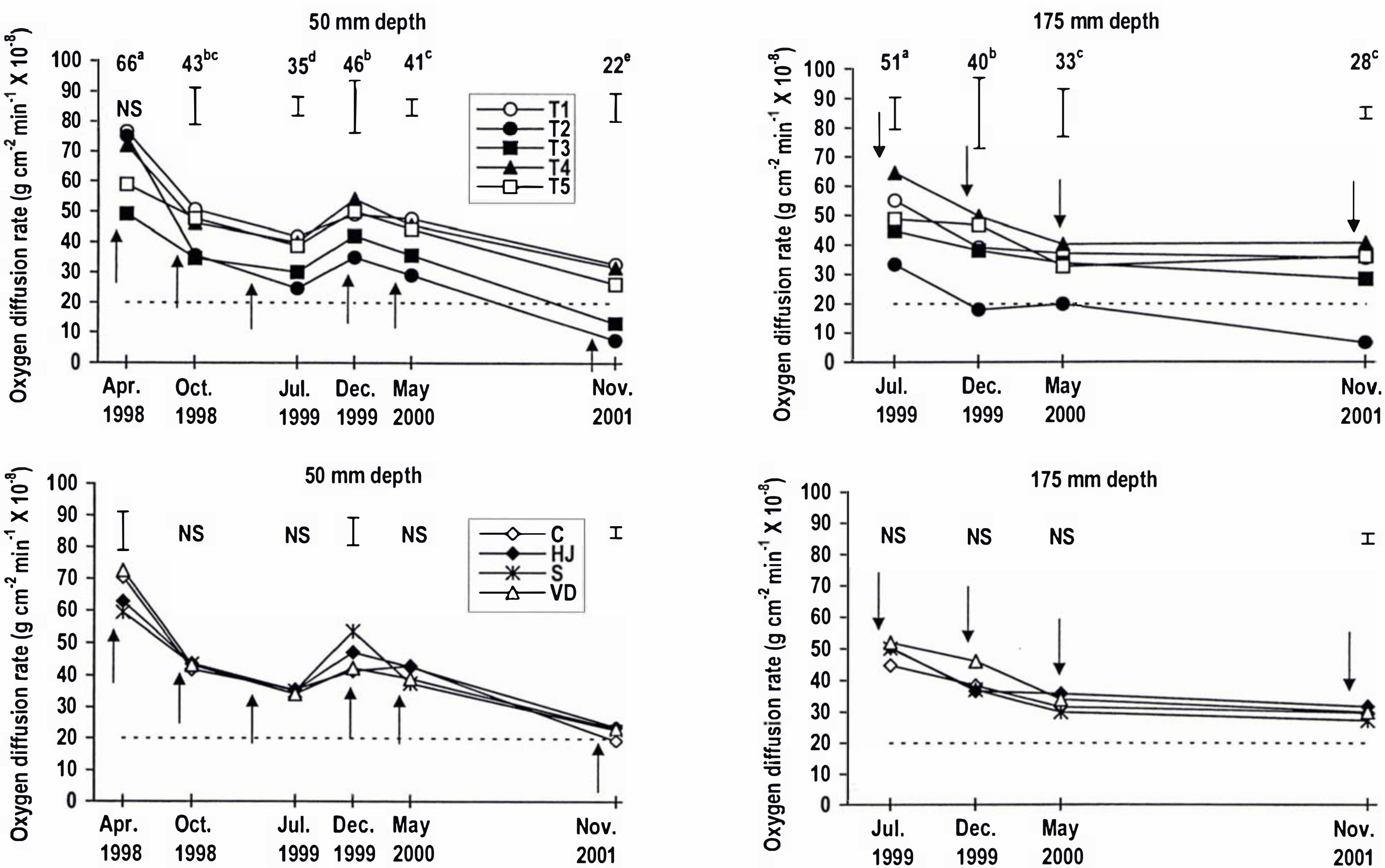



**Fig. 4-3 Changes in oxygen diffusion rate with time in relation to each rootzone type and cultivation/aeration treatment**

*NS---not significantly different at the 0.05 level of probability. Error bars show the LSD values for each group of treatments on each period of measurement. The dotted line represents a value of 20 X $10^{-8}$ g $cm^{-2}$ $min^{-1}$, the recommended minimum value for satisfactory root growth (O'Neil & Carrow 1983). Arrows show the application time of the cultivation/aeration treatment. Top row of numbers represents oxygen diffusion rate (20 X $10^{-8}$ g $cm^{-2}$ $min^{-1}$) averaged over all rootzone treatments on each measurement occasion, and the means with the same letters in the upper right hand are not significant at the 0.05 level of probability. T1---Partially amended sand rootzone; T2---Soil rootzone; T3---Pure sand rootzone; T4---Fully amended sand rootzone; T5---Partially amended sand + zeolite rootzone. C---Control; HJ---HydroJect; S---Scarification; VD---Verti-drain.*

On all other measurement occasions, there was no significant difference in ODR values between the four sand-based rootzones. Consistent and significant differences in ODR value were found only between the soil rootzone and the four sand-based rootzones at the 175 mm depth (Fig. 4-3). Furthermore, contrary to the results at the 50 mm depth, ODR values of the sand-based rootzones (including the pure sand rootzone) always remained above the critical threshold at the 175 mm depth. However, for the soil rootzone, ODR values remained consistently near to or below the critical threshold and decreased continuously with time throughout the whole experimental period.

Effects of cultivation/aeration treatments on ODR were not evident at 175 mm depth on any measurement occasion, with the exception of the November 2001 measurement where HydroJect treatment resulted in significantly larger ODR value than scarification treatment.

### 4.4.3 Water and air retention

#### *4.4.3.1 0-35 mm rootzone depth*

There was a general pattern of a progressive increase in water-filled porosity and an accompanying progressive decrease in air-filled porosity at -3 kPa moisture potential throughout the five years of the trial in the surface 35 mm for all rootzone and cultivation/aeration treatments. This change in water and air-filled porosity with time was most pronounced during the first three years of the trial and most pronounced for the four sand-based rootzones (Figs. 4-4, 4-5, 4-6). For example, by the third year (July 2000), air-filled porosity in the surface 35 mm averaged over all rootzones decreased from 25.5% in April 1998 to just 2.1%, and with significant decreases measured on each sampling occasion. After July 2000, decreases over time in air-filled porosity had leveled off, with no significant differences measured between sampling occasions over the last two years (Fig. 4-4; Table 4-1). In contrast, average water-filled porosity increased continuously from 25.8% in April 1998 to 54.5% in July 2002, and with significant increases measured on most of the sampling occasions during the five years (Fig. 4-5; Table 4-1).

Changes in total porosity with time were similar to that of water-filled porosity, and gradually increased with time for all rootzone and cultivation/aeration treatments, particularly for the soil rootzone. By July 2002, total porosity value of the soil rootzone increased above the threshold limit 55% (v/v) (Fig. 4-6; Table 4-1).

There were some significant influences of rootzone type on the water and air retention status in the surface 35 mm depth. Differences in water and air-filled porosity between the soil rootzone and the four sand-based rootzones were significant on all sampling occasions. However, the soil rootzone tended to contain more total porosity than the four sand-based rootzones in the surface 35 mm depth, and this result was significant on the last two sampling occasions (May 2001 and July 2002). There were no consistent and significant differences in water and air-filled porosity (as well as total porosity) between the four sand-based rootzones throughout the duration of the trial. The porosity values of all rootzones fell well below the critical threshold for air-filled porosity by July 2000 and above the critical threshold for water-filled porosity by May 1999 (Figs. 4-4, 4-5, 4-6).

No consistent and significant effects of cultivation/aeration treatments on water and air-filled porosity were measured during the five years at the frequency of application used in this trial. However, on a few occasions, Verti-drain treatment tended to be associated with a significant increase in air-filled porosity (May 1999) or a significant decrease in water-filled porosity (May 2001) compared with the other treatments (Fig. 4-4, 4-5). In contrast, Verti-drain and scarification treatments usually resulted in a significantly lower total porosity on the majority of occasions than the other treatments (Fig. 4-6).

Results of water and air-filled porosity in the surface 35 mm depth at -4 kPa and -5 kPa moisture potentials were similar to the results obtained at -3 kPa. The only exception was that the pure sand rootzone contained significantly higher air-filled porosity at both -4 kPa and -5 kPa than the three amended sand rootzones on one sampling occasion (July 2002) (refer to the Appendix Figs. 4-1, 4-2, 4-3, 4-4).

#### *4.4.3.2 35-70 mm rootzone depth*

Similar to the results of the 0-35 mm depth, there was a gradual increase in water-filled porosity and a gradual decrease in air-filled porosity at -3 kPa moisture potential throughout the five years of the trial in the 35-70 mm depth for all rootzone and cultivation/aeration treatments. This change in water and air-filled porosity with time

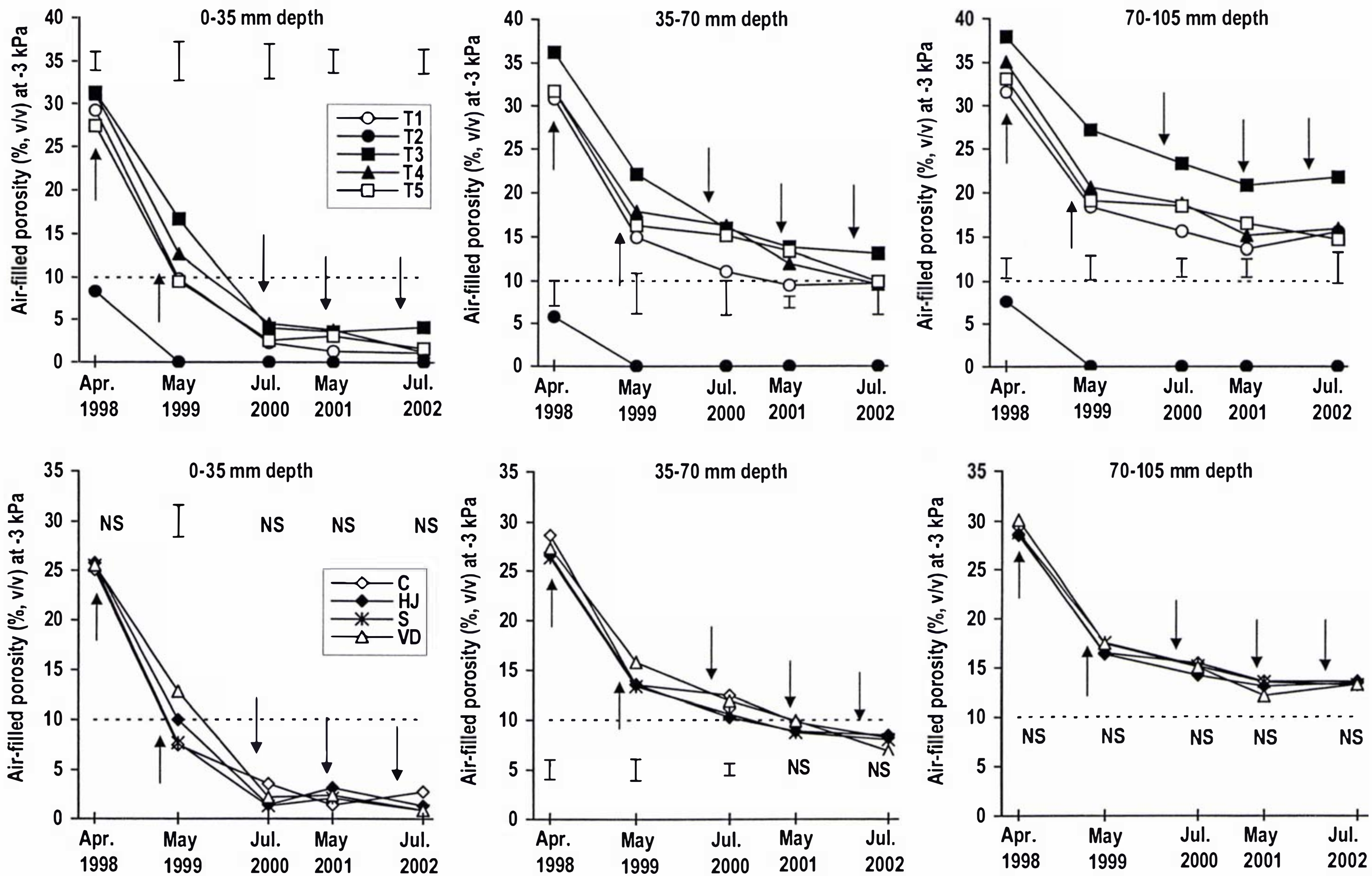



**Fig. 4-4 Changes in air-filled porosity at -3 kPa with time in relation to each rootzone type and cultivation/aeration treatment**

*NS—not significantly different at the 0.05 level of probability. Error bars represent the LSD value for each group of treatments on each period of measurement. Arrows show the application time of the cultivation/aeration treatment. The dotted line represents a value of 10 % (v/v), the recommended minimum value by Hind et al. (1995) and by Baker and Richards (1997). T1—Partially amended sand rootzone, T2—Soil rootzone, T3—Pure sand rootzone, T4—Fully amended sand rootzone, T5—Partially amended sand + zeolite rootzone. C—Control, HJ—HydroJect, S—Scarification, VD—Verti-drain.*

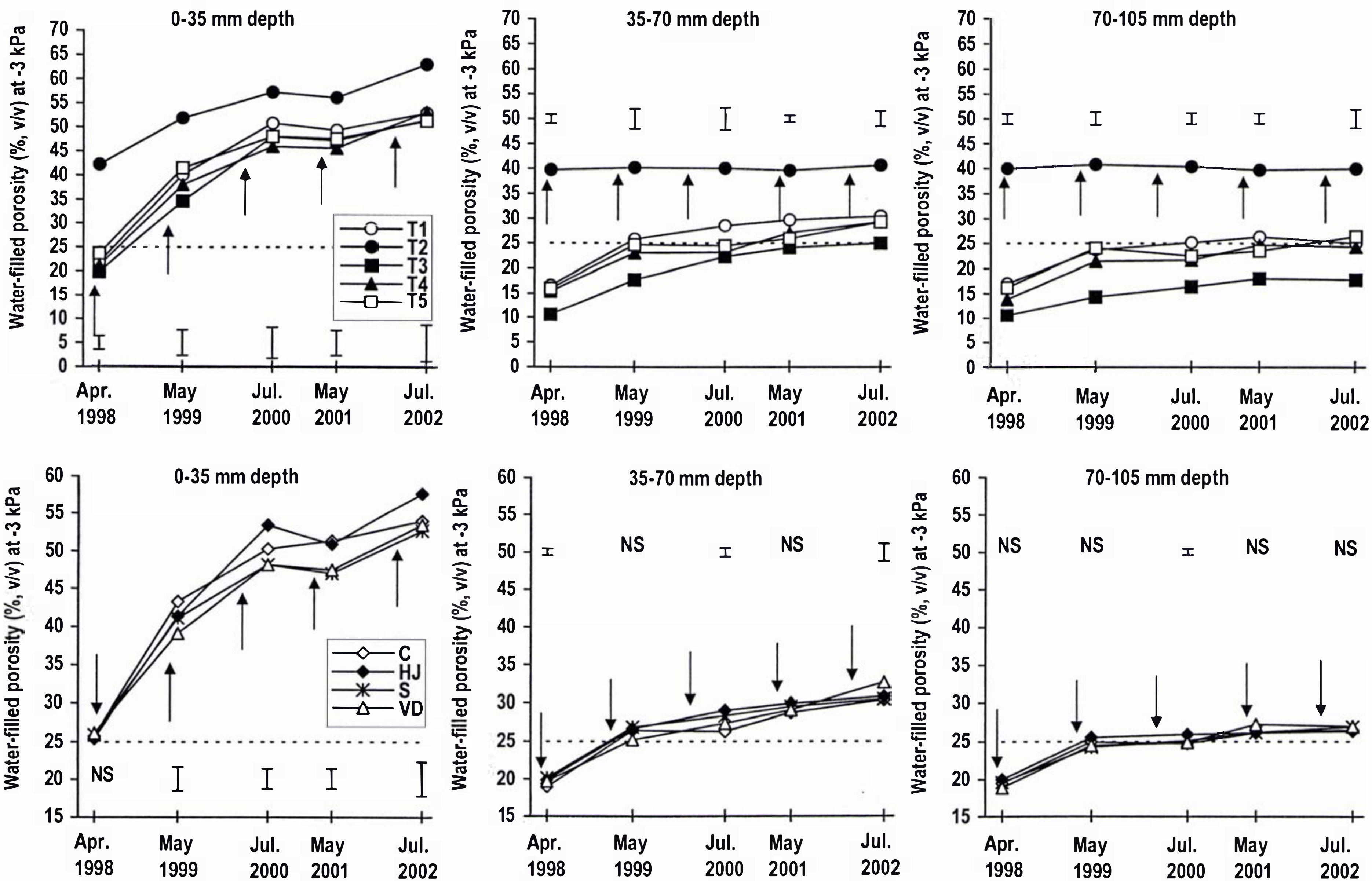



**Fig. 4-5 Changes in water-filled porosity at -3 kPa with time in relation to each rootzone type and cultivation/aeration treatment**

*NS—not significantly different at the 0.05 level of probability. Error bars represent the LSD value for each group of treatments on each period of measurement. Arrows show the application time of the cultivation/aeration treatment. The dotted line represents a value of 25 % (v/v), the recommended maxmum value for laboratory-packed samples by Hummel (1994). T1—Partially amended sand rootzone, T2—Soil rootzone, T3—Pure sand rootzone, T4—Fully amended sand rootzone, T5—Partially amended sand + zeolite rootzone. C—Control, HJ—HydroJect, S—Scarification, VD—Verti-drain.*

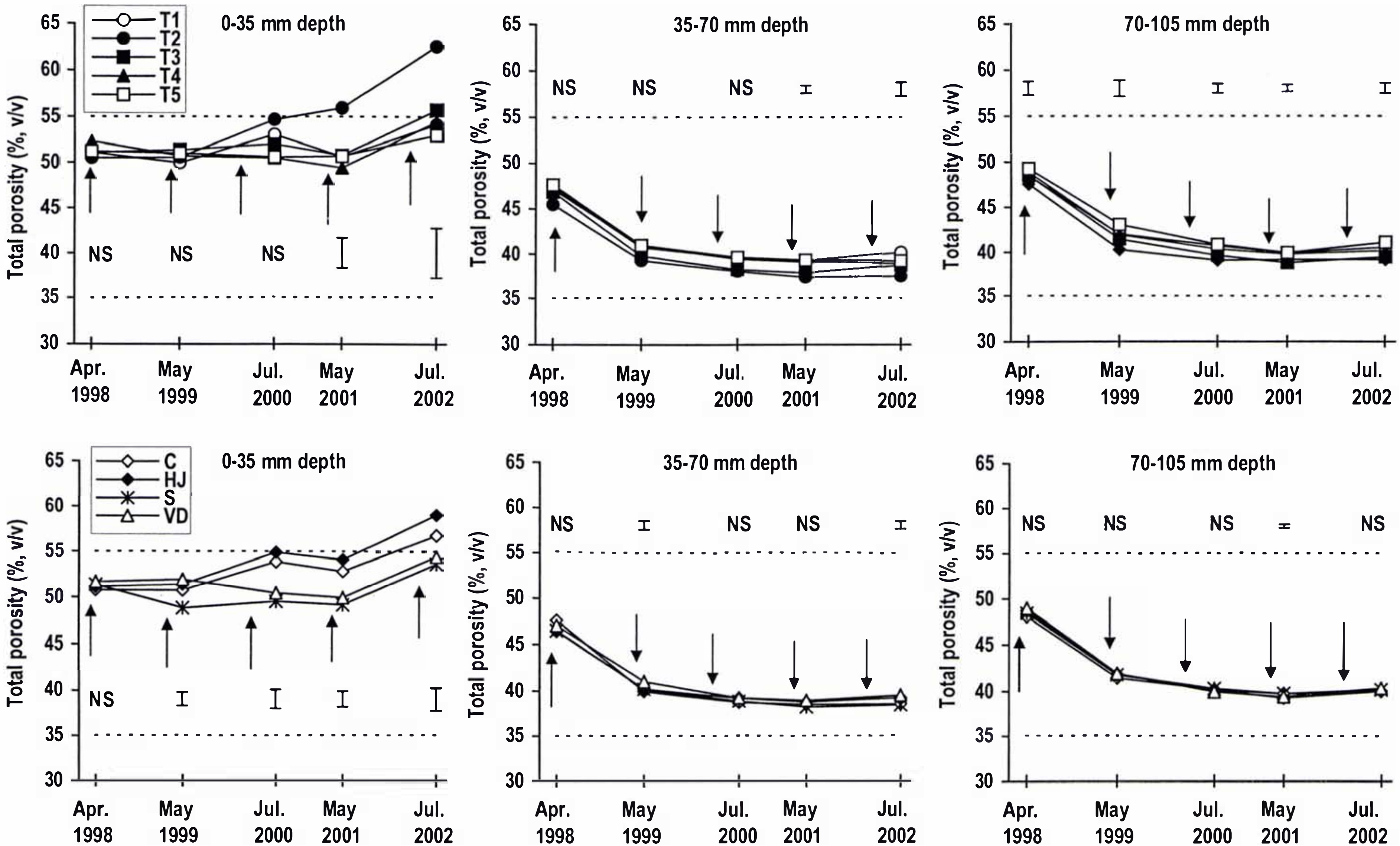



**Fig. 4-6 Changes in total porosity with time in relation to each rootzone type and cultivation/aeration treatment**

*NS---not significantly different at the 0.05 level of probability. Error bars represent the LSD value for each group of treatments on each period of measurement. Arrows show the application time of the cultivation/aeration treatment. The dotted line represents a range of 35-55 (%, v/v), the recommended acceptabe range for laboratory-packed samples by USGA (1993, 2004). T1---Partially amended sand rootzone, T2---Soil rootzone, T3---Pure sand rootzone, T4---Fully amended sand rootzone, T5---Partially amended sand + zeolite rootzone. C---Control, HJ---HydroJect, S---Scarification, VD---Verti-drain.*

Table 4-1 Changes with time in mean rootzone porosity values measured at -3 kPa moisture potentials averaged over all rootzones

| Meaurement item | | Air-filled porosity (%, v/v) | | | Water-filled porosity (%, v/v) | | | Total porosity (%, v/v) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Rootzone depth (mm) | | 0-35 | 35-70 | 70-105 | 0-35 | 35-70 | 70-105 | 0-35 | 35-70 | 70-105 |
| Sampling date | Apr-98 | 25.5$^{a}$ | 27.3$^{a}$ | 29.1$^{a}$ | 25.8$^{d}$ | 19.7$^{e}$ | 19.5$^{c}$ | 51.2$^{bc}$ | 46.9$^{a}$ | 48.5$^{a}$ |
| | May-99 | 9.5$^{b}$ | 14.1$^{b}$ | 16.9$^{b}$ | 41.2$^{c}$ | 26.3$^{d}$ | 24.8$^{b}$ | 50.7$^{c}$ | 40.4$^{b}$ | 41.7$^{b}$ |
| | Jul-00 | 2.1$^{c}$ | 11.3$^{c}$ | 15.0$^{c}$ | 50.0$^{b}$ | 27.7$^{c}$ | 25.2$^{b}$ | 52.2$^{b}$ | 39.0$^{c}$ | 40.1$^{c}$ |
| | May-01 | 2.3$^{c}$ | 9.3$^{d}$ | 13.1$^{d}$ | 49.2$^{b}$ | 29.3$^{b}$ | 26.4$^{a}$ | 51.5$^{bc}$ | 38.6$^{c}$ | 39.5$^{d}$ |
| | Jul-02 | 1.5$^{c}$ | 7.9$^{e}$ | 13.4$^{d}$ | 54.5$^{a}$ | 31.1$^{a}$ | 26.7$^{a}$ | 56.0$^{a}$ | 39.0$^{c}$ | 40.1$^{c}$ |
| LSD | | **1.6** | **1.3** | **1.0** | **1.6** | **1.2** | **0.9** | **1.3** | **0.5** | **0.4** |

***Means with the same letters in each column are not significantly different at the 0.05 level of probability. LSD--The least significant difference.***

was most pronounced during the first three years of the trial and most pronounced for the four sand-based rootzones (Figs. 4-4, 4-5, 4-6). However, the extent of changes with time in water and air-filled porosity at -3 kPa in the 35-70 mm depth was less than that in the surface. When the values of water and air-filled porosity were averaged over all rootzones, this change was still significant between all sampling occasions (Figs. 4-4, 4-5; Table 4-1).

In the 35-70 mm depth, the change in total porosity with time showed a similar pattern as with air-filled porosity, and was virtually the reverse of the trend in the 0-35 mm depth. Values of total porosity in this depth fell within the acceptable range for all rootzones throughout the duration of the trial despite the gradual decrease with time (Fig. 4-6; Table 4-1).

As with the 0-35 mm depth, some patterns of the effect of rootzone type on water and air-filled porosity were evident in the 35-70 mm depth. There were consistent and significant differences in water and air-filled porosity between the soil rootzone and the four sand-based rootzones on all sampling occasions. However, it was difficult to distinguish any significant difference in water and air-filled porosity between the three amended sand rootzones on all sampling occasions. The pure sand rootzone contained significantly less water-filled porosity and significantly more air-filled porosity than the three amended sand rootzones on the majority of occasions. For example, throughout the duration of the trial, values of water and air-filled porosity were always acceptable for the pure sand rootzone, whilst values all fell outside the acceptable range by July 2002 for all the other rootzones (Figs. 4-4, 4-5).

The effect of cultivation/aeration treatment on the aeration-moisture status was not apparent and somewhat erratic at the 35-70 mm depth. However, on two occasions, Verti-drain treatment was associated with a significant increase in air-filled porosity compared with scarification and HydroJect treatments (May 1999 and July 2000) and with a significant increase in total porosity compared with the control treatment (May 1999 and July 2002) (Figs. 4-4, 4-5, 4-6).

The results of water and air-filled porosity at -4 kPa and -5 kPa moisture potentials were similar to results obtained at -3 kPa in the 35-70 mm depth, (refer to Appendix Figs. 4-1, 4-2, 4-3, 4-4).

#### *4.4.3.3 75-105 mm rootzone depth*

There was a general trend of an increase in air-filled porosity and a decrease in water-filled porosity with the profile depth for all rootzone and cultivation/aeration treatments. The extent of this change was largest for the four sand-based rootzones. In contrast, total porosity values were largest in the surface 0-35 mm depth, intermediate in the 75-105 mm depth and lowest in the 35-70 mm depth for all rootzone and cultivation/aeration treatments (Figs. 4-4, 4-5, 4-6).

As with the other depths, the aeration-moisture status gradually deteriorated over time in the 70-105 mm depth for all rootzone and cultivation/aeration treatments, particularly during the first two years of the trial and particularly for the four sand-based rootzones. The general changes with time in water and air-filled porosity as well as total porosity in this layer were similar to the changes in the 35-70 mm depth with the exception of the following two points:

(1). Values of air-filled porosity at this depth remained well above the minimum threshold throughout the duration of the trial for the four sand rootzones (Fig. 4-4; Table 4-1).

(2). By May 1999, values of water-filled porosity were grouped statistically into three classes: the soil rootzone (highest: 40%), the amended sand rootzones (intermediate: 20-25%), and pure sand rootzone (lowest: 15%). The values of water-filled porosity remained at or just below the upper threshold limit for the four sand-based rootzones (Fig. 4-5; Table 4-1).

The results for water and air-filled porosity at -4 kPa and -5 kPa moisture potentials in the 70-105 mm of the rootzone were similar to results obtained at -3 kPa (refer to Appendix Figs. 4-1, 4-2, 4-3, 4-4).

### 4.4.4 Organic matter content (OMC)

#### *4.4.4.1 0-25 mm rootzone depth*

In the upper layer (0-25 mm), organic matter content (OMC) greatly increased with time for all rootzone and cultivation/aeration treatments, but the rate of increase was much faster for the soil rootzone and much faster during the first three years of the trial (Figs. 4-7, 4-8). For example, by April 2001 OMC averaged over all rootzones increased from 5.7% in April 1999 to 8.7% (from 7.6% to 14.0% for soil rootzone). This increase was significant between all sampling occasions over the first three years of the trial. However, after April 2001, the rate of increase appeared to have leveled off, with no significant differences in the averaged OMC being measured between the last two sampling occasions (Figs. 4-7, 4-8; Table 4-2).

The effects of the rootzone type on OMC were apparent throughout the four years of the trial. There was a consistent and significant difference in OMC values between the soil rootzone and the four sand-based rootzones. However, no significant differences in OMC values were measured between the four sand-based rootzones on all sampling occasions. OMC values in the 0-25 mm depth were not only well above the critical threshold (8%, w/w) throughout the four years of the trial for the soil rootzone, but also very close to the threshold after the third year following sowing for the four sand-based rootzones (Fig. 4-8).

Although none of the cultivation/aeration treatments was able to arrest the general increase in OMC over time, the effects of cultivation/aeration treatment on organic matter OMC were significant on most of the sampling occasions. Here, scarification and Verti-drain treatments resulted in significantly less accumulation of organic matter than the control and HydroJect treatments on three out of the four sampling occasions (Fig. 4-8).

#### *4.4.4.2 25-50 mm rootzone depth*

Organic matter content (OMC) in the 25-50 mm depth increased progressively with time for all rootzone and cultivation/aeration treatments over the five years of the trial. For example, by June 2002, OMC averaged over all rootzones increased from 1.9% in April 1999 to 3.2% (from 2.7% to 4.1% for the soil rootzone), and this increase was significant between all sampling occasions (Fig. 4-7, 4-8; Table 4-2).

The five rootzones were grouped statistically into three classes of OMC values: the soil rootzone (highest), the three amended sand rootzones (intermediate), and the pure sand rootzone (lowest). This result was significant on all sampling occasions over the first

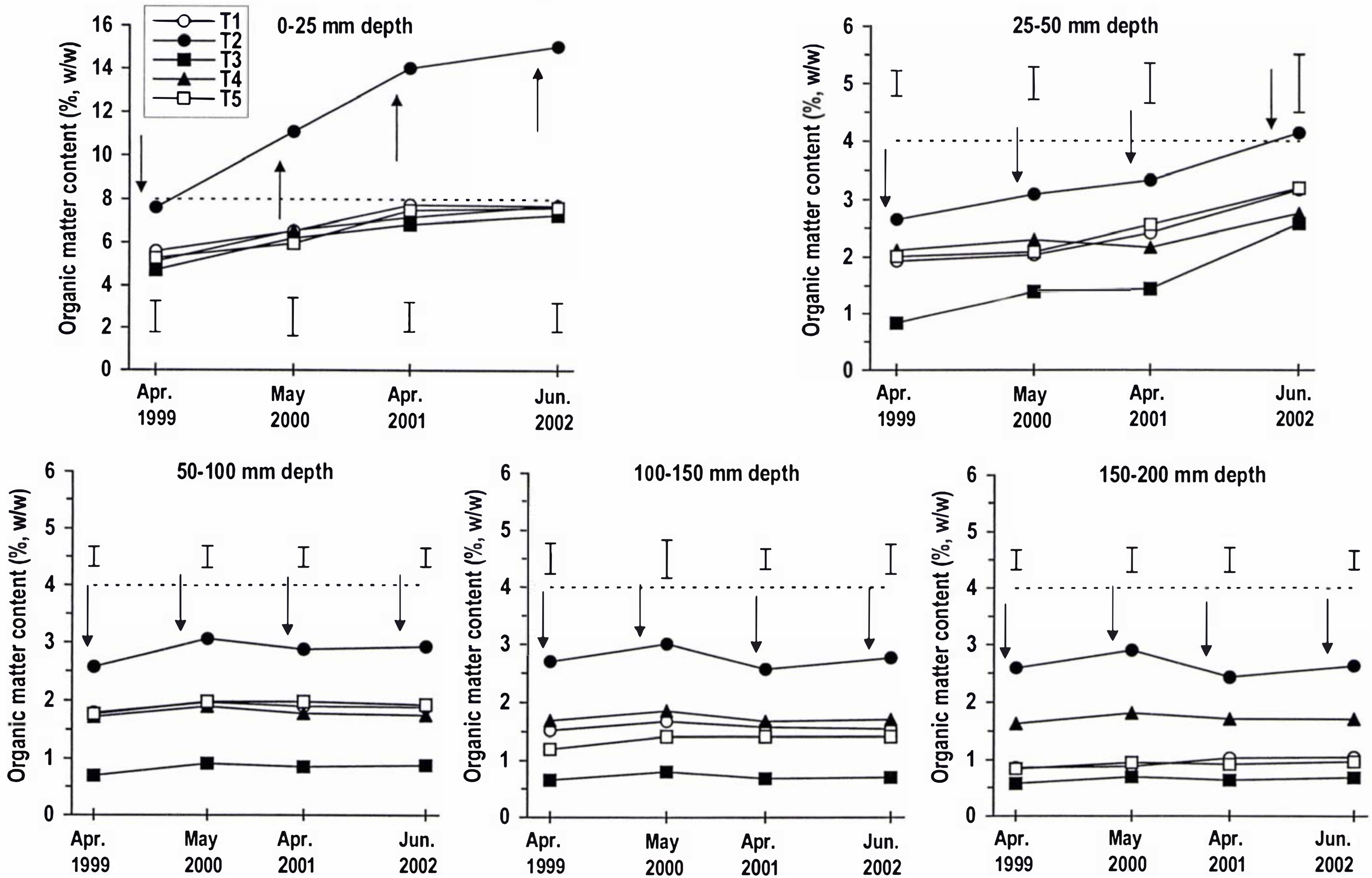



**Fig. 4-7 Changes in organic matter content with time in relation to each rootzone type**

*NS---not significantly different at the 0.05 level of probability. Error bars represent the LSD value for each group of treatments on each period of measurement. Arrows show the application time of the cultivation/aeration treatment. The dotted line represents values of 8% and 4% (w/w), recommended maximum values in the top layer (0-25 mm) and lower layer (25-250 mm) of the rootzones for New Zealand golf greens, respectively (Gibbs, Pers. comm.). T1---Partially amended sand rootzone, T2---Soil rootzone, T3---Pure sand rootzone, T4---Fully amended sand rootzone, T5---Partially amended sand + zeolite rootzone.*

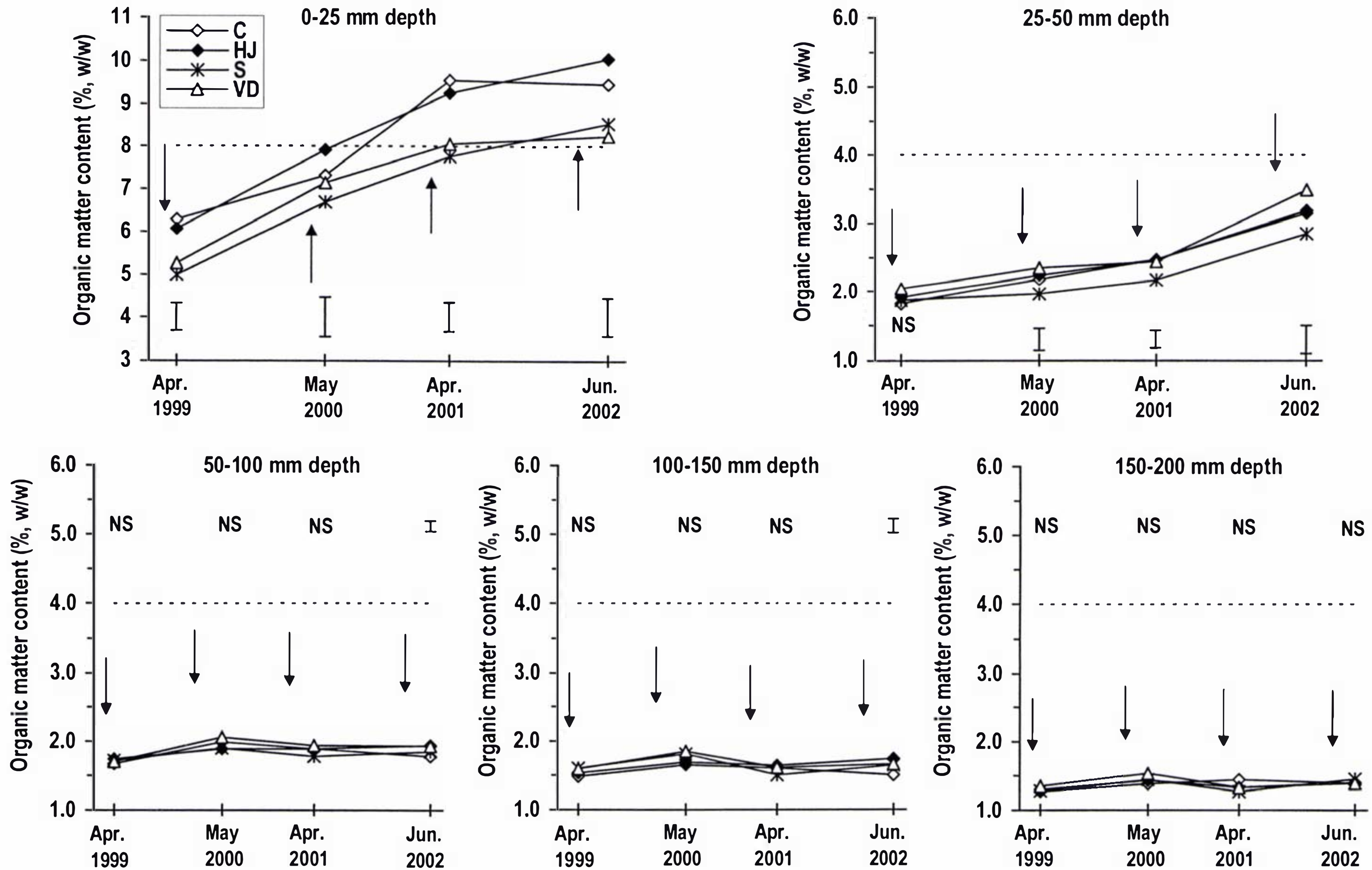



**Fig. 4-8 Changes in organic matter content with time in relation to each cultivation/aeration treatment**

*NS---not significantly different at the 0.05 level of probability. Error bars represent the LSD value for each group of treatments on each period of measurement. Arrows show the application time of the cultivation/aeration treatment. The dotted line represents values of 8% and 4% (w/w), recommended maximum values in the top layer (0-25 mm) and the lower layer (25-250 mm) of the rootzones for New Zealand golf greens, respectively (Gibbs, Pers. comm.). C---Control, HJ---HydroJect, S---Scarification, VD---Verti-drain.*

**Table 4-2 Changes with time in organic matter content (%, w/w) averaged over all rootzones**

| Sampling date | Rootzone depth (mm) | | | | |
|---|---|---|---|---|---|
| | 0-25 | 25-50 | 50-100 | 100-150 | 150-200 |
| **Apr-99** | $5.7^{c}$ | $1.9^{d}$ | $1.7^{b}$ | $1.6^{b}$ | $1.3^{c}$ |
| **May-00** | $7.3^{b}$ | $2.2^{c}$ | $2.0^{a}$ | $1.8^{a}$ | $1.5^{a}$ |
| **Apr-01** | $8.7^{a}$ | $2.4^{b}$ | $1.9^{a}$ | $1.6^{b}$ | $1.3^{bc}$ |
| **Jun-02** | $9.1^{a}$ | $3.2^{a}$ | $1.9^{a}$ | $1.6^{b}$ | $1.4^{ab}$ |
| **LSD** | **0.5** | **0.2** | **0.1** | **0.1** | **0.1** |

***Means with the same letters in each column are not significantly different at the 0.05 level of probability. LSD--The least significant difference.***

three years of the trial. After that time (April 2001), OMC values of the pure sand rootzone merged with the three amended sand rootzones, with no significant difference in OMC measured between them. OMC values in the 25-50 mm depth increased slightly above the 4% (w/w) critical threshold by June 2002 for the soil rootzone, but this did not happen for any of the sand-based rootzones (Fig. 4-7).

The effects of the cultivation/aeration treatment on OMC became evident in the 25-50 mm depth by May 2000. Here, scarification treatment resulted in significantly lower OMC than the control and the other cultivation/aeration treatments on most of the sampling occasions (Fig. 4-8).

#### *4.4.4.3 50-200 mm rootzone depth*

Organic matter content (OMC) decreased with rootzone depth for all rootzone and cultivation/aeration treatments. In each rootzone layer measured below the 50 mm depth (50-100, 100-150 and 150-200 mm), OMC values remained relatively constant over time (Figs. 4-7, 4-8; Table 4-2).

For the 50-100 mm and 100-150 mm depths, OMC values were grouped statistically into three categories: soil rootzone (highest values: 2.6-3.1%), amended sand rootzones (intermediate values: 1.2-2.0%) and pure sand rootzone (lowest values: 0.7-0.9%). This result was significant on all sampling occasions. A different categorization occurred in the bottom layer (150-200 mm) where the soil rootzone had the highest OMC, the fully amended sand rootzone intermediate, the pure sand and the two partially amended sand rootzones lowest, a reflection of the original rootzone design (Figs. 3-1, 4-7, 4-8).

Below the 50 mm depth, there was generally no significant cultivation/aeration effect on OMC on all sampling occasions.

### 4.4.5 Bulk density ($D_b$)

#### *4.4.5.1 0-35 mm rootzone depth*

Bulk density ($D_b$) in the surface 0-35 mm depth decreased with time throughout the duration of the trial for all rootzone and cultivation/aeration treatments, particularly for the soil rootzone (Fig. 4-9). For example, by July 2002 the $D_b$ value (averaged over all rootzones) decreased from 1.28 (t $m^{-3}$) in April 1998 to 1.09 (t $m^{-3}$) (from 1.32 to 0.88 t $m^{-3}$ for soil rootzone). This decrease in average $D_b$ was significant between most of the sampling occasions.

No significant differences in $D_b$ values were measured between the four sand-based rootzones on any sampling occasion. However, the soil rootzone tended to produce a lower $D_b$ value (0.9-1.3 t $m^{-3}$) than all the sand-based rootzones (1.1-1.3 t $m^{-3}$), but this result was significant only on the last two sampling occasions (May 2001, July 2002). $D_b$ values dropped below the minimum threshold (1.2 t $m^{-3}$) by July 2002 for all rootzones, and the extent of the decline was much greater for the soil rootzone than for the other rootzones (Fig. 4-9).

By May 1999, the effect of cultivation/aeration on $D_b$ became evident. Scarification and Verti-drain treatments resulted in higher $D_b$ values than the control and HydroJect treatments, and this result was significant on three out of the five sampling occasions.

#### *4.4.5.2 35-70 mm and 70-105 mm rootzone depths*

$D_b$ values in the 35-70 mm and 70-105 mm depths increased less than the surface 35 mm depth, but still significantly with time during the first three years of the trial for all rootzone and cultivation/aeration treatments. After that time (July 2000), $D_b$ values remained constant or they decreased slightly over time. By July 2002, $D_b$ values averaged over all rootzones had increased from 1.4 (t $m^{-3}$) in April 1998 to 1.6 (t $m^{-3}$) in the 35-105 mm depth and the values for the pure sand rootzone had increased slightly above the maximum threshold (1.6 t $m^{-3}$).

$D_b$ values also changed with profile depth for all rootzone and cultivation/aeration treatments. It was highest in the 35-70 mm depth, intermediate in the 70-105 mm depth and lowest in the surface 35 mm depth, and the reverse of the trend with total porosity (Fig 4-9).

No pattern could be determined between $D_b$ values of the rootzones at both lower depths measured. However, the pure sand (1.36-1.63 t $m^{-3}$) and soil (1.44-1.61 t $m^{-3}$) rootzones produced higher $D_b$ values than the other rootzones (1.33-1.59 t $m^{-3}$) although this result was not significant on most of the sampling occasions.

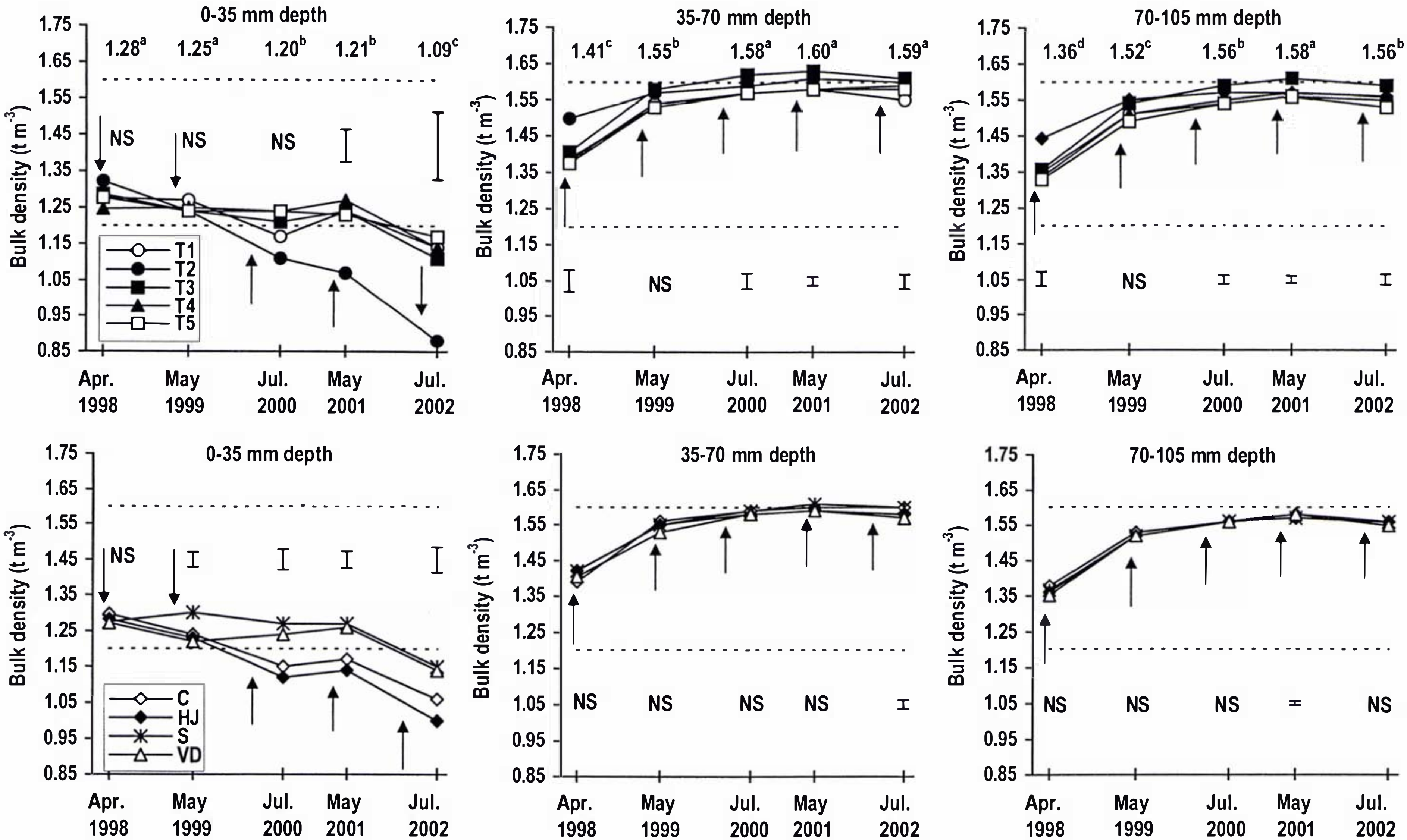



**Fig. 4-9 Changes in bulk density with time in relation to each rootzone type and cultivation/aeration treatment**

*NS---not significantly different at the 0.05 level of probability. Error bars represent the LSD value for each group of treatments on each period of measurement. Arrows show the application time of the cultivation/aeration treatment. Top row of numbers represents dry soil bulk density ($t\ m^{-3}$) averaged over all rootzones on each measurement occasion, and the means with the same letters in the upper right hand are not significant at the 0.05 level of probability. The dotted line represents a range of 1.2-1.6 ($t\ m^{-3}$), the recommended acceptabe range for laboratory-packed samples by USGA (1989, cited in Hummel 1993). T1---Partially amended sand rootzone,T2---Soil rootzone, T3---Pure sand rootzone, T4---Fully amended sand rootzone, T5---Partially amended sand + zeolite rootzone. C---Control, HJ---HydroJect, S---Scarification, VD---Verti-drain.*

There was no consistent and significant effect of cultivation/aeration treatment on $D_b$ in the 35-70 mm and 70-105 mm profile depths.

## 4.5 DISCUSSION

### 4.5.1 Water infiltration rate (IR)

The fast decrease of water infiltration rate during the first three years following establishment illustrated well the deterioration of rootzone physical properties under sports turf conditions that has been reported in many previous studies (e.g. Schmidt 1980; Gibbs & Baker 1989; Lodge & Baker 1993). After the third year following establishment, deterioration in infiltration rate leveled off and the rootzones appeared to have reached a "mature" condition, consistent with results of Curtis and Pulis (2001).

Throughout the duration of this trial it was only the soil rootzone that possessed infiltration rates well below minimum acceptable values (20 and 25 mm $h^{-1}$) recommended for golf turf by Hind *et al.* (1995) and Waddington *et al.* (1974) for UK and US conditions respectively. In contrast, the extent of the decrease in infiltration rate was not considered limiting to the greens' performance on all the four sand-based rootzones by the fifth year after establishment. This result is consistent with other similar studies (Elliot 1971; Baker 1988; Baker *et al.* 1999).

As expected, the recommended two modified USGA rootzones (Gibbs *et al.* 1997; Yang *et al.* 1998), performed as well as the standard USGA profile in terms of water infiltration rate. However, during the first three years following establishment, the unnecessarily fast infiltration rate on the pure sand rootzone would likely lead to poor water and nutrient retention in the profile (Snow 1992), and this may have been the reason why there were difficulties in the earlier stages of turf establishment on these plots (Gibbs *et al.* 2000).

Generally, none of the cultivation/aeration treatments were able to halt the overall decrease in infiltration rate at the frequency of treatment used (twice per year) though some increase in infiltration rate was evident on several occasions immediately after Verti-drain treatment. The increase in infiltration rate following Verti-drain treatment was probably due to the deeper penetration and better loosening effect from this operation (Carrow 1992; Baker 1995; Shim & Carrow 1997). However, the benefit of Verti-drain treatment was extremely short-lived (approximately two months in the present study). Similar temporary cultivation effects have been noted in other studies (Lodge & Baker 1993; McAuliffe *et al.* 1993). The implication of this result is that the cultivation/aeration treatment should be applied more frequently to maintain a consistent improvement in water infiltration rate of golf greens.

The reduction in infiltration rate resulting from scarification treatment was consistent with observations made by Engel and Alderfer (1967) where infiltration rate was reduced by 56% on twice yearly scarified plots. This result was probably associated with surface smearing and a greater potential for immediate surface compaction following the scarification operation (Carrow & Petrovic 1992; Murphy *et al* 1993a).

Consistent and significant increases in infiltration rate following HydroJect treatment, reported in several previous studies (Murphy & Rieke 1994; McAuliffe *et al.* 1993; Wu *et al.* 2001), did not occur in the present trial. This result was consistent with that of Bunnell *et al.* (2001) and likely due to the low frequency of the treatment or holes filling up quickly.

### 4.5.2 Oxygen diffusion rate (ODR)

Oxygen diffusion rate in the 50 mm depth fluctuated erratically with time or/and season in all the rootzone and cultivation/aeration treatments. Factors such as rootzone moisture and temperature, as opposed to cultivation/aeration treatments could have been responsible for this behaviour (for climate data, please refer to Appendix Figs. 3-1, 3-2) (Stolzy & Letey 1964; Mohsin & Kahn 1977; Glinski & Stepniewski 1985). However, in spite of the erratic fluctuation, a general pattern of a progressive decline over time in the ODR was still apparent. This general trend is to be expected given that the physical properties (e.g. air-filled porosity) of golf green profiles have been shown in other studies to deteriorate with time through man-made causes and natural causes (Baker 1988; Hind *et al.* 1995). However, the speed of the deterioration in the ODR in this trial, especially in the 50 mm depth, was still surprising considering it was not reflected to the same extent in other measurements (e.g. root growth). For example, by the fourth year following establishment, the ODR values in the 50 mm depth of the soil and pure sand rootzones had dropped well below the critical level, defined here as 20 ×

$10^{-8}$ g $cm^{-2}$ $min^{-1}$ for sports turf (McIntyre 1970; O'Neil & Carrow 1983). The large decrease in ODR values with time in this depth could be associated with the faster accumulation of organic matter in the upper portion of these rootzones (Carrow 1995, 2004a, b, c). The implication of this effect is that commencing a cultivation/aeration treatment earlier to control surface organic matter accumulation is likely to be important for turfgrass growth.

There was a noticeable trend for the soil and pure sand rootzones to perform consistently poorer than the three modified USGA rootzones in terms of ODR. Whilst for the soil rootzone this result can be explained on account of its poor air-filled porosity values, it is difficult to explain the result for the pure sand rootzone given that ODR is known to be positively correlated with air-filled porosity (Murphy & Field 1996). The consistently low ODR values for the pure sand rootzone might have been a reflection of the limitation of this measurement technique under the low moisture conditions prevalent in the rootzone (i.e. 7-18%) (Stolzy & Letey 1964; Mohsin & Kahn 1977; Glinski & Stepniewski 1985). In contrast, the better ODR readings for the standard USGA profile compared with the two modifications in the present trial may have been a reflection of the more favorable moisture and biological status in full compost-amended sand. This was the only result in this trial indicating some physical benefit from organically amending the whole rootzone compared with just the surface 100-150 mm being amended as recommended by Gibbs *et al.* (1997).

The effects of cultivation/aeration treatment on ODR became more and more evident with time, as physical properties of the rootzones gradually deteriorated close to the critical threshold. For example, by the fourth year after sowing when ODR values had decreased close to the critical threshold, a pattern emerged where the three cultivation/aeration treatments resulted in significantly higher ODR values in the 50 mm depth than the control. For scarification treatment, this result may be linked to better organic matter control and the resultant reduction in the blocking up of rootzone pores (Van Wijk 1980). However, for the Verti-drain and HydroJect treatments, this result may be associated with the deeper penetration and better loosening effect of these operations (Carrow 1992; Baker 1995; Shim & Carrow 1997; Bunnell & McCarty 2001).

### 4.5.3 Water and air retention

The progressive increase in water-filled porosity and the progressive decrease in air-filled porosity over time, particularly during the first three years following establishment and particularly in the 0-35 mm depth, represents a scenario that demonstrates the typical aging of physical properties within a sports turf rootzone. For example, in the 0-35 mm depth by the third year after sowing, air-filled porosity measured at -3 kPa had dropped well below the preferred value of 10-15% recommended by Hind *et al.* (1995) and by Baker and Richards (1997) for golf greens. In contrast, water-filled porosity of all rootzones measured at -3 kPa increased well above the maximum preferred value of 25% recommended for laboratory-packed samples by Hummel (1994). The primary reason for this reversal change in water and air-filled porosity over time in the surface is likely due to the occupation of air pores by surface organic matter (Curtis & Pulis 2001). This process may reduce total porosity only slightly, but its greatest impact is to shift the function of the surface profiles from aeration to water storage by reducing the percentage of macropores (Vavrek 1992; Thien 1994; Baker 1995). However, similar to findings obtained by Curtis and Pulis (2001), after the third year following establishment, all the rootzones reached a "mature" condition and the deterioration in water and air retention leveled off.

The reduced percentage of macropores in the surface will potentially lead to deficiency in oxygen supply and poor growth of turfgrass roots (Adams *et al.* 1993; Hind *et al.* 1995). However, below the 35 mm depth, water and air-filled porosity of the sand-based rootzones still remained acceptable. This result illustrates the on-going need to keep the surface open, especially for sand-based rootzones (O'Brien & Hartwiger 2003).

This trial also confirmed that the large decrease in surface air-filled porosity over time was not associated with a decline in total porosity as also reported by Vavrek (1992). In fact, total porosity gradually increased over time in the surface 35 mm of the profiles for all rootzone and cultivation/aeration treatments, though a reversal trend was observed below the 35 mm depth. Moreover, all the sand-based rootzones had higher surface air-filled porosity but lower total porosity compared with soil rootzone, and none of the rootzones indicated serious total porosity problems in the present study at any profile depth studied. This result is consistent with findings of others (Gibbs 1992;

Hind *et al.* 1995; Neylan & Robinson 1997). The implication is that total porosity is a relatively irrelevant and insensitive physical factor for predicting physical performance of golf greens (Carter 1993).

As expected, the soil rootzone showed a complete absence of air-filled porosity as well as saturation levels of water-filled porosity at -3 kPa moisture potential at all depths measured. The pure sand rootzone provided the best aeration-moisture status, but this was the only result obtained in the present study that showed that the pure sand rootzone possessed some physical advantages over the three amended sand rootzones. The standard USGA rootzone showed no advantages in aeration-moisture status compared with the two modified USGA rootzones.

None of the cultivation/aeration treatments were able to halt an overall deterioration in aeration-moisture status of all rootzones at the frequency of treatment used (twice per year). The insensitivity of HydroJect treatment in improving aeration-moisture status in the present trial has also been shown by others (Bunnell *et al.* 2001; Bunnell & McCarty 2001), but other studies have shown the opposite result (Vavrek 1992; McAuliffe *et al.* 1993; Murphy & Rieke 1994). It is difficult to explain the contradictory results obtained in previous studies. However, the insensitivity of HydroJect treatment in improving aeration-moisture status in the present trial was most likely due to the low frequency of the treatment.

The significant increase in air-filled porosity at the 0-70 mm depth associated with Verti-drain treatment supported many previous studies (Carrow 1992; Lee & Rieke 1993; McAuliffe *et al.* 1993; Shim & Carrow 1997). This result was likely due to the greater shattering/decompaction mode of action of this piece of equipment compared with HydroJect and scarification treatments (Vavrek 1992). In addition, the present study also confirmed that the positive effect of Verti-drain treatment was very short-lived (McAuliffe *et al.* 1993; Murphy & Rieke 1994). To achieve a consistent, significant and long-term improvement in soil physical performance, the cultivation/aeration treatments should be applied more frequently than twice per year under golf green conditions (Gibbs *et al.* 2001).

### 4.5.4 Organic matter content (OMC)

The progressive increase in organic matter in the surface 50 mm over time mirrored the continuous growth and death of grass shoots and roots and the gradual deterioration of rootzone physical properties that commonly occurs on golf greens (Murphy *et al.* 1993b). It has been reported in previous studies that organic matter is perhaps the most important factor affecting the possible demise of sand-based rootzones (Habeck & Christians 2000; Curtis & Pulis 2001).

The very fast accumulation of organic matter in the surface of the soil rootzone was most likely a result of a much poorer aeration status of this rootzone and a higher than necessary nitrogen input being used in order to standardize the management of the different rootzones (Gibbs *et al.* 2001). For example, by the fifth year after sowing, OMC (%, w/w) of the soil rootzone in the surface 25 mm depth was well above 8%, defined here as the maximum critical value for New Zealand golf greens (Glasgow & Gibbs 2003). It is predicted that a thatch build-up in the soil rootzone will become a serious problem well before the four sand-based rootzones.

OMC values of the pure sand rootzone had merged with the three compost-amended sand rootzones by the second year following establishment. The faster rate of organic matter accumulation in the surface of the pure sand rootzone compared with the amended sand rootzones implied that either turfgrass growth was faster, and/or there was a less favorable biotic environment (slower decomposition rate) in pure sand compared with compost-amended sand. By the fourth year following sowing, OMC values in the surface 25 mm depth of the four sand-based rootzones were also very close to the maximum critical value 8%. The speed of increase in OMC in the upper portion of the sand-based rootzones was still rapid considering the very low OMC (0-2.1%) in original profiles of the four sand-based rootzones. However, there was no measurable difference in OMC between the standard USGA profile and the two modified USGA rootzones.

By the fourth year following establishment, all rootzones appeared to have reached a "mature" condition. The increase in organic matter in the surface 25 mm depth tended to have gradually stabilized on all the rootzone treatments. This result was similar to that of the Curtis and Pulis (2001).

Below 50 mm rootzone depth, OMC values were grouped statistically into three classes: soil rootzone > compost-amended sand rootzones > pure sand rootzone. For the 50-100 mm depth, this categorization reflected the original OMC of the rootzone materials as opposed to changes in OMC associated with root growth. For the 100-150 mm depth, this categorization suggested that there had been some migration of organic material out of the 0-100 mm amended depth of the two partially amended sand rootzones. Nevertheless, below 50 mm rootzone depth, there was little increase in organic matter with time and OMC values were within the preferred range (≤ 4%) for all rootzones. So, organic matter that accumulated in the rootzones was confined only to the surface of the profiles. It is the manipulation of this surface layer by physical treatment that is perhaps the greatest safeguard in ensuring the long-term integrity of the sand-based rootzones (Habeck & Christians 2000; Curtis & Pulis 2001).

Though none of the cultivation/aeration treatments could arrest the overall increase in OMC over time, some significant cultivation/aeration effects become evident in the surface 0-25 mm by the time of the second year after the trial commence. Here, the two organic matter removal treatments (scarification and Verti-drain) resulted in significantly less surface-OMC than the control and HydroJect treatments. By the time of the third year, the cultivation/aeration effects had extended to the top 50 mm of the rootzone, but it was only scarification treatment that resulted in significantly less OMC than the other cultivation/aeration treatments. The lack of significant differences with the Verti-drain treatment in the top 50 mm depth was probably because machinery was unavailable to carry out regular Verti-drain with hollow tines. On all occasions, the effect of the cultivation/aeration treatment on organic matter accumulation was confined only to the top 50 mm depth and there were no significant cultivation/aeration effects on the control of organic matter accumulation below 50 mm.

### 4.5.5 Bulk density ($D_b$)

The gradual decrease of bulk density ($D_b$) in the surface 25 mm and the gradual increase in the lower rootzone depths over time reflected the surface accumulation of organic matter and the dynamic aging of rootzone physical properties under sports turf conditions (Schmidt 1980; Lodge & Baker 1993; Murphy *et al.* 1993b). For example, by the fifth year after sowing, $D_b$ values in the surface 35 mm of all the rootzones dropped below the minimum acceptable value of 1.2 t $m^{-3}$ recommended by the USGA

(1989, cited in Hummel 1993) for laboratory compacted materials. However, $D_b$ values were generally acceptable below the 35 mm depth. As expected, this trend was virtually the reverse of the trend for total porosity. The decrease in $D_b$ value in the surface was most likely due to the accumulation of organic matter and the structured roots in the upper portion of the rootzones (Adams 1973; Habeck & Christians 2000; Curtis & Pulis 2001). However, for the lower rootzone depths (35-70, 70-105 mm), the increase in $D_b$ values with time was a reflection of the gradual buildup of rootzone compaction under sports turf conditions (Schmidt 1980; Thien 1994). The highest $D_b$ value in the 35-70 mm depth was similar to the result of Van Wijk (1980) who reported that the subsurface (50-100mm) was most compacted under sports turf conditions. The larger decrease in surface $D_b$ values for soil rootzone and the control and HydroJect treatments was expected considering that accumulation of organic matter was fastest under these treatments (Figs. 4-7, 4-8).

However, similar to the results for total porosity, the consistent and significant effects of cultivation/aeration treatments on $D_b$ value were not found at lower rootzone depths during this study. Moreover, no pattern in $D_b$ value was evident at the lower depths between the four sand-based rootzones on all measurement occasions. These results imply that bulk density, like total porosity, is not a sensitive physical factor in predicting golf green performance (Waddington *et al.* 1974; Hummel 1993).

## 4.6 SUMMARY AND CONCLUSIONS

The soil rootzone possessed physical properties consistently below minimum acceptable values. Quantitative benefits of upgrading from a soil-based to a sand-based rootzone were significant in terms of improved infiltration rate, reduced rate of organic matter accumulation, and increased macroporosity and oxygen diffusion rate. However, physical deterioration was considerable for all the sand-based rootzones during the first three years after sowing. By the third year after sowing, porosity in the upper portion of the rootzones had also been considered limiting to the green's performance of the sand-based rootzones. After that time, the greens appeared to have reached a mature status and the physical deterioration leveled off.

There was little indication that the two modified USGA profiles conferred a worse rootzone physical performance compared with a standard USGA profile, or that there were any measurable differences in rootzone physical properties between the pure sand rootzone and the three amended sand rootzones in the long run.

Verti-drain treatment was generally associated with a significant improvement in water infiltration rate and rootzone porosity status, and a reduction in organic matter accumulation near the surface. However, beneficial effects of a single Verti-drain operation on rootzone physical properties (e.g. infiltration rate) lasted only about two months. Consistent and significant effects of HydroJect treatment on rootzone physical properties were not apparent. In contrast, scarification treatment showed that whilst it was effective in significantly reducing organic matter accumulation near the surface, it also caused a significant reduction in water infiltration rate. However, none of the cultivation/aeration treatments could halt the general physical deterioration over time under the twice-yearly frequency of the treatment. These results indicated that a) the twice-yearly frequency of the cultivation/aeration treatments appeared inadequate for golf greens, and that a higher frequency of application may be required; and (d) scarification should not be used in isolation of other physical cultivation.

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# 5. EFFECT OF ROOTZONE COMPOSITION AND CULTIVATION/AERATION TREATMENT ON SWARD CHARACTERISTICS OF GOLF GREENS

## 5.1 ABSTRACT

This chapter reports the monitoring of golf green performance during the first five years after sowing as measured by species composition, root growth and visual turf qualities of five alternative golf green rootzones under New Zealand conditions. Rootzone treatments were partially amended sand rootzone, soil rootzone, pure sand rootzone, full amended sand rootzone and partially amended sand + zeolite rootzone. A split-plot design was superimposed on the rootzone treatments consisting of twice-yearly cultivation/aeration treatments (control, HydroJect, scarification and Verti-drain).

Results showed that there was a measurable deterioration in sward performance for all rootzone and cultivation/aeration treatments during the first five years after sowing in terms of root growth, species composition and visual turf qualities. For example, there was a gradual shift of root growth towards the surface for all rootzone and cultivation/aeration treatments during the first five years. Moreover, the proportion of *Agrostis* and total weed cover in the sward increased progressively, whilst the proportion of *Festuca* and total turfgrass cover decreased progressively for all rootzone and cultivation/aeration treatments throughout the trial. Nevertheless, detrimental changes in species composition in the present study, which had a 75:25 (*Festuca: Agrostis*; w/w) seed mixture, were not as severe as has been found in some overseas trials established with a traditional UK 80:20 (*Festuca: Agrostis*; w/w) seed mixture.

There were marked differences in sward characteristics between rootzone types. The three compost-amended sand rootzones were associated not only with the best turf visual quality, but also with the least changes over time in relative balance of *Festuca* and *Agrostis* species in the sward. In contrast, the pure sand rootzone contained the best root distribution with rootzone depth on the one hand, but had the greatest incidence of dry patch disorder on the other. For the soil rootzone, although it had negligible incidence of dry patch disorder, disease and pest damage (i.e. dollar spot and sod webworm), it had the poorest root distribution, the greatest changes over time in relative balance of *Festuca* and *Agrostis*, poorest visual turf quality and greatest weed cover. These disadvantages of the soil rootzone were considered to far outweigh the practical disadvantage of the four sand-based rootzones. However, the practical

advantages of omitting organic amendment in the pure sand rootzone were outweighed by subsequent risk of dry patch disorder.

There was little indication that organic amendment of only the top 100 mm of a sand rootzone conferred any poorer green performance in terms of species composition, root growth and visual turf qualities compared with full organic amendment throughout the whole rootzone. Furthermore, there was no indication that a buried layer of zeolite-amended sand conferred better root growth and distribution.

HydroJect treatment was particularly effective in minimizing the occurrence of dry patch disorder on sand-based rootzones when used in conjunction with a proprietary wetting agent. However, twice yearly HydroJect treatment (with wetting agent) tended to induce higher incidence of disease and pest damage (i.e. dollar spot and sod webworm). In contrast, scarification treatment gave variable response, reducing root mass, hence organic matter accumulation, near the surface on the one hand, but decreasing visual scores of turf density and inducing more weed invasion on the other. Beneficial effects of twice yearly Verti-drain treatment on root growth and distribution were not apparent.

It was concluded that: (1) the New Zealand practice of constructing only the top 100 mm of the sand rootzone with organic-amended sand was of no disadvantage in terms of sward characteristics compared with a fully amended USGA-type rootzone; (2) the supposed advantage of burying a zeolite-amended sand layer at 100-200 mm depth ostensibly for encouraging deep rooting in the long term was not apparent under the current experimental conditions; (3) HydroJect treatment is likely to be an effective management tool for prevention of dry patch on sand-based golf greens when used in conjunction with a proprietary wetting agent.

**KEYWORDS**: Dry patch, HydroJect, root growth, species composition, scarification, Verti-drain, visual turf quality and zeolite.

## 5.2 INTRODUCTION

Turf is a covering of grass vegetation plus the matted, upper stratum of rootzone media filled with roots and/or rhizomes (Beard 1973). An ideal golf green should possess sward characteristics that have green, uniform, dense and relatively stable turfgrass cover with deep, healthy and well distributed root systems, as well as minimum incidences of dry patch disorder and other diseases, weeds and pests. The sward characteristics of golf greens, as represented by species composition, root growth and visual turf qualities, have large influences on their playing quality and visual attractiveness (Baker *et al.* 1995, 1997b). The measurement of sward characteristics together with rootzone physical properties may help target management practices more accurately towards improving green performance. This could come about by a better understanding of the hidden processes taking place in the rootzone media through illustrating any causal relationships between rootzone physical properties and observed sward characteristics (Lodge & Lawson 1993).

Much research has been conducted in the above area during the last decade. For cool season turf, studies have shown that the relative ratios of *Festuca*/*Agrostis*, visual turf qualities and dry patch disorder of golf greens are greatly influenced by the rootzone composition and subsequent management. These sward characteristics have changed dynamically with wear and green age (York & Baldwin 1992; Lodge & Lawson 1993; Baker *et al.* 1997b; Lawson 2000). Root growth and distribution in the rootzone has been shown to be significantly affected by layered structures of rootzones (Leboucher 1989) and by incorporation of zeolite into sand (Ferguson *et al.* 1986). Hannaford and Baker (2000) reported that different types of sand and amendment also had large effects on rooting depth in sand-based golf greens, and rooting depth reduced with time in sand culture (McAuliffe & Wells 1988; Carrow 1995). Despite this work, there is little quantitative information on the relative advantages and disadvantages in the long-term sward characteristics between the standard USGA profile, the two modified USGA profiles (Gibbs *et al.* 2000; Myer *et al.* 2003) and a pure sand profile.

Published information on effects of the newly introduced cultivation/aeration management (i.e. HydroJect, scarification and Verti-drain) on species composition, visual turf quality and dry patch disorder is also limited under golf green conditions.

Especially, it appears that effects of rootzone composition on root growth and distribution are relatively neglected areas of research in sports turf (Hannaford & Baker 2000). Moreover, findings on effects of cultivation/aeration treatments on root growth and distribution under sports turf conditions are rather contradictory (Rieke & Murphy 1989; McAuliffe *et al.* 1993; Murphy *et al.* 1993; Murphy & Rieke 1994; Carrow & Shim 1997). Therefore, it is necessary to carry out further studies on these aspects.

The aim of this trial is to study effects of rootzone type (including zeolite incorporation and layered structure of rootzones) and cultivation/aeration treatment on species composition, root growth and visual turf qualities of golf greens.

## 5.3 MATERIALS AND METHODS

For details of the trial design, methods and statistical analysis, prefer to the Chapter three in this thesis.

## 5.4 RESULTS

Whilst significant differences between individual rootzone and cultivation/aeration treatments were found on several occasions, at no stage in this trial were any significant interaction effects found between rootzone and cultivation/aeration treatments.

### 5.4.1 Species composition and stability

There was a general trend for a decreasing percentage of *Festuca* and total turfgrass cover (*Festuca* + *Agrostis*), and for an increasing percentage of *Agrostis* (browntop) and total weed cover (i.e. a sum of *Poa annua*, moss and flat-weeds) in the swards throughout the four years of the trial for all rootzone and cultivation/aeration treatments. For example, between the period from September 1999 to September 2002, when the turf cover of each sward component was averaged over all rootzones, the percentage of *Festuca* and total turfgrass cover decreased from 23.7% and 97.6% to 5.8% and 93.3% respectively, whilst the percentage of *Agrostis* and total weed cover increased from 73.9% and 2.1% to 87.5% and 6.1% respectively, with significant changes measured on most of the measurement occasions (for climate data, please refer to Appendix Figs. 3-1, 3-2). However, the percentage of bare-ground remained relatively constant over the same time period (Figs. 5-1, 5-2; Table 5-1).

The relative proportion of *Festuca* and *Agrostis*, and the relative cover of total turfgrass and total weeds was significantly affected by rootzone type, with the greatest contrast being between the sand-based rootzones and the soil rootzone (Figs. 5-1, 5-2). However, there were generally no significant differences in the relative proportion of *Festuca* and *Agrostis*, or total turfgrass and total weed cover between the four sand-based rootzones during the whole measurement period. For example, during the four years of the trial, the four sand-based rootzones possessed higher percentage of *Festuca* (5-34%) and total turfgrass cover (95-96%) compared with only 1-10% and 89% cover, respectively, on the soil rootzone. This result was significant for *Festuca* on two of the four measurement occasions (Sept. 1999, Sept. 2001) and significant for total turfgrass cover on one occasion (Sept. 2001). A reverse pattern was evident for *Agrostis* and total weed cover, with the four sand-based rootzones showing smaller, though usually not significant, percentage of *Agrostis* (63-85%) and total weed cover (0.7-7%) compared with 85-90% and 3.5-10% cover, respectively, on the soil rootzone (Figs. 5-1, 5-2).

The relative proportion of *Festuca*, total turfgrass and total weed cover was significantly affected by cultivation/aeration treatment, but the relative proportion of *Agrostis* was generally insensitive to cultivation/aeration treatment. For example, HydroJect treatment as associated with increased *Festuca* cover, and this result was significant compared with scarification treatment on two occasions (Nov. 2000, Sept. 2002) and the control on one occasion (Nov. 2000). In contrast, scarification treatment resulted in significantly lower total turfgrass cover on one occasion compared with HydroJect treatment (Sept. 2002) and the control (Sept. 2001), but significantly higher total weed cover compared with HydroJect treatment (Sept. 2002) and the control (Sept. 2001, Sept. 2002) (Figs. 5-1, 5-2).

### 5.4.2 Root growth and distribution

For reasons of brevity, results are presented here for the 0-5C mm and 50-250 mm depths only, with results expressed both as an absolute total root mass (living and dead roots) and as a percentage of roots (a percentage of roots in the whole profile).

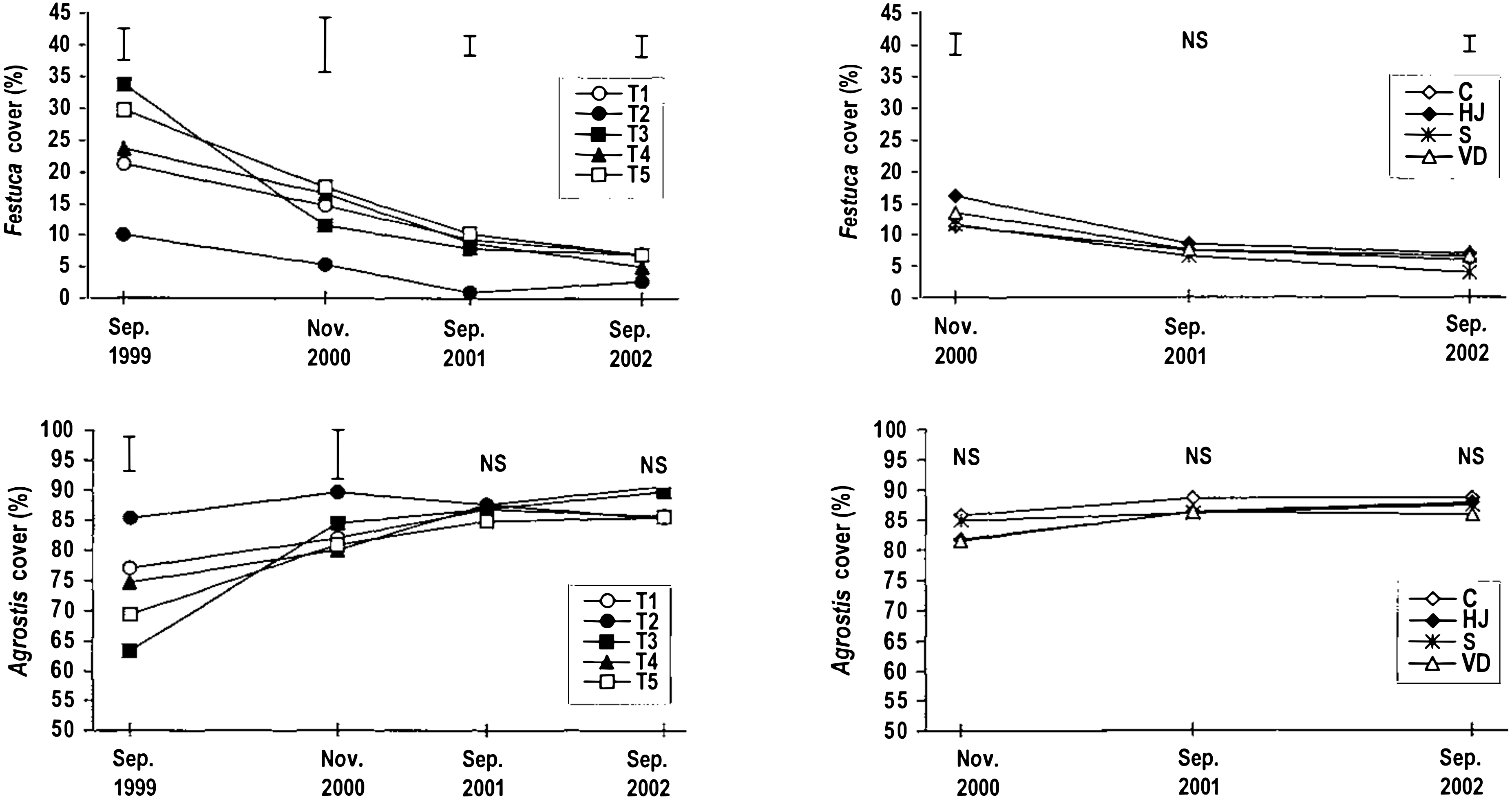


**Fig. 5-1 Changes with time in relative ground cover (%) of *Agrostis* and *Festuca* in turf sward in relation to rootzone type and cultivation/aeration treatment**

*NS---not significantly different at the 0.05 level of probability; Error bars represent the LSD values for each group of treatments on each period of measurement; T1---Partially amended sand rootzone, T2---Soil rootzone, T3---Pure sand rootzone, T4---Fully amended sand rootzone, T5---Partially amended sand + zeolite rootzone; C---Control, HJ---HydroJect, S---Scarification, VD---Verti-drain.*

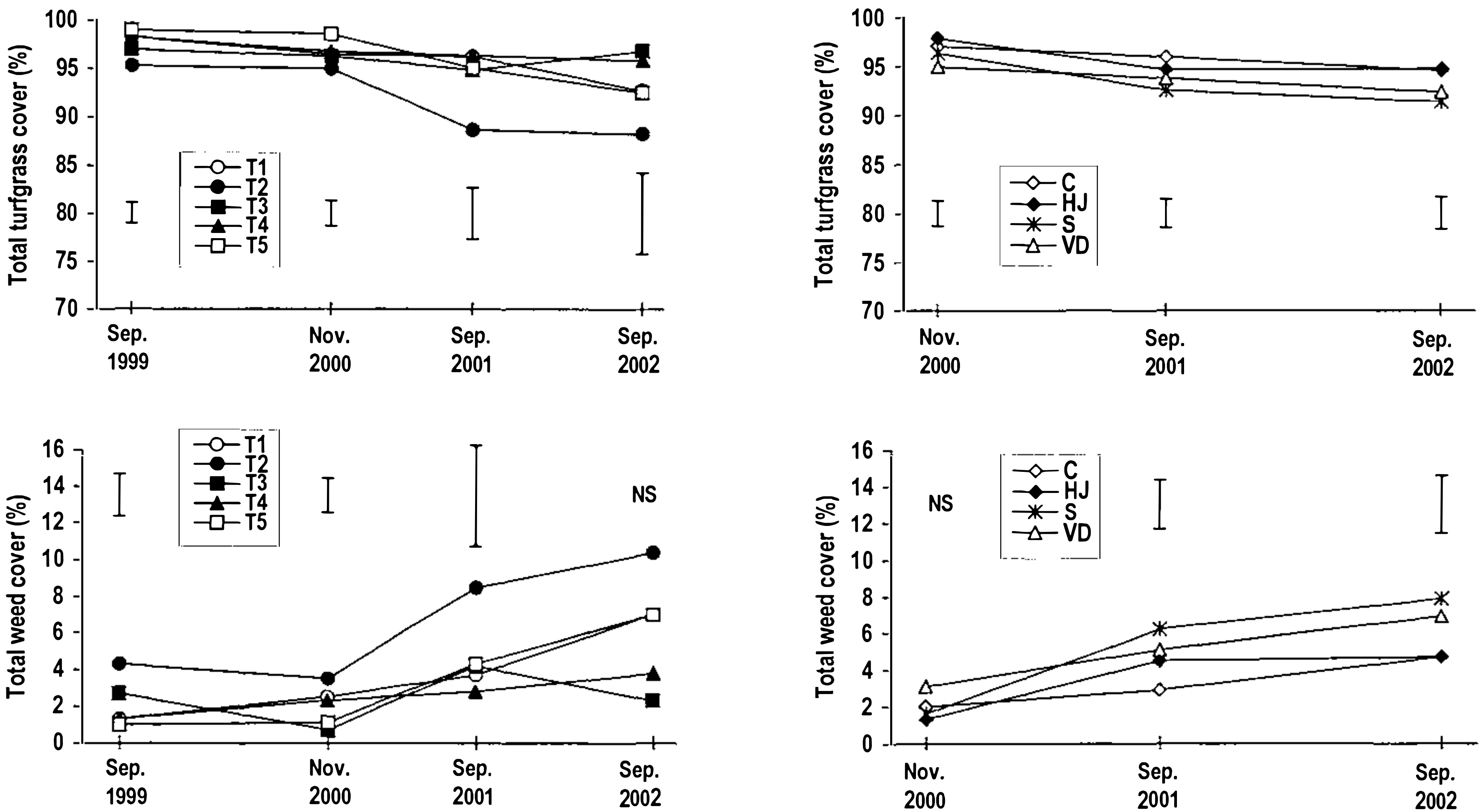


**Fig. 5-2 Changes with time in relative ground cover (%) of total turfgrasses and total weeds in turf sward in relation to rootzone type and cultivation/aeration treatment**

*NS---not significantly different at the 0.05 level of probability; Error bars represent the LSD values for each group of treatments on each period of measurement; T1---Partially amended sand rootzone, T2---Soil rootzone, T3---Pure sand rootzone, T4---Fully amended sand rootzone, T5---Partially amended sand + zeolite rootzone; C---Control, HJ---HydroJect, S---Scarification, VD---Verti-drain.*

**Table 5-1 Changes with time in species composition (%) averaged over all rootzones**

| Meaurement date | Relative ground cover (%) | | | | |
|---|---|---|---|---|---|
| | *Festuca sp.* | *Agrostis sp.* | Total turfgrasses | Total weeds | Bare ground |
| **Sep-99** | 23.7$^{a}$ | 73.9$^{c}$ | 97.6$^{a}$ | 2.1$^{b}$ | 0.3$^{c}$ |
| **Nov-00** | 13.1$^{b}$ | 83.5$^{b}$ | 96.6$^{a}$ | 2.0$^{b}$ | 1.4$^{a}$ |
| **Sep-01** | 7.4$^{c}$ | 86.8$^{a}$ | 94.3$^{b}$ | 4.7$^{a}$ | 1.0$^{ab}$ |
| **Sep-02** | 5.8$^{c}$ | 87.5$^{a}$ | 93.3$^{b}$ | 6.1$^{a}$ | 0.6$^{bc}$ |
| **LSD** | **2.22** | **2.93** | **1.53** | **1.47** | **0.41** |

***Means with the same letters in each column are not significantly different at the 0.05 level of probability. LSD--The least significant difference.***

### *5.4.2.1 0-50 mm rootzone depth*

In the 0-50 mm depth, both the absolute root mass and the percentage of roots increased progressively during the first five years following establishment for all rootzone and cultivation/aeration treatments (Fig. 5-3). For example, by January 2003, total root mass averaged over all rootzones tripled from 613 $g/m^2$ in April 1998 to 2153 $g/m^2$, with significant increases measured between most of the sampling occasions. In this same time period, the mean percentage of roots in the 0-50 mm depth increased from 85% to 97%, with significant changes also measured on the majority of sampling occasions (Table 5-2).

There was an effect of rootzone type on the absolute root mass in the 0-50 mm depth. During the first two years following establishment, the pure sand rootzone contained significantly more root mass than all other rootzones. After the third year, the highly compacted soil rootzone contained more root mass than the four sand-based rootzones though this result was not always significant. There was no significant difference in the absolute root mass between the three amended sand rootzones during the whole measurement period or between the four sand-based rootzones after the third year following establishment (Fig. 5-3).

Differences in root growth were more apparent by examining the percentage of roots as opposed to absolute root mass. During the five years of the trial, the soil rootzone contained the greatest percentage of root mass (90-98%) in the surface 50 mm compared with the four sand-based rootzones though this result was not always significant. In contrast, from April 1999, the pure sand rootzone contained the smallest percentage of roots (82-94%) compared with the other rootzones, and this result was significant on four out of the ten measurement occasions. Similar to the result for the absolute root mass, there was no significant difference in the percentage of roots between the three compost-amended rootzones on any sampling occasion (Fig. 5-3).

Significant cultivation/aeration trends developed two years following establishment, with scarification and Verti-drain treatments containing less root mass in the surface 50 mm compared with the control and HydroJect treatments. For example, from April 1999, scarification treatment resulted in significantly less root mass compared with the control and HydroJect treatments on seven out of the eight measurement occasions. For

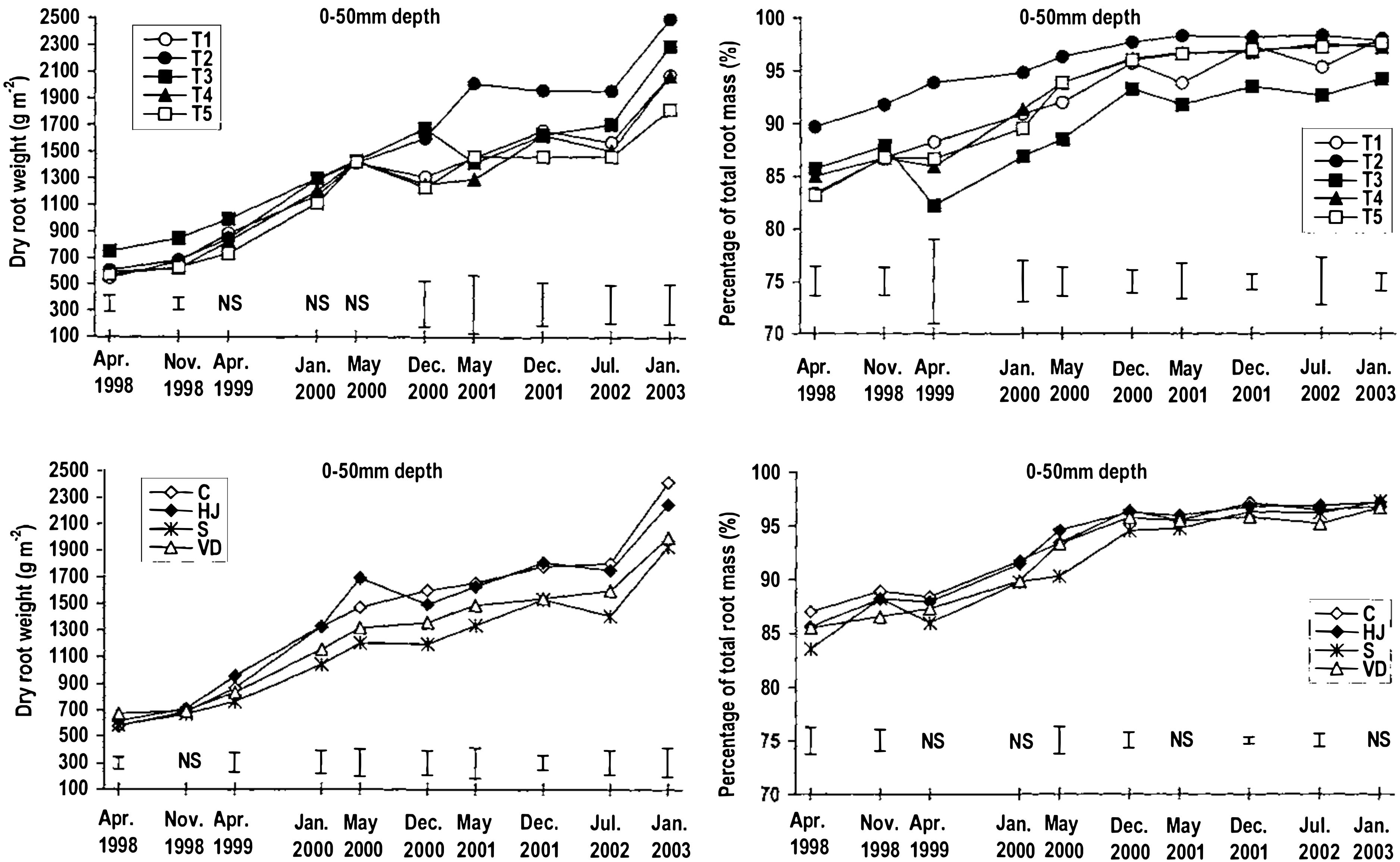


**Fig. 5-3 Changes in root mass and percentage root distribution with time in relation to rootzone type and cultivation/aeration treatment in the 0-50 mm rootzone depth**

*NS--not significantly different at the 0.05 level of probability; Error bars represent the LSD value for each group of treatments on each period of measurement; T1---Partially amended sand rootzone, T2---Soil rootzone, T3---Pure sand rootzone, T4---Fully amended sand rootzone, T5---Partially amended sand + zeolite rootzone; C---Control, HJ---HydroJect, S---Scarification, VD---Verti-drain.*

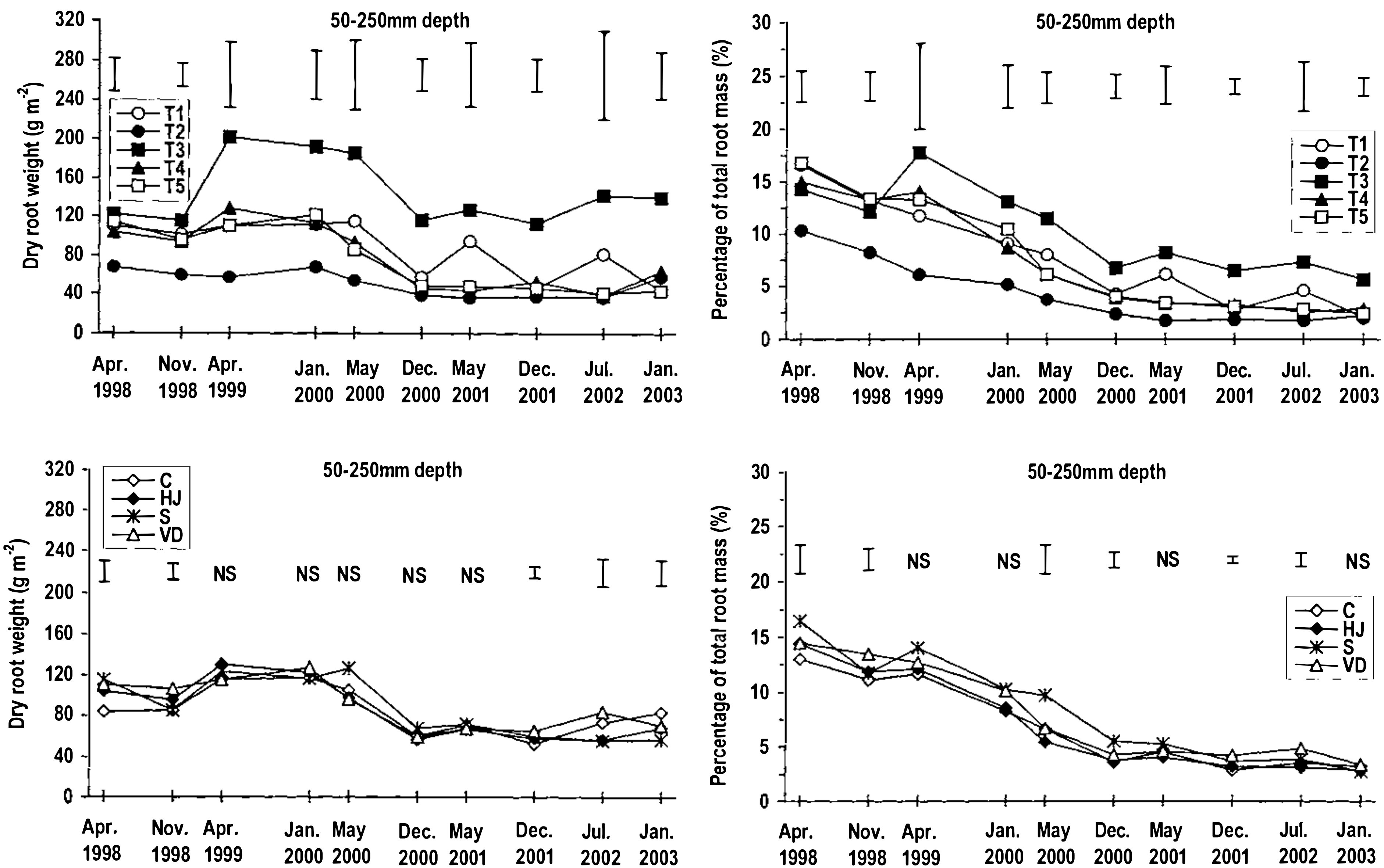


**Fig. 5-4 Changes in root mass and percentage root distribution with time in relation to rootzone type and cultivation/aeration treatment in the 50-250 mm rootzone depth**

*NS---not significantly different at the 0.05 level of probability; Error bars represent the LSD value for each group of treatments on each period of measurement; T1---Partially amended sand rootzone, T2---Soil rootzone, T3---Pure sand rootzone, T4---Fully amended sand rootzone, T5---Partially amended sand + zeolite rootzone; C---Control, HJ---HydroJect, S---Scarification, VD---Verti-drain.*

**Table 5-2 Changes with time in dry root mass (g $m^{-2}$) and root mass percentage (%) averaged over all rootzones**

| Sampling date | Rootzone depth (mm) | | | |
|---|---|---|---|---|
| | Dry root mass (g $m^{-2}$) | | Root mass percentage (%) | |
| | 0-50 | 50-250 | 0-50 | 50-250 |
| **Apr-98** | $613^{g}$ | $104^{b}$ | $85^{f}$ | $14.6^{a}$ |
| **Nov-98** | $692^{g}$ | $93^{b}$ | $88^{e}$ | $12.0^{b}$ |
| **Apr-99** | $857^{f}$ | $122^{a}$ | $87^{e}$ | $12.6^{b}$ |
| **Jan-00** | $1212^{e}$ | $121^{a}$ | $91^{d}$ | $9.3^{c}$ |
| **May-00** | $1422^{d}$ | $107^{ab}$ | $93^{c}$ | $7.1^{d}$ |
| **Dec-00** | $1414^{d}$ | $61^{c}$ | $96^{ab}$ | $4.3^{ef}$ |
| **May-01** | $1531^{c}$ | $69^{c}$ | $95^{b}$ | $4.6^{e}$ |
| **Dec-01** | $1667^{b}$ | $59^{c}$ | $97^{ab}$ | $3.5^{ef}$ |
| **Jul-02** | $1643^{b}$ | $68^{c}$ | $96^{ab}$ | $3.8^{ef}$ |
| **Jan-03** | $2153^{a}$ | $70^{c}$ | $97^{a}$ | $3.0^{f}$ |
| **LSR** | **93.0** | **15.1** | **1.2** | **1.2** |

***Means with the same letters in each column are not significantly different at the 0.05 level of probability.***
***LSR--The minimum critical range value of the Duncan's Multiple Range Test.***

Verti-drain treatment, this result was significant on two occasions (Dec. 2001 and July 2002) compared with the control and HydroJect treatments (Fig. 5-3).

### *5.4.2.2 50-250 mm rootzone depth*

There was a decrease in absolute root mass in the 50-250 mm depth for all rootzone and cultivation/aeration treatments over the first five years after sowing. For example, by January 2003, root mass in this depth averaged over all rootzones decreased from 104 $g/m^2$ in April 1998 to 70 $g/m^2$, with a significant decrease between measurement occasions measured on only one out of the ten occasions (i.e. between May 2000 and Dec. 2000). However, when root growth in this depth was expressed as the percentage of roots, it showed a large decrease with time for all treatments, in response to the general increase in root mass in the surface 50 mm. For example, in this same time period, the mean percentage of roots in 50-250 mm depth decreased from 15% to 3%, with significant decreases measured between most of the sampling occasions (Fig. 5-4; Table 5-2). Despite this reduction, there was still a significant root mass in the 250 mm depth for all rootzone and cultivation/aeration treatments by the sixth year after sowing when the root result was presented as an average of each treatment. However, when the root results were examined for individual replicates at each sampling occasion, roots were not found at 200-250 mm depth by July 2002 in most of the plots for all rootzone and cultivation/aeration treatments, with the only exception being the pure sand rootzone (original raw data not shown).

The 50-250 mm depth generally contained between 2% and 18% of total root mass, with the pure sand rootzone containing the greatest (6-18%) and the soil rootzone containing the least (2-10%), though this result was not always significant. However, there were no significant differences in root growth below 50 mm (either as an absolute amount or as a percentage) between the three amended sand rootzones at any stage of this trial. There was no evidence to suggest that root mass and root percentage were significantly affected by the layered structures of the two partially amended sand rootzones, or by the incorporation of zeolite into sand at the 100-200 mm rootzone depth. Significant, consistent and long-term differences in root growth (either as an absolute amount or as a percentage) were measured only between the pure sand rootzone and the soil rootzone (Fig. 5-4).

Consistent and significant effects of cultivation/aeration treatment on root growth were not apparent in the 50-250 mm depth. In a few cases Verti-drain treatment tended to result in better root growth in the 50-250 mm depth compared with the control, this result being significant on three out of the ten measurement occasions. When root mass in the 50-250 mm depth was expressed as a percentage of the total, scarification treatment also resulted in significantly higher root percentage than the control on four of the ten measurement occasions (Fig. 5-4).

### 5.4.3 Visual turf qualities

#### *5.4.3.1 Dry patch severity*

Dry patch affected parts of the experimental area over all the four summers of the trial, which usually lasted from early November to late April of the following year. During these periods, the four sand-based rootzones always exhibited worse dry patch disorder than the soil rootzone, though a consistent and significant difference in visual dry patch severity was observed only between the soil and pure sand rootzones. The soil rootzone contained negligible dry patch disorder throughout the whole experimental period. On most occasions, the pure sand rootzone also had significantly worse dry patch disorder than the three compost-amended sand rootzones, but this trend became less evident as the green aged. There was no significant difference in visual dry patch severity between the three amended sand rootzones on all the measurement occasions.

Cultivation/aeration treatments had a major effect on visual dry patch severity. Throughout the period of measurement, HydroJect treatment generally gave better, though not always significant, control of dry patch disorder compared with all other treatments. On most measurement occasions, dry patch severity was equally or significantly worse under Verti-drain treatment compared with the control, whereas scarification treatment was intermediate in result. However, over the last summer of the trial (from Nov. 2002 to March 2003), a statistical pattern in visual dry patch severity emerged between cultivation/aeration treatments: the control worst, Verti-drain and scarification treatments intermediate and HydroJect treatment lightest.

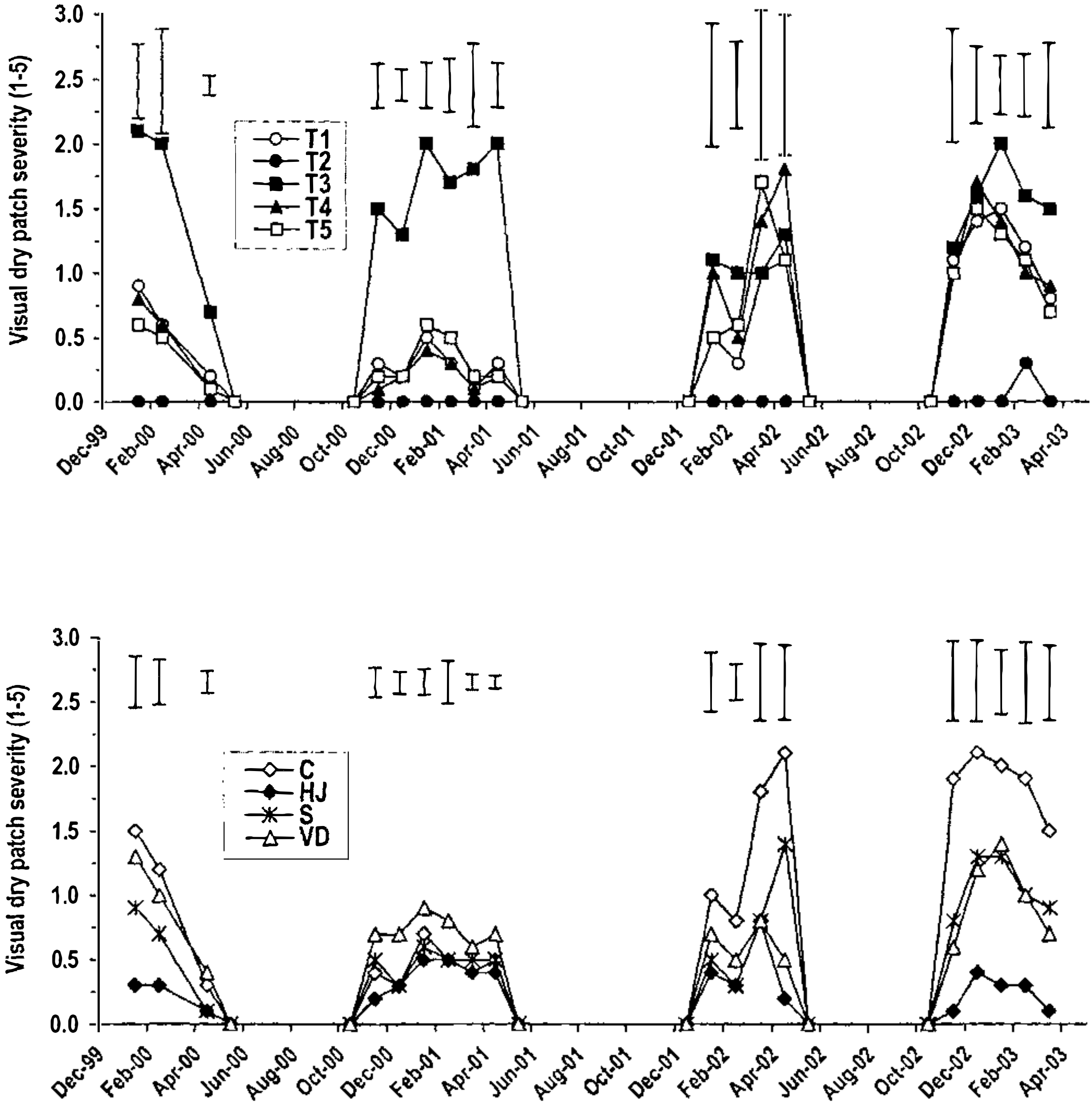


**Fig. 5-5 Changes in mean visual scores of dry patch severity* with time in relation to rootzone type and cultivation/aeration treatment**

** 0--No dry patch, 5--worst, results were presented as the mean score of each month; NS---not significantly different at the 0.05 level of probability; Error bars represent the LSD value for each group of treatments on each period of measurement; T1---Partially amended sand rootzone, T2---Soil rootzone, T3---Pure sand rootzone, T4---Fully amended sand rootzone, T5---Partially amended sand + zeolite rootzone; C---Control, HJ---HydroJect, S---Scarification, VD---Verti-drain.*

**Table 5-3 Mean visual scores* of turf uniformity and density in relation to rootzone type and cultivation/aeration treatment**

| Treatment | | Visual scores (0-9) of turf quality | | | | | |
|---|---|---|---|---|---|---|---|
| | | Turf uniformity | | | Turf density | | |
| | | Sep. 2000 | Sep. 2001 | Sep. 2002 | Sep. 2000 | Sep. 2001 | Sep. 2002 |
| Rootzone type | T1 | $8.4^{a}$ | $7.7^{ab}$ | $7.6^{a}$ | $8.6^{a}$ | $8.2^{ab}$ | $7.8^{ab}$ |
| | T2 | $5.7^{c}$ | $7.0^{b}$ | $6.4^{b}$ | $5.9^{c}$ | $6.7^{c}$ | $7.0^{c}$ |
| | T3 | $7.3^{b}$ | $8.4^{a}$ | $7.5^{a}$ | $7.8^{b}$ | $7.8^{b}$ | $7.5^{b}$ |
| | T4 | $8.6^{a}$ | $8.4^{a}$ | $8.0^{a}$ | $8.8^{a}$ | $8.5^{a}$ | $8.2^{a}$ |
| | T5 | $8.7^{a}$ | $8.3^{ab}$ | $7.7^{a}$ | $8.8^{a}$ | $8.4^{ab}$ | $8.0^{a}$ |
| | LSD | **0.7** | **1.3** | **0.9** | **0.5** | **0.7** | **0.4** |
| Cultivation/aeration treatment | C | $7.9^{a}$ | $8.3^{a}$ | $7.6^{a}$ | $8.2^{a}$ | $8.1^{b}$ | $7.8^{a}$ |
| | HJ | $7.9^{a}$ | $8.2^{a}$ | $7.5^{ab}$ | $8.0^{a}$ | $8.2^{a}$ | $7.8^{a}$ |
| | S | $7.5^{a}$ | $7.8^{b}$ | $7.2^{b}$ | $7.6^{b}$ | $7.5^{d}$ | $7.6^{b}$ |
| | VD | $7.6^{a}$ | $7.5^{b}$ | $7.4^{ab}$ | $8.1^{a}$ | $7.8^{c}$ | $7.7^{ab}$ |
| | LSD | **0.5** | **0.5** | **0.4** | **0.4** | **0.2** | **0.1** |

** 0--worst, 9 --best; Columns of numbers with same letter are not significantly different at the 0.05 level of probability for each group of rootzones or cultivation/aeration treatments on each period of measurement; LSD--The least significant difference; T1---Partially amended sand rootzone, T2---Soil rootzone, T3---Pure sand rootzone, T4---Fully amended sand rootzone, T5---Partially amended sand + zeolite rootzone; C---Control, HJ---HydroJect, S---Scarification, VD---Verti-drain.*

**Table 5-4 Mean visual scores* of dollar spot and sod webworm incidence in relation to rootzone type and cultivation/aeration treatment**

| Treatment | | Visual dollar spot severity (0-5) | | | | | Visual sod webworm severity (0-5) |
|---|---|---|---|---|---|---|---|
| | | Mar. 2002 | Dec. 2002 | Jan. 2003 | Feb. 2003 | Mar. 2003 | Jun. 2002 |
| Rootzone type | T1 | $0.8^{b}$ | $1.5^{a}$ | $0.9^{a}$ | $1.2^{a}$ | $1.4^{a}$ | $2.3^{a}$ |
| | T2 | $0.1^{b}$ | $1.0^{a}$ | $0.5^{a}$ | $0.2^{b}$ | $0.1^{b}$ | $0.3^{b}$ |
| | T3 | $2.4^{a}$ | $2.1^{a}$ | $0.9^{a}$ | $1.5^{a}$ | $2.0^{a}$ | $2.6^{a}$ |
| | T4 | $1.0^{b}$ | $1.7^{a}$ | $0.7^{a}$ | $1.4^{a}$ | $2.0^{a}$ | $2.1^{a}$ |
| | T5 | $0.9^{b}$ | $1.5^{a}$ | $0.4^{a}$ | $1.4^{a}$ | $1.7^{a}$ | $2.8^{a}$ |
| | LSD | **0.9** | **0.6** | **1.0** | **0.8** | **1.1** | **0.6** |
| Cultivation/aeration treatment | C | $0.6^{b}$ | $1.3^{bc}$ | $0.6^{b}$ | $1.0^{b}$ | $1.4^{b}$ | $1.5^{b}$ |
| | HJ | $1.1^{ab}$ | $2.8^{a}$ | $1.2^{a}$ | $2.1^{a}$ | $2.9^{a}$ | $2.6^{a}$ |
| | S | $0.8^{b}$ | $0.7^{c}$ | $0.2^{b}$ | $0.6^{c}$ | $0.9^{bc}$ | $1.3^{b}$ |
| | VD | $1.6^{a}$ | $1.4^{b}$ | $0.6^{b}$ | $0.8^{bc}$ | $0.6^{c}$ | $2.7^{a}$ |
| | LSD | **0.5** | **0.7** | **0.4** | **0.4** | **0.6** | **0.4** |

* *0--No damage, 5 --The worst, values were presented as the average of each month; Columns of numbers with same letter are not significantly different at the 0.05 level of probability for each group of rootzones or cultivation/aeration treatments on each period of measurement; LSD--The least significant difference; T1---Partially amended sand rootzone, T2---Soil rootzone, T3---Pure sand rootzone, T4---Fully amended sand rootzone, T5---Partially amended sand + zeolite rootzone; C---Control, HJ---HydroJect, S---Scarification, VD---Verti-drain.*

### *5.4.3.2 Uniformity/density*

Results of the visual assessment of turf uniformity and density in the three spring periods of the trial showed that the three compost-amended sand rootzones gave significantly higher scores of uniformity and density on all three measurement occasions compared with the soil rootzone. On one measurement occasion (Sept. 2000), the three compost-amended sand rootzones also gave significantly higher scores of uniformity and density than the pure sand rootzone (Table 5-3). However, there were no significant differences in visual scores of uniformity and density between the three compost-amended sand rootzones on all the three measurement occasions.

There were some significant effects of cultivation/aeration treatments on turf uniformity and density. HydroJect treatment usually resulted in higher visual scores of uniformity and density than scarification and Verti-drain treatments though this result was not always significant. In contrast, scarification treatment resulted in significantly lower visual scores of turf density than the other three cultivation/aeration treatments, and this result was significant on most of the measurement occasions.

### *5.4.3.3 Incidence of dollar spot/sod webworm*

The four sand-based rootzones showed significantly more severe incidence of both sod webworm and dollar spot damage than the soil rootzone, with the result for dollar spot being significant on two out of the five measurement occasions. On one measurement occasion (March 2002), the pure sand rootzone also showed significantly more severe dollar spot damage than the three amended sand rootzones. However, there were no significant differences in both the dollar spot and the sod webworm incidence between the three amended sand rootzones on all measurement occasions.

Cultivation/aeration treatment effects on the incidence of dollar spot and sod webworm were evident. HydroJect and Verti-drain treatments resulted in significantly higher incidence of sod webworm damage than both scarification and control treatments. In addition, HydroJect treatment was generally associated with a higher incidence of dollar spot damage compared with the three other treatments, and this result was significant on most of the measurement occasions.

## 5.5 DISCUSSION

### 5.5.1 Species composition and stability

The progressive increase in *Agrostis* and total weed cover and the progressive decrease in *Festuca* and total turfgrass cover during the four years of the trial illustrated well the typical succession in species composition with age and usage under golf green conditions as reported in several similar studies (Lodge & Lawson 1993; Baker *et al.* 1997b, 1999b). Previous studies showed that the key catalysts inducing changes in relative balance of *Festuca/Agrostis* in a green sward were rootzone fertility and moisture conditions (Lodge & Lawson 1993). Therefore, this change in species composition also reflected the dynamic deterioration in rootzone physical properties occurring within the rootzone media over time. However, by the fifth year after establishment, although the percentage of *Festuca* greatly decreased, the percentage of weed cover remained minimal (< 10%) compared with findings in previous studies (Baker & Isaac 1987; Lodge *et al.* 1991; Lodge & Lawson 1993). In addition, total turfgrass cover on all rootzone and cultivation/aeration treatments was still well above 80%, which is regarded as the minimum acceptable turfgrass cover for 'mature' golf greens (Baker *et al.* 1997a). Baker *et al.* (1997b, 1999b) speculated that the traditional UK seed mixture of 80:20 ratio of *Festuca* : *Agrostis* (by weight) may produce a sward with too much *Festuca* and too little *Agrostis* when used on sand-dominant rootzones, resulting in the *Festuca* component sharply declining though wear, only to be replaced by *Poa annua*. In this trial, the percentage of *Agrostis* was generally greater than that found in UK studies for a similar time after sowing. Moreover, a higher rate of ingress of *Poa annua* on the soil rootzone, as found in similar studies in UK (Baker & Isaac 1987; Lodge *et al.* 1991; Lodge & Lawson 1993), also did not occur. The implication of this result is that either the 75:25 (*Festuca* : *Agrostis*, w/w) seed mixture, which was used in the present trial, may be a more favorable seed mixture for golf greens under New Zealand conditions (refer to Appendix Table 5-3) or the experimental plots in the present study have less opportunity to be contaminated.

The significant higher percentage of *Festuca* species in the sward on the sand-based rootzones compared with the soil rootzone, and in some cases on the pure sand rootzone compared with the three compost-amended rootzones, can be explained mainly by different fertility and moisture conditions between these rootzones. This result is also consistent with those found in similar studies in the UK (Baker 1991; Lodge *et al.* 1991; Baker *et al.* 1995, 1997b, 1999b). Moreover, in the present trial, the incidence of take-all disease on the four sand-based rootzones during the pre-experimental period of this trial (Gibbs *et al.* 2000) was also likely to be another contributing factor to the higher ratio of *Festuca* to *Agrostis* on these sand-based rootzones relative to the soil rootzone, given that *Agrostis* is highly susceptible to this pathogen (Burpee 1993).

However, as expected, the two modified USGA rootzones (T1 and T5) did not show any measurable differences in the relative balance of *Festuca/Agrostis*, total turfgrass and weed cover compared with the standard USGA rootzone on all the measurement occasions throughout the four years of the trial.

Different responses of sward characteristics to cultivation/aeration treatments were evident. The reduced percentage of turfgrass cover and greater percentage of weeds in the sward associated with scarification treatment indicated injurious nature of this type of cultivation to golf greens, as also reported in previous studies (Engel & Alderfer 1967; Cooper & Skogely 1981, cited in Bunnell & McCarty 2001). In contrast, the less aggressive HydroJect treatment always showed negligible disturbance and was less injurious to the sward, this result being consistent with that of Bunnell and McCarty (2001).

### 5.5.2 Root growth and distribution

The gradual increase in root growth in the 0-50 mm depth and the gradual decrease in the lower part of the profile (50-250 mm), both as an absolute root mass and as a percentage of roots in the whole profile, for all rootzone and cultivation/aeration treatments during the first five years after sowing, expressed typical redistribution of root growth over time under golf green conditions. Similar results have been reported in many previous studies (van der Horst & Kappen 1970; Boeker 1978, both cited in Canaway 1984; Carrow 1995; Hannaford & Baker 2000). This result mirrored the dynamic deterioration in rootzone physical properties taking place within the media (e.g. progressive decline in air-filled porosity and oxygen diffusion rate, and saturated water conditions in the lower profiles) (refer to Chapter 4).

The deeper and more balanced root distribution (i.e. smaller root percentage in the surface 50 mm and the larger root percentage in the lower part of the profile) in the pure sand rootzone was likely due to lower moisture and nutrition levels in pure sand, requiring roots to search more for their requirements, as well as better aeration status in this part of the rootzone (refer to Chapter 4). This result was consistent with the findings of Baker and Richards (1993). In contrast, the shift of roots towards the surface in the soil rootzone would be detrimental to turfgrass growth because the supply of water, nutrients and oxygen available to plants are usually limited in the surface layer (Agnew & Carrow 1985; Agnew 1993; Couillard *et al.* 1997). Moreover, excess accumulation of root materials near the surface could potentially give rise to serious thatch problems on golf greens (Agnew 1993; Couillard *et al.* 1997).

No obvious differences could be determined in root growth and root distribution during the first five years following establishment between the standard USGA profile and the two modified USGA profiles. Furthermore, there was no evidence to suggest that root mass and distribution were significantly affected by the layered structures of the two modifications as reported in a previous study (Leboucher 1989). Also, the proposed advantages of sand amended with zeolite ostensibly for encouraging deep rooting (Ferguson *et al.* 1986) were not observed under the current experimental conditions. This result was not unexpected given that none of the rootzones were managed under nutrient or moisture stress where benefits of zeolite as reported by others (Ferguson *et al.* 1986; Myer *et al.* 2003) might have been observed.

The two media removal treatments (scarification and Verti-drain with hollow tines), especially the dethatching treatment (scarification), significantly reduced root accumulation in the surface compared with the control and HydroJect treatments, similar to that found in previous studies (White & Dickens 1984; Field & Murphy 1991; Murphy & Rieke 1994). However, none of the cultivation/aeration treatments were able to halt the overall progressive increase in both absolute root mass and root percentage in the 0-50 mm depth of all rootzone treatments during the five years of the trial. This result was probably due to short-lived nature of these types of cultivation

(Gibbs *et al.* 2000, 2001). The implication of this is that the current twice-yearly treatment frequency practiced in New Zealand is not sufficient for effective control of excess accumulation of surface root material, hence organic matter, under golf green conditions.

The effect of cultivation/aeration treatment on root growth were restricted mainly to the surface 50 mm. There was generally no apparent effect in the 50-250 mm depth in the present study. The deeper root development that followed HydroJect treatment, as has been reported by several researchers (Vavrek 1992; Murphy & Rieke 1994), was not observed under the current frequency of treatment. However, in a few cases, scarification and Verti-drain treatment resulted in significantly higher root percentages in the lower part of the profile than with the control and HydroJect treatment. For Verti-drain treatment, this result may have been due to deeper rooting as a result of its deep cultivation and loosening effects (Carrow 1992). The scarification treatment result was considered to be not due to better root development *per se*, but a result of less root mass accumulation in the surface layer (Gibbs *et al.* 2001).

### 5.5.3 Visual turf qualities

#### *5.5.3.1 Dry patch severity*

The present experiment confirmed that dry patch disorder affected mainly sand-based golf greens during dry, hot summers, and that the severity of dry patch disorder increased greatly as the content of sand in the rootzone mixture increased (with the pure sand rootzone containing the worst dry patch disorder). This phenomenon is usually explained by the fact that dry patch is caused by water-repellent organic matter coatings being deposited onto soil mineral particles, and that sand particles are more readily coated because they have relatively low "specific surface areas" (Wallis & McAuliffe 1988; Tucker *et al.* 1990; York & Baldwin 1992; of Baker *et al.* 1999a). The two modified USGA profiles showed no measurable differences in dry patch severity compared with the standard USGA profile.

HydroJect treatment was very effective in controlling the occurrence of dry patch disorder when used in conjunction with a wetting agent. Similar findings have been reported in previous studies (Murphy & Rieke 1994; Karcher *et al.* 1996, 2001). As this treatment causes little disturbance on the green surface, regular HydroJect treatment in conjunction with a wetting agent is probably an essential management tool for prevention of dry patch on sand-based golf greens.

### *5.5.3.2 Uniformity/density*

An advantage of the three compost-amended sand rootzones and HydroJect treatment was that these treatments could produce a more uniform and denser sward than the other rootzone and cultivation/aeration treatments. Others have reported similar results for HydroJect treatment (Murphy & Rieke 1994; Bunnell & McCarty 2001). In contrast, regular scarification treatment resulted in a more open sward (i.e. lower turf density) than the other cultivation/aeration treatments. In the long run, this is an obvious disadvantage because weeds invade and spread more easily in an open green sward.

### *5.5.3.3 Incidence of dollar spot/sod webworm*

The higher incidence of sod webworm on the four sand-based rootzones (compared with the soil rootzone) may be partially due to less soil compaction in these rootzones. In particular, the higher incidence of dollar spot on the four sand-based rootzones was possibly due to differences in pH value (Cook & Baker 1998), given that favorable conditions for this disease include sandy soils with a relatively higher pH value (Burpee 1993). The pH levels in the compost-amended rootzone were affected greatly by the initial high alkalinity of the urban compost used in the rootzone mix (Table 3-1). This type of compost is widely used in New Zealand as an ecologically-sustainable alternative to the preferred USGA recommendation of peat, even though high pH is a recognized feature of such compost (Handreck & Black 1994) and is likely to result in increased disease and weed incidence (Cook & Baker, 1998). Despite these undesirable side-effects, the success in eliminating pest and disease and the fact that three compost-amended rootzone treatments finally produced a more uniform and denser sward in the present experiment, supports the view of Cook and Baker (1998) that the disadvantages of non-peat organic rootzones with high pH values can be managed in the long-term for best results.

The only disadvantage observed in the present experiment for HydroJect treatment was that it could induce higher incidence of dollar spot and sod webworm compared with the three other treatments. Similarly, Verti-drain treatment also resulted in higher incidence of sod webworm compared with the control and scarification treatments. This result may be explained partially by the less compaction rootzone surface or holes caused by the cultivation. However, little published information is available on this aspect, further monitoring may be required.

## 5.6 SUMMARY AND CONCLUSIONS

There was a general deterioration in sward characteristics for all rootzone and cultivation/aeration treatments during the first five years after sowing. This change over time was reflected by a gradual shift of root growth towards the surface of the profile as well as by a progressive increase in the percentage of *Agrostis* and weeds.

Rootzone type greatly affected relative balance of *Festuca* and *Agrostis* species present, with the greatest proportion of *Festuca* remaining on the pure sand rootzone and the least on the soil rootzone five years after sowing. Compared with the soil rootzone, the four sand-based rootzones generally produced a more stable, more uniform, denser and less weedy sward with deeper and more balanced root distribution. Against this advantage was that the sand-based rootzones had much greater incidence of dry patch, disease and pest (i.e. dollar spot and sod webworm) disorders. However, the disadvantages of the sand-based rootzones were not considered to be as serious as the practical disadvantages of the soil rootzone.

Compared with the three compost-amended rootzones, after five years growth the pure sand rootzone not only contained an equal amount of root mass in the surface layer of the profile, but it also contained better root distribution with profile depth. Against this advantage was that the pure sand rootzone had a greater tendency for incidence of dry patch disorder. In contrast, higher visual scores of turf quality were always associated with the three compost-amended rootzones. The advantages of amending medium-coarse sand with an approved organic amendment were considered to far outweigh those of the pure sand rootzone throughout the first five years following establishment.

There was little evidence from this study that the New Zealand practice of constructing only the top 100 mm of the sand rootzone with organic-amended sand resulted in any poorer green performance in terms of species composition, root growth and visual turf qualities compared with a fully amended USGA-type rootzone. In addition, there was no indication that a buried layer of zeolite-amended sand lead to better root growth and distribution, and the potential detrimental effects of a layered structure on root development were not apparent.

Although HydroJect treatment tended to induce higher disease and pest incidence (i.e. dollar spot and sod webworm), it was particularly effective in controlling dry patch disorder when used together with a wetting agent. In the long-term, regular use of this type of cultivation is probably an essential management tool for control of dry patch on sand-based golf greens. In contrast, scarification treatment gave a variable response, on the one hand reducing root mass, and hence organic matter accumulation, near the surface, but on the other hand decreasing turf density or inducing more weed invasion. Beneficial effects of twice yearly Verti-drain treatment on root growth and distribution were not apparent.

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# 6. EFFECT OF ROOTZONE COMPOSITION AND CULTIVATION/AERATION TREATMENT ON PLAYING QUALITY OF GOLF GREENS

## 6.1 ABSTRACT

This chapter reports monitoring of playing quality during the first five years after sowing as measured by green speed and surface hardness of five contrasting golf green rootzones. Rootzone treatments were partially amended sand rootzone, soil rootzone, pure sand rootzone, full amended sand rootzone and partially amended sand + zeolite rootzone. A split-plot design was superimposed on the rootzone treatments consisting of twice yearly cultivation/aeration treatments (i.e. the control, HydroJect, scarification and Verti-drain).

The results showed that there was a general trend for a progressive increase in green speed and surface hardness for all rootzone and cultivation/aeration treatments during the first five years after sowing despite fluctuations with seasons. However, the playing quality was still acceptable for all rootzone and cultivation/aeration treatments by the fifth year of the trial.

Although effects of rootzone type on green speed were not apparent, there were significant effects of rootzone type on surface hardness on half of the measurement occasions with the soil and pure sand rootzones showing the greatest fluctuations in values. The study also indicated that the New Zealand practice of constructing only the top 100 mm of the sand rootzone with organic-amended sand conferred a similar playing quality performance to a fully amended USGA profile.

Playing quality of golf greens was influenced significantly by cultivation/aeration treatment with the hardest and fastest surfaces being generally associated with the scarification treatment, and the softest and slowest surfaces being associated with Verti-drain and HydroJect treatments.

**KEYWORDS**: Green speed, HydroJect, sand-based rootzones, scarification, soil-based rootzone, surface hardness and Verti-drain.

## 6.2 INTRODUCTION

A high proportion of shots (approximately two-thirds) played in a round of golf take place onto or within a golf green (Lodge & Baker 1991). The playing quality of golf greens is one of the most important factors by which players judge the performance of a golf course. It has a profound influence on the playing enjoyment of players, as well as their final score for a round (Baker 1994).

There has been increasing interest in the characterization of components of playing quality for golf greens as this produces objectives for construction, management, surface preparation and future research work (Canaway & Baker 1993). Previous research has shown that the playing quality of golf greens is influenced mainly by the way in which the ball interacts with the surface following an approach shot and by the ball roll characteristics during putting (Baker 1994). Most researchers have identified ball roll distance (i.e. green speed) and ball impact properties (i.e. surface hardness) as the two most important components of playing quality characteristics of golf greens (Baker & Richards 1991; Baker 1994; Baker *et al.* 1999a).

The selection of rootzone materials will affect not only the mechanical properties of the surface layer, but also the survival and dominance of particular grass species, both of which will be likely to affect the playing quality of golf greens (Baker *et al.* 1999a,b). The effects of rootzone composition, management practices (e.g. cutting and rolling) and the resultant sward characteristics on the playing quality of golf greens have been much researched in the last two decades (Bell *et al.* 1985; Haake 1991; Canaway & Baker 1992, 1993; Lodge 1992; Baker & Canaway 1993; Baker *et al.* 1996, 1997, 1999a,b). These studies have demonstrated that surface hardness of golf greens are strongly influenced by the rootzone composition and moisture content, and that their responses to cutting height and species composition are insensitive or inconsistent. In contrast, the ball roll distance has been shown to be controlled greatly by cutting height, rolling and species composition, but it is typically not significantly affected by rootzone composition (Baker & Richards 1991; Baker 1994). Nevertheless, one recent study (Baker *et al.* 1999a) showed that rootzone composition (i.e. amendment type and mixing ratio) had a significant influence not only on surface hardness, but also on ball roll distance for sand-based golf greens.

To date, there is little published information available on differences in playing quality between a standard USGA profile and the two modified USGA profiles recommended for golf green construction in New Zealand (Gibbs *et al.* 1997, 2000; Yang *et al.* 1998; Myer *et al.* 2003), and the pure sand profile, which is a preferred method of golf green construction by golf superintendent in many countries. Moreover, although it has been proposed that cultivation treatments (e.g. Verti-drain and scarification) might interfere with surface uniformity and firmness of golf greens (Baker 1994), little quantitative data has been published on effects of cultivation/aeration treatments (HydroJect, scarification and Verti-drain) on ball roll distance and surface hardness of golf greens.

Therefore, the aim of this trial was to compare the relative advantages and disadvantages in terms of ball roll distance and surface hardness between the five alternative rootzones (i.e. two modified USGA rootzones, pure sand rootzone, a standard USGA rootzone and a conventional soil rootzone) managed under the four alternative cultivation/aeration treatments (i.e. the control, HydroJect, scarification and Verti-drain) during the first five years after sowing. Meanwhile, the methodology (hammer weight and drop times) of the Clegg Impact Soil Tester used for measurement of surface hardness of golf greens was also evaluated under a wide range of turf conditions.

## 6.3 MATERIALS AND METHODS

For details of the trial design, methods and statistical analysis, refer to Chapter Three in this thesis.

## 6.4 RESULTS

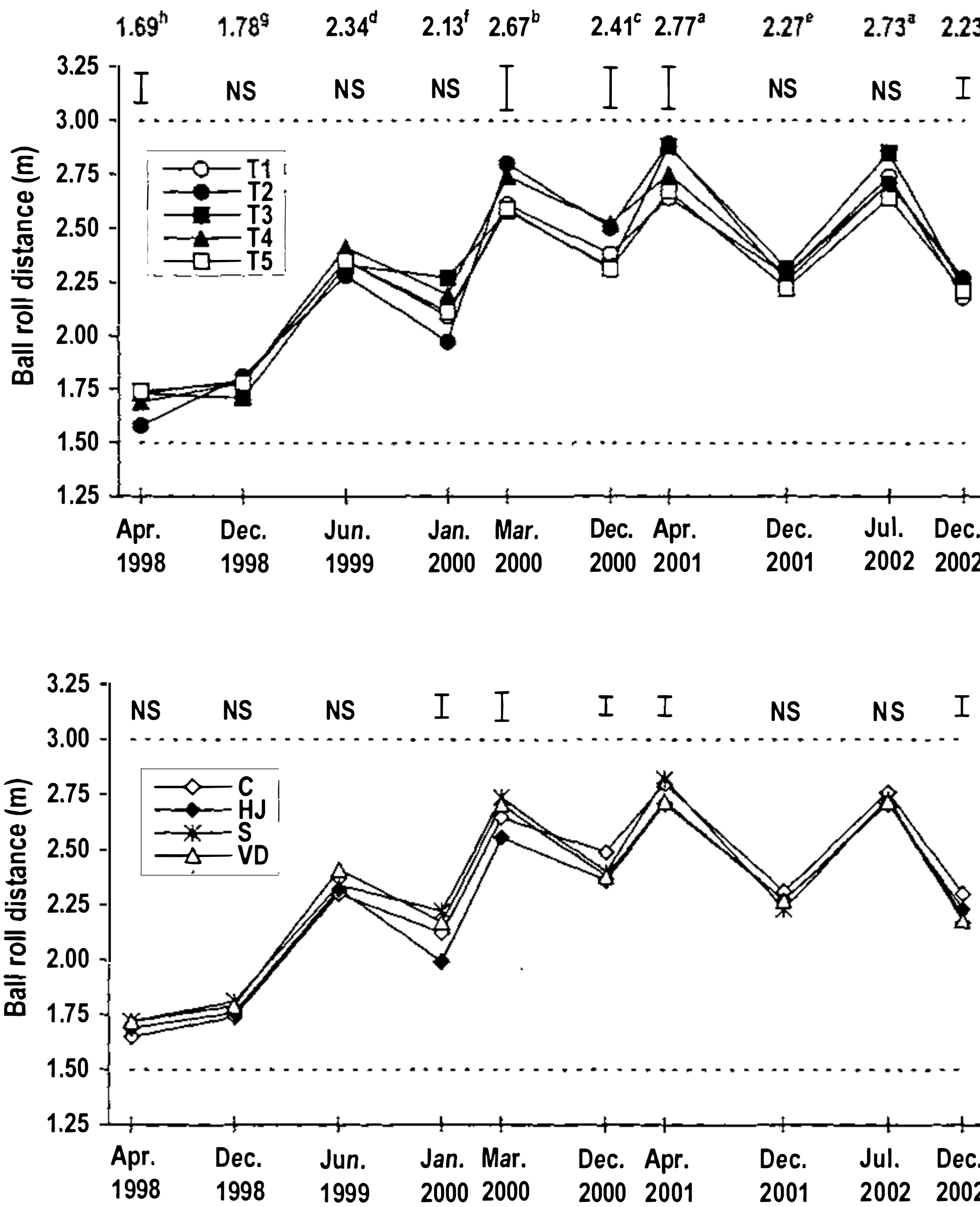
There were significant differences between individual rootzone and cultivation/aeration treatments on several occasions, but at no stage in this trial were any significant interaction effects found between rootzone and cultivation/aeration treatments.

### 6.4.1 Ball roll distance (green speed)

Despite the remarkable and consistent fluctuation of green speed with seasons, which was reflected by the significantly longer ball roll distance in winter than in summer, there was a general trend for ball roll distance to increase progressively throughout the first five years after sowing for all rootzone and cultivation/aeration treatments (for climate data, please refer to Appendix Figs. 3-1, 3-2). For example, by December 2002, the ball roll distance averaged over all rootzones increased from 1.69 m in April 1998 to 2.23 m, with a significant increase measured on most of the measurement occasions. This general trend was particularly pronounced between the period from April 1998 to April 2001. After April 2001, this trend appeared to have levelled off for all rootzone and cultivation/aeration treatments. However, in spite of this significant increase, the values of ball roll distance were still within the 1.5-3.0 m preferred range for all rootzone and cultivation/aeration treatments on all measurement occasions during this study (Fig. 6-1).

With regard to effects of rootzone type on ball roll distance, results were somewhat erratic. On five out of the ten measurement occasions, there were no significant differences in ball roll distance between all rootzones. On other occasions (i.e. Apr. 1998, Mar. 2000, Dec. 2000 and Dec. 2002), significant differences in ball roll distance were measured between rootzones, but it was only between the soil rootzone and the sand-based rootzones that showed some erratic, though significant, differences in ball roll distance (Fig. 6-1).

Significant influences of cultivation/aeration treatment on ball roll distance were observed on five out of the ten measurement occasions (i.e. Jan., Mar. and Dec. of 2000, Apr. 2001 and Dec. 2002). Here, the control treatment produced longer ball roll distance than the other three cultivation/aeration treatments though this result was not always significant. Significant differences in ball roll distance were also measured between the three cultivation/aeration treatments (i.e. HydroJect, scarification and Verti-drain) on these measurement occasions. For example, HydroJect treatment produced a significantly shorter ball roll distance in January and May of 2000 compared with Verti-drain and scarification treatments. However, there was no significant difference in ball roll distance between Verti-drain and scarification treatments on the majority of measurement occasions, with the exception of April 2001




## Fig. 6-1 Changes in ball roll distance with time in relation to each rootzone type and cultivation/aeration treatment

*NS---not significantly different at the 0.05 level of probability. Error bars represent the LSD values for each group of treatments on each period of measurement. The dotted lines represent a range of 1.5-3.0 m, the recommended acceptable (minimum and maximum value) ball roll distance for the UK golf green turf (Baker et al. 1996). Top row of numbers represents ball roll distance (m) averaged over all rootzones on each measurement occasion, and the means with the same letters in the upper right hand are not significant at the 0.05 level of probability. T1---Partially amended sand rootzone; T2---Soil rootzone; T3---Pure sand rootzone; T4---Fully amended sand rootzone; T5---Partially amended sand + zeolite rootzone. C---Control; HJ---HydroJect; S---Scarification; VD---Verti-drain.*

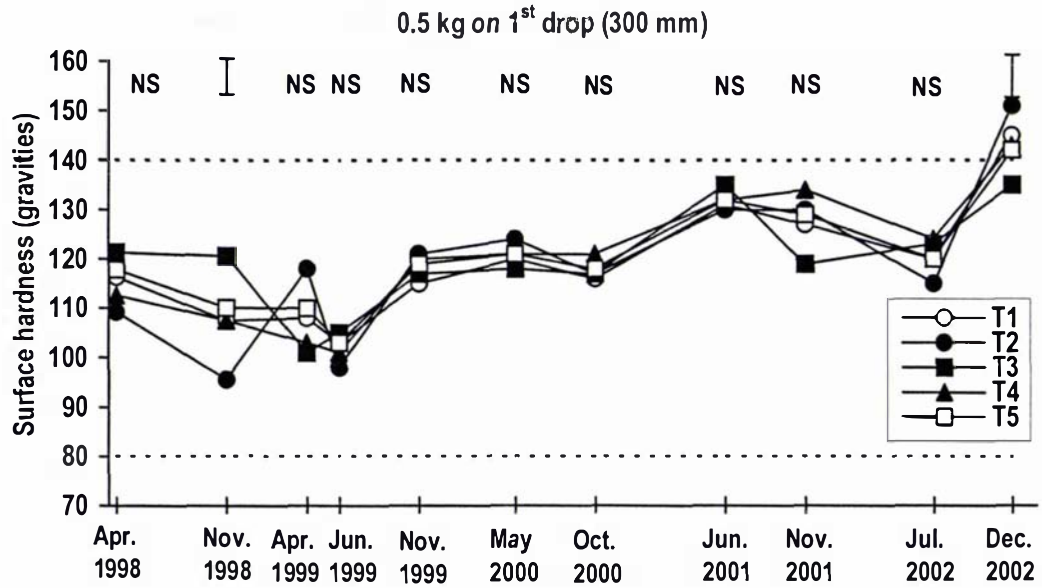
where scarifying treatment produced significantly longer ball roll distance than Verti-drain treatment (Fig. 6-1).

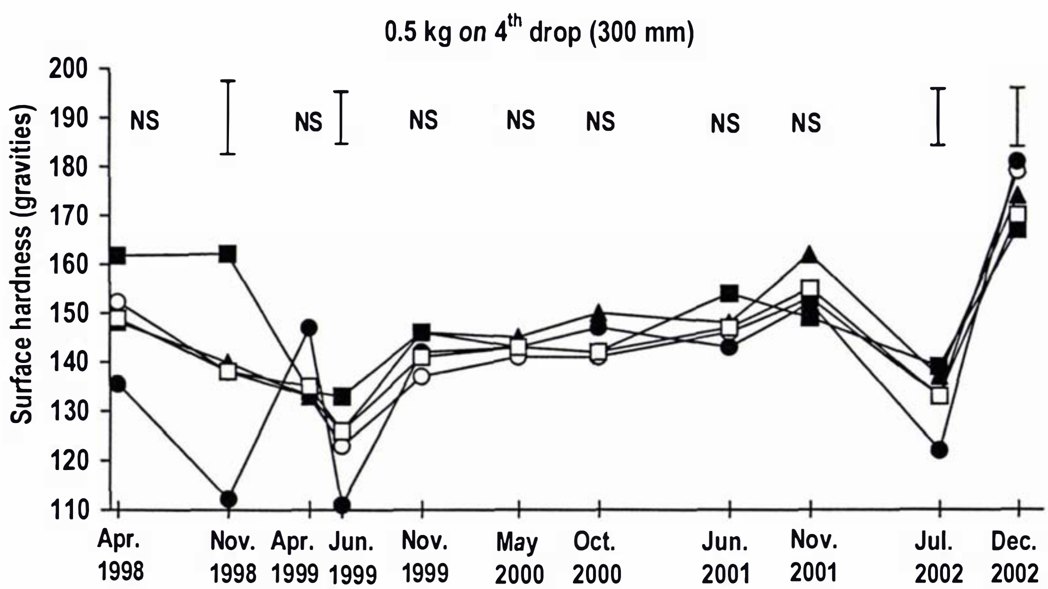
## 6.4.2 Surface hardness

There was a general trend for surface hardness to increase gradually throughout the first five years following establishment for all rootzone and cultivation/aeration treatments despite considerable fluctuation between measurement occasions. For example, surface hardness averaged over all rootzones increased from 108, 136 and 87 in April 1998 to 143, 174 and 115 gravities in December 2002 for the three Clegg hammer tests respectively ($1^{st}$ drop of the 0.5 kg hammer; $4^{th}$ drop of the 0.5 kg hammer; $1^{st}$ drop of the 2.25 kg hammer). This increase was significant between most of the measurement occasions. The hardness values ($1^{st}$ drop of the 0.5 kg hammer) fell within the preferred range (80-140 gravities) for all rootzone and cultivation/aeration treatments on all the measurement occasions, with the exception of the measurement on December of 2002, where hardness values increased above the upper preferred limit for the soil and the three amended sand rootzones as well as Verti-drain and scarification treatments (Figs. 6-2, 6-3; Table 6-1).

Results showed considerable fluctuation between measurement occasions for all rootzones. The soil and pure sand rootzones showed the greatest fluctuation in hardness values, a feature that was accentuated by the $4^{th}$ drop reading of the 0.5 kg Clegg hammer. Hardness values for the soil rootzone ranged from 96 to 151 gravities over the measurement period compared with 101 to 145 gravities for the pure sand and three compost-amended sand rootzones (0.5 kg Clegg hammer, $1^{st}$ drop). However, the fluctuation in hardness results for the three compost-amended rootzones appeared to be less than that for the pure sand rootzone (Fig. 6-2).

On several occasions there were significant differences in surface hardness between rootzones, but it was the 2.25 kg Clegg hammer that showed the most sensitivity. With the heavier hammer, significant differences were found on six of the eleven measurement occasions compared with three occasions for the $4^{th}$ drop of the 0.5 kg Clegg hammer and only two for the $1^{st}$ drop of the 0.5 kg Clegg hammer. However, most of the significant differences observed were between the soil and pure sand rootzone. For example, at the $4^{th}$ drop of the 0.5 kg Clegg hammer, the soil rootzone



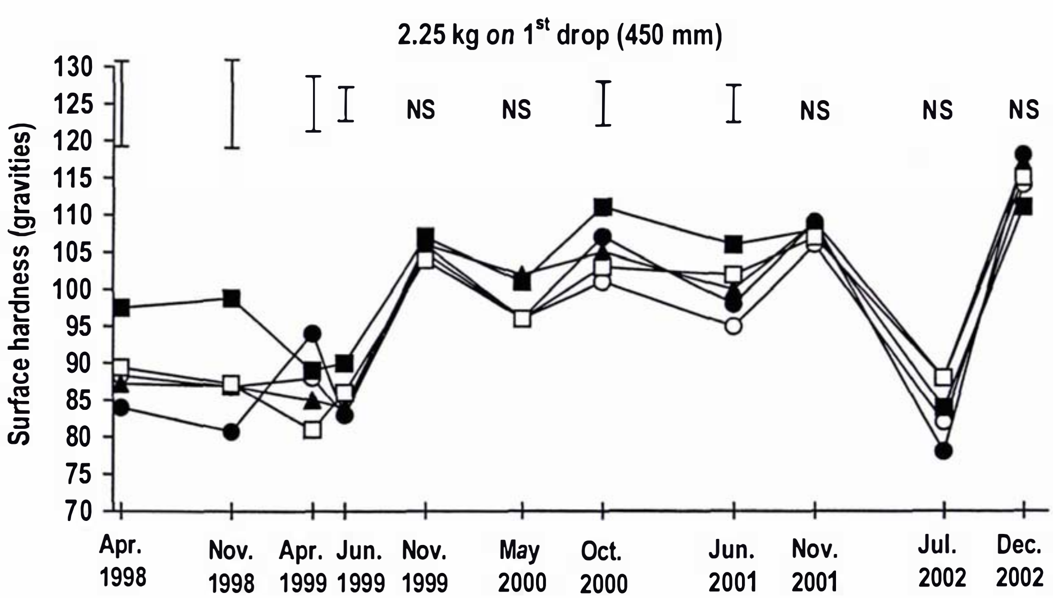




**Fig. 6-2 Changes in green surface hardness with time in relation to each rootzone type**

*NS---not significantly different at the 0.05 level of probability. Error bars represent the LSD values for each group of treatments on each period of measurement. The dotted lines represent a value range of 80-140 (gravities), the recommended acceptable (minimum and maximum value) green surface hardness range for New Zealand golf green turf (Gibbs pers. comm.). T1---Partially amended sand rootzone; T2---Soil rootzone; T3---Pure sand rootzone; T4---Fully amended sand rootzone; T5---Partially amended sand + zeolite rootzone.*

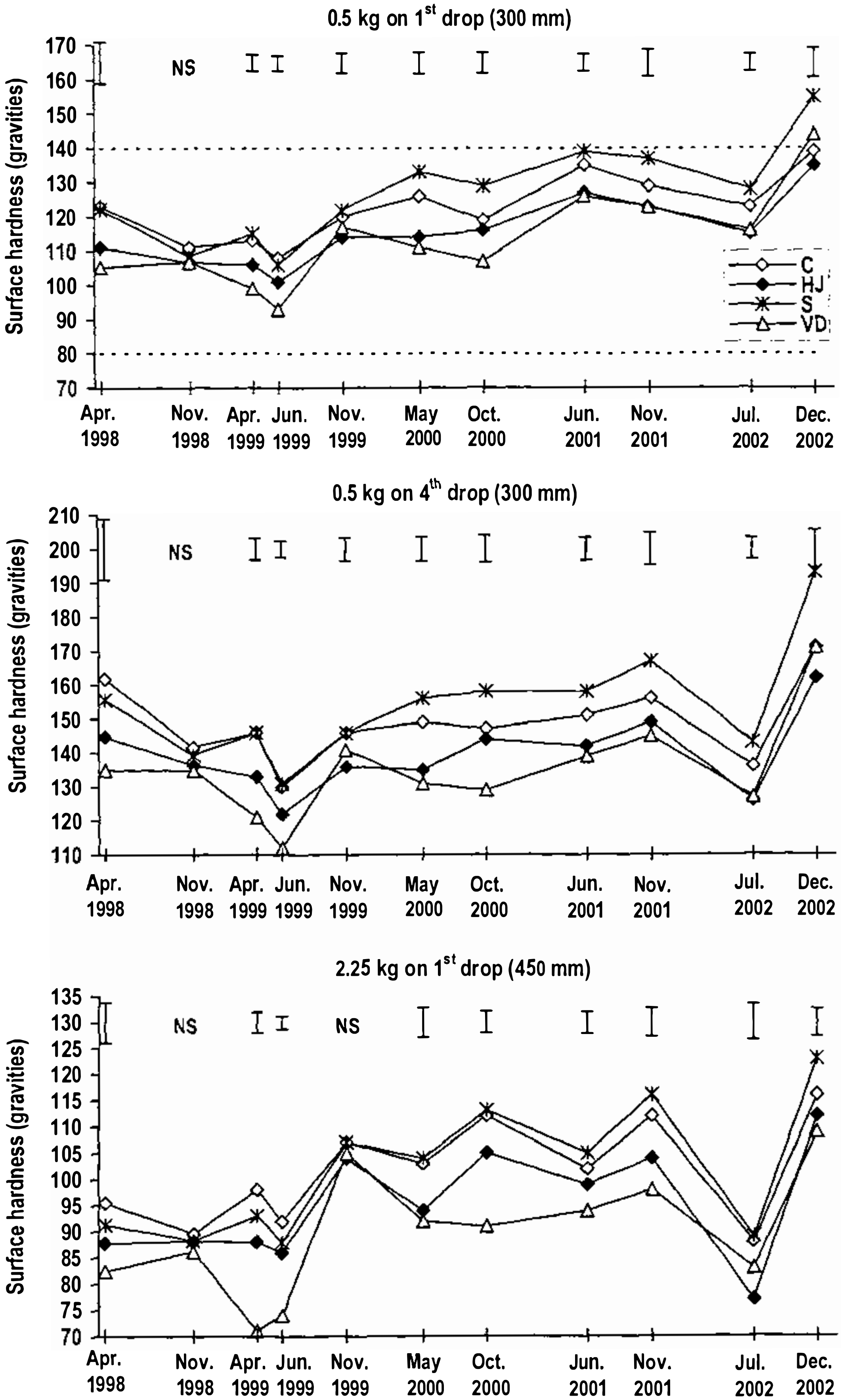



**Fig. 6-3 Changes in green surface hardness with time in relation to each cultivation/aeration treatment**

*NS---not significantly different at the 0.05 level of probability. Error bars represent the LSD values for each group of treatments on each period of measurement. The dotted lines represent a value range of 80-140 (gravities), the recommended acceptable (minimum and maximum value) green surface hardness range for New Zealand golf green turf (Gibbs pers. comm.). C---Control; HJ---HydroJect; S---Scarification; VD---Verti-drain.*

Table 6-1 Changes with time in mean green surface hardness (gravities) averaged over all rootzones

| Date of Measurement | Mean green surface hardness (gravities) measured under different methodology | | |
|---|---|---|---|
| | 0.5 kg (1st drop) | 0.5 kg (4th drop) | 2.25 kg (1st drop) |
| Apr-99 | 108[e] | 136[e] | 87[d] |
| Jun-99 | 102[f] | 124[f] | 85[de] |
| Nov-99 | 118[d] | 142[d] | 106[b] |
| May-00 | 121[d] | 143[d] | 98[c] |
| Oct-00 | 118[d] | 144[cd] | 106[b] |
| Jun-01 | 132[b] | 148[c] | 100[c] |
| Nov-01 | 128[c] | 154[b] | 108[b] |
| Jul-02 | 121[d] | 133[e] | 84[e] |
| Dec-02 | 143[a] | 174[a] | 115[a] |
| **LSR** | **3.4** | **4.1** | **2.6** |

***Means with the same letters in each column are not significantly different at the 0.05 level of probability.***
***LSR--The minimum critical range value of the Duncan's Multiple Range Test.***

possessed a significantly softer surface than the pure sand rootzone in June 1999 and July 2002. In contrast, in December 2002, the soil rootzone possessed a significantly harder surface (181 gravities) than the pure sand rootzone (167 gravities). However, there were no significant differences in surface hardness between the three amended sand rootzones measured by any of the Clegg hammer methods on all the measurement occasions (Fig. 6-2).

All three methods of surface hardness measurement picked up regular, significant differences between cultivation/aeration treatments, with the 4$^{th}$ drop of the 0.5 kg Clegg hammer again accentuating the results of the 1$^{st}$ drop from the same hammer. It was only on the second measurement occasion that no significant differences between cultivation/aeration treatments were found for all the three measurement techniques. The general pattern of results was that Verti-drain and HydroJect treatments resulted in a significantly softer surface than the control and scarification treatments, with scarification treatment resulting in the hardest and Verti-drain treatment the softest surface on most measurement occasions (Fig. 6-3).

## 6.5 DISCUSSION

### 6.5.1 Ball roll distance (green speed)

The progressive increase in ball roll distance during the first three years following establishment was most likely a reflection of the progressive reduction in cutting height from 7 mm in 1998 to 5 mm in 2000, to 4 mm in 2001 and thereafter in conjunction with regular, heavy roller-type wear from early 1999. After the third year following establishment, the increase in ball roll distance tended to have leveled off and the plots appeared to have reached a 'mature' and steady playing condition at this age. Throughout the trial period, green speed (ball roll distance) values of all rootzone and cultivation/aeration treatments remained within the accepted range (1.5 to 3.0 m) recommended for UK golf green conditions by Baker *et al.* (1996). The values also represented all the categories from 'medium-slow' (1.68 m) to 'fast' (> 2.59 m), as determined by the USGA classification system for regular membership play (Radko 1980).

One of the unexpected features for ball roll distance was that significantly longer ball roll distance was recorded in winter than in summer. This result may be explained by a more uniform and denser sward in winter than in summer under the conditions of this trial.

Rootzone type had minimal effect on ball roll distance. This result agrees with observations that ball roll distance is inevitably related to conditions in the immediate surface rather than underlying rootzone composition (Baker & Richards 1991; Baker *et al.* 1999a,b). However, all three cultivation/aeration treatments generally reduced ball roll distance compared with the control. For Verti-drain and scarification treatments, the greater interference with surface uniformity and firmness associated with these treatments might have resulted in a slower green speed (Baker 1994). However, it is difficult to explain why HydroJect treatment resulted in a slightly (but significantly) slower green speed than the control and the other two cultivation/aeration treatments on several measurement occasions, as HydroJect treatment is reported to cause minimal surface disturbance (Handreck & Black 1994). HydroJect treatment did possess a significantly softer surface on several measurement occasions (Fig. 6-2) and this could in part explain the observed reduction in ball roll distance, but so did Verti-drain treatment and no reduction in ball roll distance was observed with this latter treatment, and more observations may be required.

### 6.5.2 Surface hardness

There was a progressive increase in surface hardness over time for all rootzone and cultivation/aeration treatments. This result was inconsistent with Baker *et al.* (1997), who found that five years after sowing hardness values (by 0.5 kg hammer) all fell below the suggested limit of 55 gravities on both peat and fensoil amended sand-based golf greens. In the present trial, surface hardness values, measured using the 0.5 kg Clegg hammer and 0.3 m single drop height were slightly above the acceptable range of 80-140 gravities recommended for New Zealand golf greens (Table 3-6) by the fifth year for the soil and the three amended sand rootzones, as well as for Verti-drain and scarification treatments. Compared with the limits recommended for UK golf green conditions by Baker *et al.* (1996), most of the values in the present trial were also well above the acceptable range (55 to 120 gravities) or normal range (70 to 100 gravities). None of the readings in present trial came close to the 'soft' end of the normal or acceptable range, even in the winter of July 2002 when the measured gravimetric moisture content of the upper 50 mm of the profiles was at its highest value (55% for the soil rootzone, 34% for the sand-based rootzones). This result meant that it was difficult to see a consistent association pattern of surface hardness with season or soil moisture, unlike previous studies (e.g. Baker *et al.* 1999b), but the result may also be a reflection of the rolling-type nature of the wear treatment regularly applied during the present trial.

This trial confirmed that rootzone composition had a greater effect on surface hardness than on green speed (Baker *et al.* 1999b). The larger fluctuations in hardness values for the soil rootzone between measurement occasions were also consistent with previous studies (Baker & Richards 1991; Lodge & Baker 1991). Here, it was found that hardness was more consistent on the sand-based rootzones, whereas the soil-based rootzones tended to be soft in wet rootzone conditions and hard during dry. For the pure sand rootzone, the larger fluctuations in surface hardness between measurements may have been influenced by a looser surface of the pure sand rootzone under dry rootzone conditions. However, as expected, there were no significant differences in both green speed and surface hardness between a standard USGA profile and the two partially amended sand rootzones.

Cultivation/aeration treatments showed a greater influence on surface hardness than did rootzone type. Here, Verti-drain treatment produced the softest and scarification treatment produced the hardest surface, an effect that might have resulted from lifting action during Verti-draining and less thatch accumulation associated with scarification treatment.

The results in the present trial suggested that the Clegg hammer should be used in different ways depending on what property of the green's profile is of interest. A single drop of the 0.5 kg Clegg hammer may be the best method for determining the immediate surface characteristics related to the holding power of a green. However, for gaining hardness information related to rootzone composition and cultivation/aeration treatments, dropping the 0.5 kg hammer four times before taking a reading (as was originally intended with this device), or a single drop of the 2.25 kg Clegg hammer may be more apparent.

## 6.6 SUMMARY AND CONCLUSIONS

There was a general trend for a progressive increase in green speed and surface hardness for all rootzone and cultivation/aeration treatments during the first five years after sowing despite fluctuations with seasons. However, playing quality performance was generally acceptable on all measurement occasions, with the exception of surface hardness being slightly above the acceptable range by the fifth year after sowing.

There were significant effects of rootzone type on surface hardness though its effects on green speed were minimal. The soil and pure sand rootzones showed the greatest fluctuation in surface hardness. There was no indication from this trial that the New Zealand practice of constructing only the top 100 mm of the sand rootzone with organic-amended sand conferred any poorer playing quality performance compared with a fully amended USGA rootzone.

Surface hardness was significantly influenced by cultivation/aeration treatment with the hardest surfaces being associated with scarification treatment, and the softest surfaces being associated with Verti-drain and HydroJect treatment. Results for green speed also showed a marginal decrease with HydroJect treatment compared with Verti-drain and scarification treatment.

The sensitivity of surface hardness measurements depended on the weight of Clegg hammer and number of drops used. Immediate surface firmness appeared to be best represented by a single drop of the 0.5 kg Clegg hammer. However, to determine hardness characteristics related to deeper layers of the profile, dropping the 0.5 kg hammer four times before taking a reading, or using a single drop of the 2.25 kg Clegg hammer may be more appropriate on golf greens.

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# 7. A MATHEMATICAL MODEL FOR COMPREHENSIVE ASSESSMENT AND DYNAMIC MONITORING OF THE LONG-TERM PERFORMANCE OF GOLF GREENS

## 7.1 ABSTRACT

This chapter reports a prediction of golf green performance over a 30 year period in terms of rootzone physical properties, sward characteristics and playing qualities of five alternative golf green rootzones by means of an Integrated Rate Methodology (IRM) model. Rootzone treatments were: partially amended sand rootzone, soil rootzone, pure sand rootzone, full amended sand rootzone and partially amended sand + zeolite rootzone, managed under a range of alternative cultivation/aeration treatments (HydroJect, scarification and Verti-drain).

The results showed that the Integrated Rate Methodology (IRM) model could give an objective, quantitative and comprehensive assessment and monitoring of the long-term performance of golf greens at both the surface and rootzone level under changeable field conditions by computing a Comprehensive Golf Green Performance Index ($CGGP_I$).

Advantages of the sand-based rootzones over the conventional soil rootzone were significant in terms of a large increase in Comprehensive Golf Green Performance Index ($CGGP_I$). However, there was a general deterioration over time in the Index for all sand-based rootzones, particularly for the three amended sand rootzones. The advantages of the sand-based rootzones, especially the three amended sand rootzones, over the conventional soil rootzone diminished with time. Under the management conditions used, not only did the Index of the conventional soil rootzone always remain well below the minimum acceptable threshold, but the Index of the three amended sand rootzones and pure sand rootzone were also predicted to be unacceptable by the 14$^{th}$ and 27$^{th}$ year after sowing, respectively. The principal factor causing such a general deterioration in the Index of the sand-based rootzones was considered to be excess accumulation of organic matter in the upper portion of the profiles. A second key factor causing a relatively larger deterioration in the Index of the three amended sand rootzones compared with the pure sand rootzone appeared to be a faster shift of rooting depth toward the surface of the profiles.

There were negligible differences in the Comprehensive Golf Green Performance Index ($CGGP_I$) between the three amended sand rootzones on all occasions predicted. In contrast, when compared with the three amended sand rootzones the pure sand rootzone

gave variable responses, having a significantly lower Index during the first two years after sowing, but possessing a significantly higher Index on all predicted occasions afterwards.

None of the cultivation/aeration treatments were able to halt the general deterioration in the Comprehensive Golf Green Performance Index ($CGGP_I$) at the imposed frequency of twice-yearly treatment. Model simulation indicated that the optimum improvement in the simulated $CGGP_I$ by the cultivation/aeration treatment (e.g. Verti-drain and scarification) could be achieved at a frequency of up to six times per year on sand-based rootzones under New Zealand conditions.

It is concluded that: (a) neither of the two modified USGA profiles conferred a poorer green performance compared with a standard USGA profile; (b) the pure sand rootzone system was of no long-term disadvantage compared with the amended sand rootzones; (c) the cultivation/aeration treatment (e.g. Verti-drain and scarification) should theoretically be used at a frequency of up to six times per year on sand-based rootzones under New Zealand conditions to maximize the benefits of the cultivation/aeration treatment; (d) the Integrated Rate Methodology (IRM) model appears a potential tool in consultancy, seasonal management and performance assessment and monitoring of golf greens.

**KEYWORDS**: Compost, Comprehensive Golf Green Performance Index ($CGGP_I$), Integrated Rate Methodology (IRM) model, HydroJect, playing quality, rootzone physical properties, scarification, sward characteristics, Verti-drain and zeolite.

## 7.2 INTRODUCTION

A sports turf ecosystem, like other agro-ecosystems, consists of numerous components that interact continuously with each other. Each of these components makes certain contributions to overall turf performance as represented by rootzone physical properties, sward characteristics and playing quality (Barr 1993; Gibbs *et al.* 2000, 2001; Power 2004). In addition, sports turf is a highly dynamic medium and overall turf performance will change with time and usage. Therefore, it is difficult to provide a comprehensive assessment of changes in long-term performance of a sports turf based on conventional evaluation methods that measure a small number of factors under only static conditions (Wu *et al.* 1996).

The quantitative, objective and comprehensive assessment of changes with time in the long-term performance of a sports turf system should use a systems analysis methodology based on a given mathematical model (Wu *et al.* 1994, 1996). Ideally, a systems analysis model for the above purpose should be able to directly represent multi-faceted components, monitor the system performance over time, and explicitly deal with many influences (including interactions) between the components in a relatively simple model structure (Wu *et al.* 1996). Most importantly, the model should be capable of integrating quantitative factors with qualitative factors.

Since the 1960s, systems analysis and models of ecosystems have progressed from a purely descriptive to an interpretative level (Wu *et al.* 1996). Although little published information is currently available on development of systems analysis models in turf science, numerous models of grasslands, forests and crops have been developed and incorporated with goal-oriented management approaches to agricultural practices in the last 15 years (Thomas & Neil 1991; Dawes & Hatton 1993; Farahani *et al.* 1993; Reddy, *et al.* 1995; Boote *et al.* 1996; Gijsman *et al.* 1996; Wu *et al.* 1994, 1996; Kiniry *et al.* 1996; Fritz *et al.* 1997; Rossiter & Riha 1999). Of these existing models, a resource integration approach may best serve the modeling requirements of a sports turf ecosystem.

A resource integration approach, which is based on Integrated Rate Methodology (IRM) introduced by Sharpe *et al.* (1987, cited in Li *et al.* 1990) and Wu *et al.* (1994) for multi-factor modeling, was developed to simulate ecological systems where underlying biological processes are tightly integrated with output responses. A specific advantage of this approach is the capability for integrating quantitative factors with qualitative factors through direct mathematical linkages (Wu *et al.* 1994, 1996). This is especially important for sports turf, as overall turf performance cannot be measured quantitatively and directly like crop yields, and many effects of turf management practices have to be evaluated qualitatively.

Performance assessment of golf courses dates back several decades (McAuliffe 2001). For example, the Stimpmeter, which was introduced over 30 years ago, has been used widely by golf clubs throughout the world to measure ball roll distance (Radko 1978; McAuliffe 2001). This is single factor testing, that focuses mainly on defining and quantifying the speed of golf greens, but it is not sensitive to rootzone physical performance (Rieke *et al.* 1996; Baker *et al.* 1999c). Barr (1993), Power (2004) and Moore (1998) proposed more comprehensive assessment methods for golf greens. Though their approaches have merit, they rely heavily on operator subjective judgment (McAuliffe 2001), and lack an appropriate method to accurately link various performance attributes together. Many researchers have emphasized the importance and benefits of having objective, quantitative and comprehensive assessment of course quality, rather than relying on opinions or subjective views of club members (Oatis 1990; Howard 1995; McAuliffe & Gibbs 1993; McAuliffe 2001). In New Zealand, the idea of developing a more comprehensive, objective and quantitative method for golf course quality assessment and a bench marking system has been a subject of recent interest (McAuliffe 2001; 2003).

The aim of this study was to quantitatively, objectively and comprehensively assess and monitor the long-term performance of five alternative golf green rootzones in terms of their rootzone physical properties, sward characteristics and playing quality by using a modified Integrated Rate Methodology (IRM) model with particular respect to the following aspects:

(a) To determine the advantages and disadvantages of the performance of five alternative golf green rootzones, particularly between the standard USGA profile and the three other alternative sand-based rootzones.

(b) To determine the general long-term trend in golf green performance with trial for all rootzone treatments.

(c) To determine key factors that limited golf green performance and caused general deterioration with time in their rootzone physical properties, sward characteristics and playing quality of sand-based rootzones.

(d) To determine the relative effectiveness of three contrasting cultivation/aeration treatments (i.e. HydroJect, scarification and Verti-drain) in their ability to manipulate general deterioration of golf green performance under New Zealand conditions.

## 7.3 STRUCTURES AND PARAMETERIZATION OF THE INTEGRATED RATE METHODOLOGY (IRM) MODEL

### 7.3.1 The general Integrated Rate Methodology (IRM) model

In this part, three separate sub-models (i.e. Rootzone, Sward and Playing Quality) have been coupled into a general IRM model to simulate the golf green performance in terms of rootzone physical performance, sward characteristics and playing quality at both surface and rootzone level. Effects of turf maintenance practices have also been incorporated into each of the sub-models, even though there is no separate turf management sub-model. The output of such a coupled general IRM model is a normalized Comprehensive Golf Green Performance Index ($CGGP_I$) (scaled from 0 to 1), which is computed by integrating the indexes of the three sub-models into the general IRM model. Therefore, $CGGP_I$ can be used as an important criterion to audit the surface quality of golf greens at rootzone level for research, consultancy, construction, management and surface preparation purposes.

For example, the threshold value of '0.5' is defined as the minimum acceptable $CGGP_I$ value. A value lower than the '0.5' indicates that the green performance is not acceptable, so some corrective management measures must be taken. Therefore, the $CGGP_I$ can not only be used as a criterion to assess overall performance of a golf green, and to monitor the long-term performance trend when the $CGGP_I$ is updated over time in half-year steps, but it can also be used as a guideline for seasonal planning in golf green management.

The conceptual model for a golf green ecosystem is illustrated in Fig. 7-1. According to the principle of the IRM (Wu *et al.* 1994, 1996), the $CGGP_I$ is calculated using Eq. 7-1. The justification and calculation for all statistical models and scaling factors used the following general IRM model, and three IRM sub-models are given in Table 7-1.

$$CGGP_I = CGGP_0 \left[\sum_{i=1}^{n} W_i \div \sum_{i=1}^{n} (W_i \div X_i)\right]$$

$$= \frac{a+b+c}{\frac{a}{R_I} + \frac{b}{S_I} + \frac{c}{P_I}} \qquad (7\text{-}1)$$

where:

$X_i$ Normalized (i.e. scaled from 0 to 1) input variables. Realistic values for the $X_i$ inputs are not necessarily extended across the entire range 0 to 1. For instance, the range for the effect of maintenance could be set between 0.30 and 0.70 (Wu *et al.* 1996);

$CGGP_I$ Normalized Comprehensive Golf Green Performance Index, scaled from 0 to 1;

$CGGP_0$ The maximum potential Comprehensive Golf Green Performance Index, scaled from 0 to 1;

$W_i$ The weighting factors that reflect the relative insensitivity (i.e. contribution) of resource *i* with respect to the output $CGGP_I$. In absence of relevant information, $W_i$ value is sometimes set as 1 (Wu *et al.* 1996);

n The total number of resources or sub-models;

$R_I$ A normalized golf green Rootzone Index scaled from 0 to 1;

$S_I$ A normalized golf green Sward Index scaled from 0 to 1;

$P_I$ A normalized golf green Playing Quality Index, scaled from 0 to 1;

a,b,c Weighting factors for Rootzone (a), Sward (b) and Playing Quality (c) sub-models respectively, determined by the relative percentage of the accumulated factor weightings of all sub-model factors (Wu *et al.* 1994). Here, 'a' is set to 0.39, 'b' = 0.37 and 'c' = 0.24 (Table 7-1).

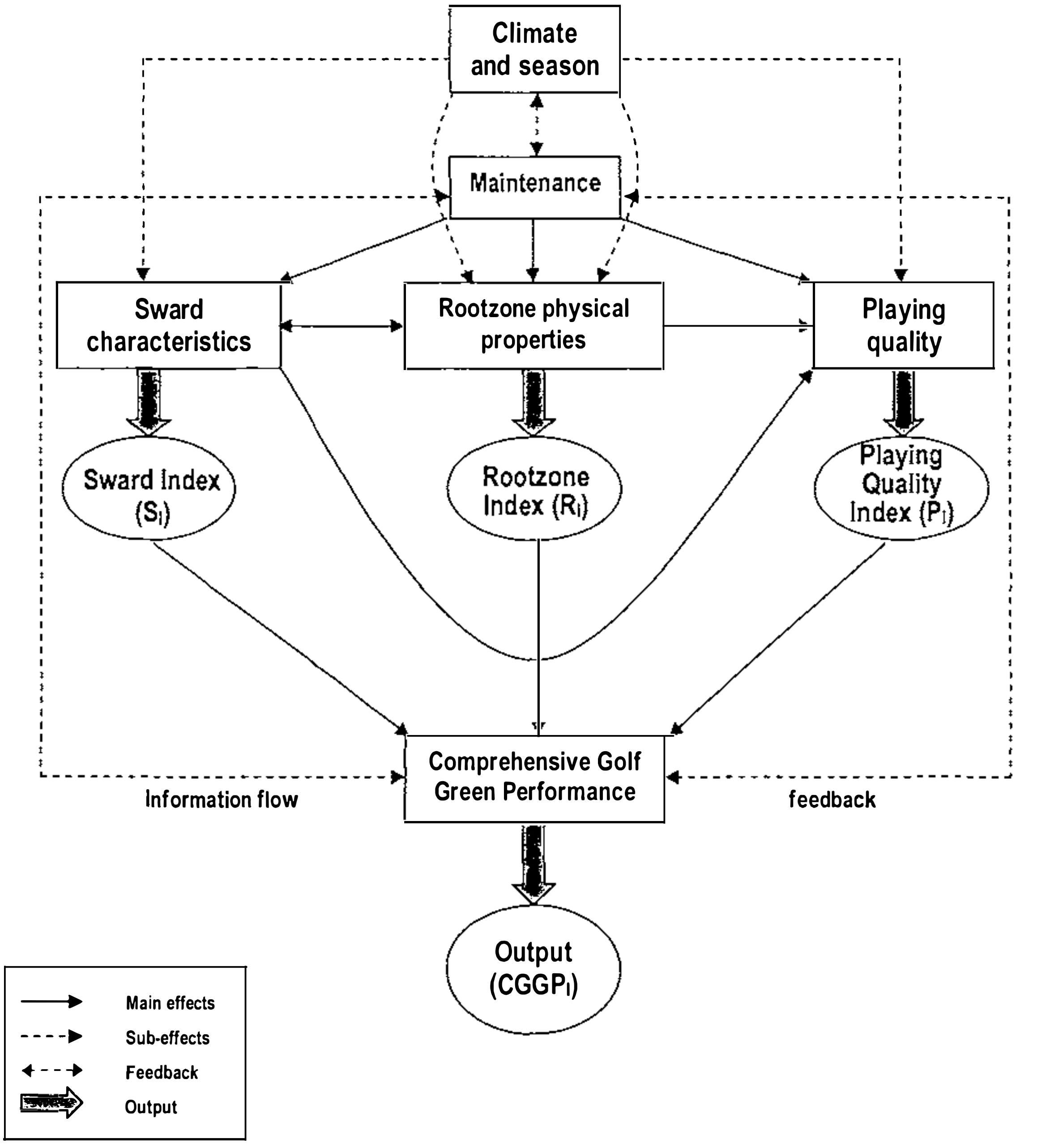


**Fig. 7-1 A schematic representation of a general Integrated Rate Methodology model for a golf green ecosystem**

**Table 7-1 Justification of all statistical models and scaling factors used in the general IRM model and three IRM sub-models**

| Statistic models or scaling factors | | Symbol in the model | Value | Justification |
|---|---|---|---|---|
| **Weighting factors for sub-models** | Rootzone | a | 0.39 | Details of the calculation are given in Appendix Table 7-1 |
| | Sward | b | 0.37 | |
| | Playing quality | c | 0.24 | |
| **Effects of season and climate** | Rootzone | Winter | 0.50 | Details of the calculation are given in Appendix Table 7-2a |
| | | Summer | 0.65 | |
| | Sward | Summer & winter | 0.50 | Details of the calculation are given in Appendix Table 7-2b |
| | | Spring & autumn | 0.59 | |
| | Playing quality | Winter | 0.50 | Details of the calculation are given in Appendix Table 7-2c |
| | | Summer | 0.51 | |
| **Effects of daily maintenance** | For all sub-models | $M_l(t)$ | 0.50 | The current maintenance practice is considered as a standard practice for New Zealand putting greens. |
| **Effects of cultivation/aeration treatment** | Rootzone | $C_f$ | 0.80-1.00 for sand-based, and 0.29-0.90 for soil-based rootzones | Details of the calculation are given in Appendix Table 7-3a |
| | Sward | | 0.88-0.93 for sand-based, and 0.90-0.96 for soil-based rootzones | Details of the calculation are given in Appendix Table 7-3b |
| | Playing quality | | 0.82-0.98 for sand-based, and 0.81-1.00 for soil-based rootzones | Details of the calculation are given in Appendix Table 7-3c |
| **Scaling factor for overall management practices and seasonal climate changes** | Rootzone | $Y$ | 0.55 for sand-based rootzones, and 0.96 for soil-based rootzones | Details of the calculation are given in Appendix Table 7-3a |
| | Sward | | 0.34 for sand-based rootzones, and 0.35 for soil-based rootzones | Details of the calculation are given in Appendix Table 7-3b |
| | Playing quality | | 0.37 for sand-based rootzones, and 0.40 for soil-based rootzones | Details of the calculation are given in Appendix Table 7-3c |
| **Scaling factor for overall human management practices** | Rootzone | $h_m$ | Four times more sensitive than seasonal climate changes | Details of the calculation are given in Appendix Table 7-3a |
| | Sward | | Three times more sensitive than seasonal climate changes | Details of the calculation are given in Appendix Table 7-3b |
| | Playing quality | | 37.5 times more sensitive than seasonal climate changes | Details of the calculation are given in Appendix Table 7-3c |
| **Scaling factor for a given cultivation/aeration treatment** | Rootzone | $h_c$ | Four times more sensitive than daily maintenance practice | Details of the calculation are given in Appendix Table 7-3a |
| | Sward | | 1.5 times less sensitive than daily maintenance practice | Details of the calculation are given in Appendix Table 7-3b |
| | Playing quality | | 1.5 times more sensitive than daily maintenance practice | Details of the calculation are given in Appendix Table 7-3c |
| **Statistical models for normalization of factor values measured** | Rootzone | Eq. 7-9 to 7-13 | Refer to Chapter 7 | Details of the calculation are given in Appendix Figure 7-1 |
| | Sward | Eq. 7-24 to 7-27 | | |
| | Playing quality | Eq. 7-37 to 7-38 | | |
| **Natural diminishing equations for each modeling factor** | Rootzone | $\int d[R_l(t)]/dt$ | Refer to Chapter 7 | Details of the calculation are given in Appendix Figures 7-6 to 7-9 |
| | Sward | | | Details of the calculation are given in Appendix Figures 7-10 to 7-13 |
| | Playing quality | | | Details of the calculation are given in Appendix Figures 7-14 to 7-15 |

### 7.3.2 The Rootzone sub-model

Based on the field study, rootzone physical attributes (i.e. infiltration rate, water-filled and air-filled porosity and organic matter content) of golf greens are selected and mathematically coupled into the Rootzone sub-model. The conceptual structure of a Rootzone sub-model for golf greens is illustrated in Fig. 7-2. The output from the Rootzone sub-model is Rootzone Index ($R_I$), a normalized value scaled from 0 to 1, which represents the overall rootzone physical performance of a studied golf green under certain maintenance practices. Updating over time in half-year steps, the $R_I$ can simulate and monitor changes in the overall physical performance of a given rootzone under certain ecological and management conditions. According to the principle of the IRM (Wu *et al.* 1994, 1996), the $R_I$ can be calculated as:

$$R_I(t) = \text{Min}\,[1, R_I(t-1) - \Delta_- R_I + \Delta_+ R_I] \tag{7-2}$$

with

$$\Delta_+ R_I = \frac{5\Upsilon}{\dfrac{4}{h_m} + \dfrac{1}{S_w}} \tag{7-3}$$

where

$$h_m = \frac{5}{\dfrac{4}{h_c} + \dfrac{1}{M_I(t)}} \tag{7-4}$$

$$h_c = C_f \times \ln(1.15 + C_n/4) \tag{7-5}$$

and

$$\Delta_- R_I = \int d[R_I(t)]/dt \qquad \text{(from t-1 to t)} \tag{7-6}$$

and

$$R_I(t-1) - \Delta_- R_I = \frac{\sum_{i=1}^{n} W_i}{\sum_{i=1}^{n} \dfrac{W_i}{X_i}} \quad (i = 1, 2, 3, \ldots, n;\ n = \text{number of variables};\ t \geq 1)$$

$$= \frac{W_{ir} + W_{Fa} + W_{O35} + W_{O70} + W_{Fw}}{\frac{W_{ir}}{X_{ir}} + \frac{W_{Fa}}{X_{Fa}} + \frac{W_{O35}}{X_{O35}} + \frac{W_{O70}}{X_{O70}} + \frac{W_{Fw}}{X_{Fw}}} \quad (7\text{-}7)$$

and $$t = \mathrm{INT}\,[\beta / \varphi] \qquad (\beta \geq t\varphi) \quad (7\text{-}8)$$

where:

Min [···] = The minimum of the terms within the brackets;

$\Delta_+$ and $\Delta_-$ = Positive and negative effects on Rootzone Index respectively;

$M_I(t)$ = Daily maintenance effect, reflecting combined effects from all daily maintenance practices (e.g. mowing, rolling, irrigating, fertilizing, pesticides and wetting agent application) with the exception of effects from cultivation/aeration treatments at time t. Under the maintenance practices used, the value of $M_I(t)$ is set to 0.50 (Table 7-1);

$\Upsilon$ = Scaling factor, reflecting how overall management practices (including cultivation/aeration treatments) and seasonal climate change affect physical properties of golf greens; here the value of $\Upsilon$ is set to 0.55 for sand-based rootzones, and the value of $\Upsilon$ is set to 0.96 for soil-based rootzones (Table 7-1);

$h_c$ = Scaling factor, reflecting how rootzone physical properties are influenced by a given type of cultivation/aeration treatment applied at known frequency. It is four times more sensitive than the effect of daily maintenance practice [$M_I(t)$] (Table 7-1);

$h_m$ = Scaling factor, reflecting how rootzone physical properties are influenced by the overall management practices (including cultivation/aeration treatments). It is four times more sensitive than the effect of seasonal climate change ($S_w$) (Table 7-1);

$C_n$ = Frequency of a cultivation/aeration treatment applied per year;

$C_f$ = Effect of a cultivation/aeration treatment (for sand-based rootzones, the value for hollow tine Verti-drain is set to 1.00, solid tine Verti-drain = 0.90, HydroJect = 0.86, scarification = 0.80, the control = 0.81; for soil-based rootzones, the value for hollow tine Verti-drain is set to 0.90, solid tine Verti-drain = 0.80, HydroJect = 0.29, scarification = 0.45, control = 0.62) (Table 7-1);

$S_w$ = Reflects how seasonal climate change affects the overall rootzone physical performance; here if the value in the winter is set to 0.50, then the value in the summer is 0.65 (Table 7-1);

$\int d[R_I(t)]/dt$ = Natural diminishing integral equation computed by plot fitting (Table 7-1);

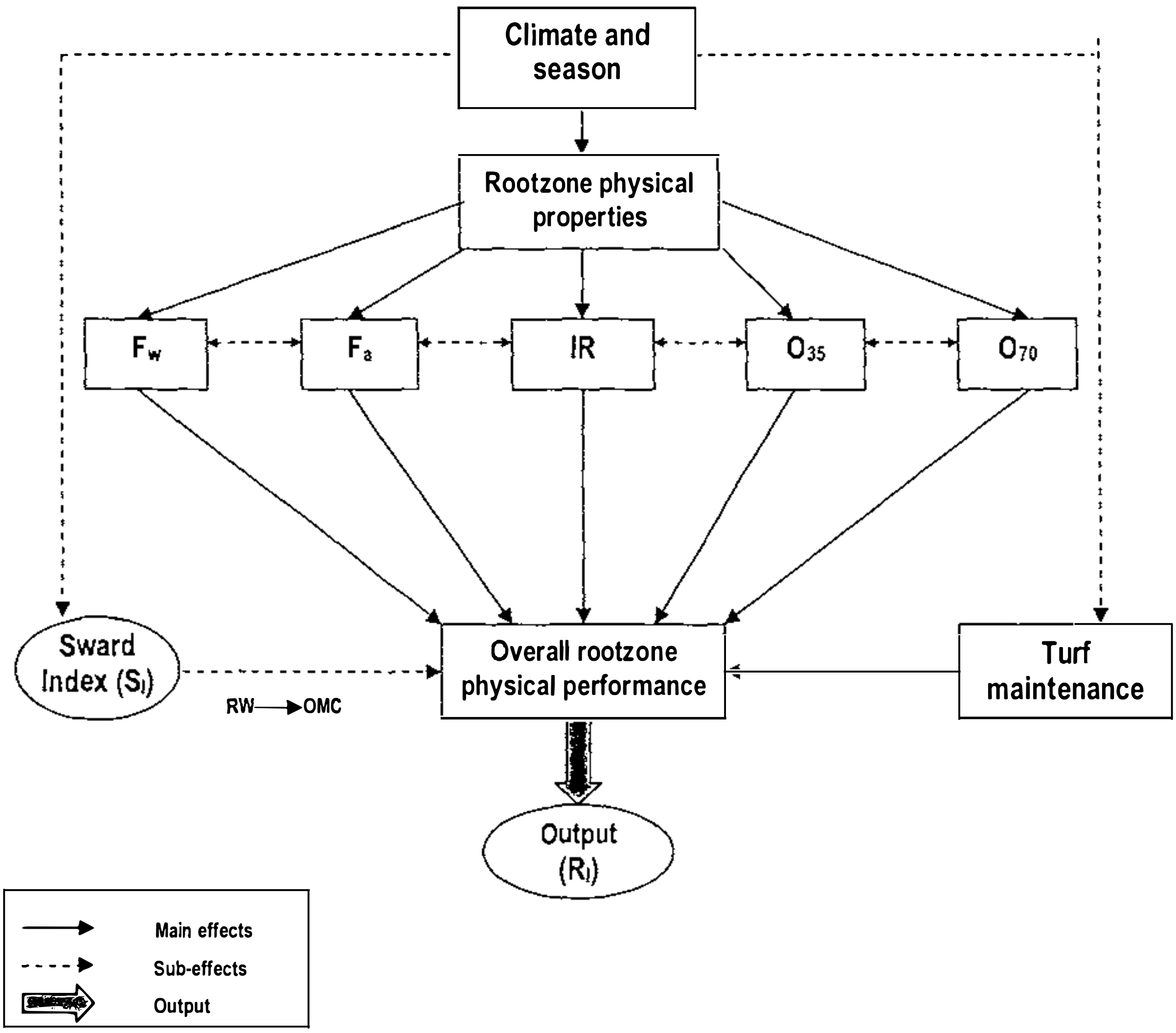


**Fig. 7-2 A conceptual Rootzone sub-model for a golf green ecosystem**

$F_w$: water-filled porosity (%, v/v) at –3 kPa in the 35-70 mm of the rootzone; $F_a$: air-filled porosity (%, v/v) at –3 kPa in the 35-70 mm of the rootzone; IR: infiltration rate (mm $h^{-1}$); $O_{35}$: organic matter content (%, w/w) at the top 35 mm of the rootzone; $O_{70}$: organic matter content (%, w/w) at the 35-70 mm of rootzone depth; OMC: rootzone organic matter content (%, w/w); RW: Root mass (g $m^{-2}$).

t = Runs of simulation;

$\Phi$ = Simulation time step in months; here the value is given as 6;

$\beta$ = Months following turf establishment;

INT [$\beta$ / $\varphi$] = The largest integer less than or equal to $\beta$ / $\varphi$;

$X_{ir}$ = Normalized infiltration rate, scaled from 0 to 1;

$X_{Fa}$ = Normalized air-filled porosity at -3kPa in the 35-70 mm rootzone depth;

$X_{O35}$ = Normalized organic matter content at the top 0-35 mm of the rootzone;

$X_{O70}$ = Normalized organic matter content at the 35-70 mm rootzone depth;

$X_{Fw}$ = Normalized water-filled porosity at -3kPa in the 35-70 mm depth;

$W_i$, $W_{ir}$, $W_{Fa}$, $W_{O35}$, $W_{O70}$ and $W_{Fw}$ = Weighting factors for each rootzone physical factor (Table 7-2), which is determined by solving the simultaneous equations (Eq. 7-14, 7-15, 7-16) (Wu *et al.* 1994). For details of development of the Eq 7-9 to 7-13, please refer to Table 7-1:

where

$$X_{ir} = \text{Min}\ [1,\ 0.3014\text{Ln(IR)} - 0.3900)] \quad (7\text{-}9)$$

and

$$\begin{cases} X_{Fa} = \dfrac{F_a}{20} & (F_a \le 20) \\ X_{Fa} = \dfrac{10}{F_a - 10} & (F_a > 20) \end{cases} \quad (7\text{-}10)$$

and

$$\begin{cases} X_{O35} = \dfrac{O_{35} + 1}{4} & (O_{35} \le 3\%) \\ X_{O35} = \dfrac{3}{O_{35}} & (O_{35} > 3\%) \end{cases} \quad (7\text{-}11)$$

and

$$\begin{cases} X_{O70} = \dfrac{O_{70}}{2} & (O_{70} \le 2\%) \\ X_{O70} = \dfrac{1}{O_{70} - 1} & (O_{70} > 2\%) \end{cases} \quad (7\text{-}12)$$

and

$$\begin{cases} X_{Fw} = 0.0016(F_w)^2 - 0.0073F_w + 0.0052 & (F_w \leq 27.5) \\ X_{Fw} = 0.0015(F_w)^2 - 0.1567F_w + 4.2101 & (F_w > 27.5) \end{cases} \quad \textbf{(7-13)}$$

where:

Min [···] = The minimum of the terms within the brackets;

IR : Measured infiltration rates (mm $h^{-1}$); the acceptable infiltration rate range for golf greens is set at ≥ 20 (mm $h^{-1}$) (Table 3-6);

$F_a$ : Measured air-filled porosity (%, v/v) at -3 kPa in the 35-70 mm rootzone depth; the acceptable air-filled porosity range for golf greens is set at 10-30 (%, v/v) (Table 3-6);

$O_{35}$: Measured organic matter content (%, w/w) at the top 0-35 mm rootzone; the maximum acceptable $O_{35}$ value for golf greens at the topsoil is set at ≤ 6 (%, w/w) (Table 3-6);

$O_{70}$: Measured organic matter content (%, w/w) at the 35-70 mm rootzone depth; the maximum acceptable $O_{70}$ value for golf greens at the sub-surface is set at ≤ 3 (%, w/w) (Table 3-6);

$F_w$ : Measured water-filled porosity (%, v/v) at -3 kPa in the 35-70 mm rootzone depth; the acceptable water-filled porosity range for golf greens is set at 20-35 (%, v/v) (Table 3-6);

### *7.3.2.1 Determination of factor weightings*

The factor weightings are determined by calculating the following simultaneous equations that are derived according to the acceptable range (i.e. 'half-saturation' and 'saturation' responses) (Wu *et al.* 1994) of each rootzone physical factor in relation to the overall green performance.

$$\begin{cases} w_2 + w_3 + w_4 + w_5 + \left(2 - \dfrac{1}{(x_1)_{1/2}}\right) = 0 \\ \left(2 - \dfrac{1}{(x_2)_{1/2}}\right) w_2 + w_3 + w_4 + w_5 + 1 = 0 \\ w_2 + \left(2 - \dfrac{1}{(x_3)_{1/2}}\right) w_3 + w_4 + w_5 + 1 = 0 \\ w_2 + w_3 + \left(2 - \dfrac{1}{(x_4)_{1/2}}\right) w_4 + w_5 + 1 = 0 \\ w_2 + w_3 + w_4 + \left(2 - \dfrac{1}{(x_5)_{1/2}}\right) w_5 + 1 = 0 \end{cases} \qquad (7\text{-}14)$$

To guarantee a unique set of solutions, the determinant of the *w*-coefficient matrix must be zero (Wu *et al.* 1994), i.e.,

$$\begin{pmatrix} 1 & 1 & 1 & 1 & 2-\dfrac{1}{(x_1)_{1/2}} \\ 2-\dfrac{1}{(x_2)_{1/2}} & 1 & 1 & 1 & 1 \\ 1 & 2-\dfrac{1}{(x_3)_{1/2}} & 1 & 1 & 1 \\ 1 & 1 & 2-\dfrac{1}{(x_4)_{1/2}} & 1 & 1 \\ 1 & 1 & 1 & 2-\dfrac{1}{(x_5)_{1/2}} & 1 \end{pmatrix} = 0 \qquad (7\text{-}15)$$

If the *w*-coefficient matrix of the above simultaneous equation is not equal to zero, there may be many solutions. Under this situation, the Eq. 7-14, 7-15 cannot be used. According to the calculation method of factor weightings for two resources cases (Wu *et al.* 1994), the following equation can be used to estimate the factor weightings under such a situation.

$$\frac{1}{(x_1)_{1/2}} = \frac{W_2}{(x_2)_{1/2}} = , \ldots , = \frac{W_i}{(x_i)_{1/2}} \quad (i = 1, 2, \ldots, n;\ n = \text{number of factors}) \qquad (7\text{-}16)$$

where:

$(X_1)_{1/2} = (X_{ir})_{1/2} = 0.20$;
$(X_2)_{1/2} = (X_{Fa})_{1/2} = 0.50$;
$(X_3)_{1/2} = (X_{O35})_{1/2} = 0.33$;
$(X_4)_{1/2} = (X_{O70})_{1/2} = 0.50$;
$(X_5)_{1/2} = (X_{Fw})_{1/2} = 0.73$;

Thus, if water infiltration rate ($X_1$) is selected as the reference factor and its weighting ($W_1$) is set to 1, then:

$(W_2) = (W_{Fa}) = 2.50$;
$(W_3) = (W_{O35}) = 1.67$;
$(W_4) = (W_{O70}) = 2.50$;
$(W_5) = (W_{Fw}) = 3.64$;

### 7.3.3 The Sward sub-model

Based on the field study, effects of various sward characteristic attributes (i.e. root distribution, species composition, visual turf quality and dry patch severity) of golf greens are selected and mathematically linked together by the Sward sub-model. Then, a normalized Sward Index ($S_I$, scaled from 0 to 1) is computed to give a comprehensive assessment of sward characteristics of golf greens at both the surface and rootzone level. Updating over time in half-year steps, the $S_I$ can simulate and monitor changes of the long-term sward characteristics of a studied golf green under certain maintenance practices. The sub-model structure is conceptually illustrated in Fig. 7-3. According to principles of the IRM (Wu *et al.* 1994, 1996), the $S_I$ is calculated by the following equations:

$$S_I(t) = \text{Min}\,[1, S_I(t-1) - \Delta_- S_I + \Delta_+ S_I] \qquad (7\text{-}17)$$

with $$\Delta_+ S_I = \frac{4\gamma}{\dfrac{3}{h_m} + \dfrac{1}{S_w}} \qquad (7\text{-}18)$$

where

$$h_m = \frac{2.5}{\frac{1}{h_c} + \frac{1.5}{M_l(t)}} \quad (7\text{-}19)$$

$$h_c = C_f \times \ln(1.15 + C_n/4) \quad (7\text{-}20)$$

and $$\Delta_{-}S_l = \int d[S_l(t)]/dt \quad \text{(from t-1 to t)} \quad (7\text{-}21)$$

and $$S_l(t-1) - \Delta_{-}S_l = \frac{\sum_{i=1}^{n} W_i}{\sum_{i=1}^{n} \frac{W_i}{X_i}} \quad (i = 1, 2, 3, \cdots, n;\ n = \text{number of variables};\ t \geq 1)$$

$$= \frac{W_r + W_d + W_v + W_b}{\frac{W_r}{X_r} + \frac{W_d}{X_d} + \frac{W_v}{X_v} + \frac{W_b}{X_b}} \quad (7\text{-}22)$$

and $$t = \mathrm{INT}\,[\beta / \varphi] \quad (\beta \geq t\varphi) \quad (7\text{-}23)$$

where:

Min [$\cdots$] = The minimum of the terms within the brackets;

$\Delta_+$ and $\Delta_-$ = Positive and negative effects on Sward Index respectively;

$M_l(t)$ = Daily maintenance effect, reflecting combined effects from all daily maintenance practices (e.g. mowing, rolling, irrigating, fertilizing, pesticides and wetting agent application) with the exception of effects from cultivation/aeration treatments at time t. Under the current daily maintenance practices, the value of $M_l(t)$ is set to 0.50 (Table 7-1);

$\Upsilon$ = Scaling factor, reflecting how overall management practices (including cultivation/aeration treatments) and seasonal climate change affect sward characteristics of golf greens; here the value of $\Upsilon$ is set to 0.34 for sand-based rootzones, and 0.35 for soil-based rootzones (Table 7-1);

$h_c$ = Scaling factor, reflecting how sward characteristics are influenced by a given type of cultivation/aeration treatment applied at known frequency. The effect of daily maintenance practice is 1.5 times more sensitive than the effect of a given cultivation/aeration treatment for sward characteristics (Table 7-1);

$h_m$ = Scaling factor, reflecting how sward characteristics are influenced by the overall management practices (including cultivation/aeration treatments). It is three times more sensitive than effects of seasonal climate change (Table 7-1);

$C_n$ = Frequency of a cultivation/aeration treatment applied per year;

$C_f$ = Effect of a cultivation/aeration treatment (for sand-based rootzones, the value for Verti-drain is set to 0.93, HydroJect = 0.92, scarification = 0.93, the control = 0.88; for soil-based rootzones, the value for Verti-drain is set to 0.91, HydroJect = 0.96, scarification = 0.93, the control = 0.90) (Table 7-1);

$S_w$ = Reflects how seasonal climate change affects the overall sward characteristics. If the value in the winter and summer is set to 0.50, then the value in the spring and autumn is 0.59 (Table 7-1);

$\int d[S_i(t)]/dt$ = Natural diminishing integral equation computed by plot fitting (Table 7-1);

t = Runs of simulation;

$\Phi$ = Simulation time step in months; here the value is given as 6;

$\beta$ = Months following turf establishment;

INT $[\beta / \varphi]$ = The largest integer less than or equal to $\beta / \varphi$;

$X_r$ = Normalized root distribution (i.e. normalized dry root mass percentage at the 50-250 mm soil depth in the total rootzone), scaled from 0 to 1;

$X_d$ = Normalized dry patch severity;

$X_v$ = Normalized turf quality (i.e. normalized turf uniformity and turf density);

$X_b$ = Normalized species composition (i.e. normalized total turfgrass cover and relative balance of the two sown turfgrass species in the sward);

$W_i$, $W_r$, $W_d$, $W_v$ and $W_b$ = Weighting factors for each sward factor (Table 7-2), which is determined by solving the simultaneous equations (Eq. 7-14, 7-15, 7-16) (Wu *et al.* 1994). For details of development of the Eq. 7-24 to 7-27, please refer to Table 7-1.

where

$$X_r = \text{Min}\,[1,\ 0.0002(R_p)^3 - 0.0106(R_p)^2 + 0.1770(R_p) + 0.0029] \quad (7\text{-}24)$$

and

$$X_d = \text{Max}\,[0.0001,\ 1 - \frac{D_p + 1}{6}] \quad (7\text{-}25)$$

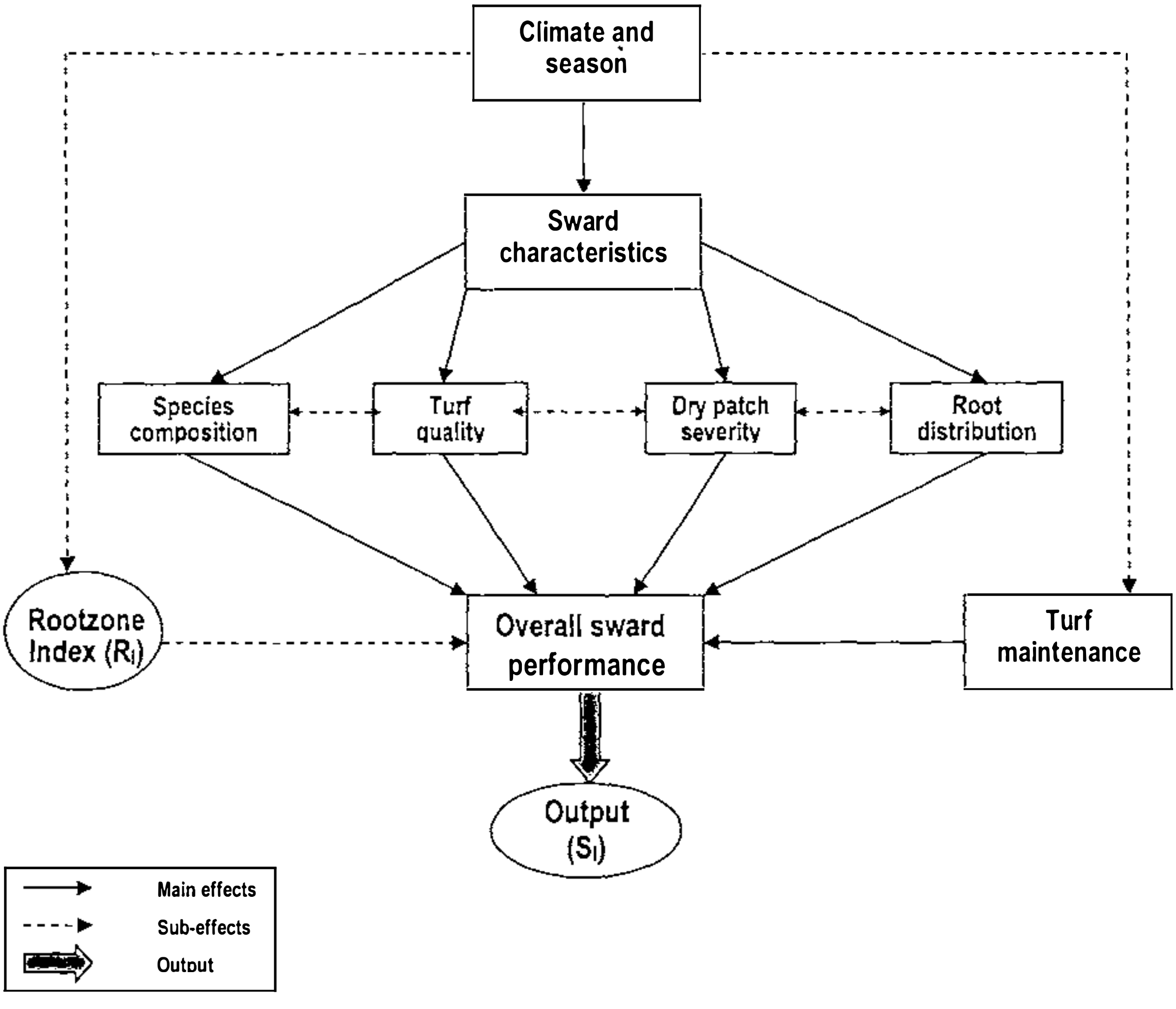


**Fig.7-3 A Conceptual Sward sub-model for a golf green ecosystem**

Turf quality = (visual turf uniformity scores + visual turf density scores) ÷ 2; Dry patch severity: visual scores of dry patch disorder; Root distribution: dry root mass percentage (%) at the 50-250 mm of depth in the total rootzone (i.e. dry root weight at 50-250 mm rootzone depth ÷ total dry root weight at 0-250 mm rootzone depth); Species composition = (total turfgrass coverage + relative balance of the two sown turfgrass species in the sward) ÷ 2, i.e.

$$= \left[\left(\frac{\text{fescue} + \text{browntop}}{100}\right) + \left(1 - \frac{\text{browntop} - \text{fescue}}{\text{browntop} + \text{fescue}}\right)\right] \div 2$$

and
$$X_v = \frac{2}{\frac{1}{0.0198(U_t)^2 - 0.0734U_t + 0.0504} + \frac{1}{0.0198(D_t)^2 - 0.0734D_t + 0.0504}} \quad (7\text{-}26)$$

and
$$X_b = \frac{2}{\frac{1}{\text{Max}\{0.0001, [2.9563\text{Ln}(C_t) - 12.6258]\}} + \frac{1}{\text{Min}[1, 1.4 - (C_b - C_f) \div C_t]}} \quad (7\text{-}27)$$

where:

Min[···] = The minimum of the terms within the brackets;

Max[···] = The maximum of the terms within the brackets;

$R_p$ : Measured dry root mass percentage at the 50-250 mm rootzone depth in the total rootzone; the acceptable root mass percentage at the 50-250 mm depth for golf greens is ≥ 3.50% (Table 3-6);

$D_p$ : Visual scores of dry patch severity (0-5); the acceptable dry patch score range for golf greens is 0-2 (Table 3-6);

$U_t$ : Visual scores of turf uniformity (0-9); the acceptable uniformity score range for golf greens is 7-9 (Table 3-6);

$D_t$ : Visual scores of turf density (0-9); the acceptable turf density score range for golf greens is 7-9 (Table 3-6);

$C_b$ : Measured relative cover (%) of browntop in green sward;

$C_f$ : Measured relative cover (%) of Chewing's fescue in green sward;

$C_t$ = $C_b + C_f$: represents total turfgrass cover (%). The acceptable turfgrass cover for golf greens is ≥ 85%, while the acceptable relative balance $[1-(C_b - C_f) \div C_t]$ index range of the two sown turfgrass species for golf greens is 0.03-0.40 (Table 3-6).

### *7.3.3.1 Determination of factor weightings*

The factor weightings are determined by calculating the following simultaneous equations that are derived according to the acceptable range (i.e. 'half-saturation' and 'saturation' responses) of each sward factor in relation to the overall green performance (Wu *et al.* 1994).

$$\begin{cases} w_7 + w_8 + w_9 + \left(2 - \dfrac{1}{(x_6)_{1/2}}\right) = 0 \\ \left(2 - \dfrac{1}{(x_7)_{1/2}}\right) w_7 + w_8 + w_9 + 1 = 0 \\ w_7 + \left(2 - \dfrac{1}{(x_8)_{1/2}}\right) w_8 + w_9 + 1 = 0 \\ w_7 + w_8 + \left(2 - \dfrac{1}{(x_9)_{1/2}}\right) w_9 + 1 = 0 \end{cases} \tag{7-28}$$

To guarantee a unique set of solutions the determinant of $w$-matrix must be zero (Wu *et al.* 1994), i.e.,

$$\begin{pmatrix} 1 & 1 & 1 & 2-\dfrac{1}{(x_6)_{1/2}} \\ 2-\dfrac{1}{(x_7)_{1/2}} & 1 & 1 & 1 \\ 1 & 2-\dfrac{1}{(x_8)_{1/2}} & 1 & 1 \\ 1 & 1 & 2-\dfrac{1}{(x_9)_{1/2}} & 1 \end{pmatrix} = 0 \tag{7-29}$$

where:

$(X_6)_{1/2} = (X_r)_{1/2} = 0.35;$

$(X_7)_{1/2} = (X_d)_{1/2} = 0.60;$

$(X_8)_{1/2} = (X_v)_{1/2} = 0.78;$

$(X_9)_{1/2} = (X_b)_{1/2} = 0.46.$

As the $w$-coefficient matrix of the above simultaneous equation is not equal to zero, Eq. 7-16 can be used to calculate the factor weightings instead. In this case, if the root distribution ($X_6$) is selected as the reference factor, and its weighting ($W_8$) is set to 1, then $W_7 = 1.71$, $W_8 = 2.22$, $W_9 = 1.30$.

### 7.3.4 The Playing Quality sub-model

The conceptual structure for the Playing Quality sub-model is illustrated in Fig. 7-4. The Playing Quality sub-model integrates effects of the two selected playing quality attributes (i.e. green speed and surface hardness, based on the field study) into an IRM model. The output from the Playing Quality sub-model is the normalized Playing Quality Index ($P_I$), scaled from 0 to 1, which represents the overall surface playing quality of a given golf green under certain maintenance practices. Updating over time in half-year steps, the $P_I$ can simulate and monitor changes in the long-term playing quality of a studied golf green or effects of a given type cultivation/aeration treatment. According to the principle of IRM (Wu *et al.* 1994, 1996), the $P_I$ is calculated as:

$$P_I(t) = \mathrm{Min}\,[1, P_I(t-1) - \Delta_- P_I + \Delta_+ P_I] \tag{7-30}$$

with

$$\Delta_+ P_I = \frac{38.5\gamma}{\dfrac{37.5}{h_m} + \dfrac{1}{S_w}} \tag{7-31}$$

where

$$h_m = \frac{2.5\gamma}{\dfrac{1.5}{h_c} + \dfrac{1}{M_I(t)}} \tag{7-32}$$

$$h_c = C_f \times \ln(1.5 + C_n/4) \tag{7-33}$$

and

$$\Delta_- P_I = \int d[P_I(t)]/dt \quad \text{(from t-1 to t)} \tag{7-34}$$

and

$$P_I(t-1) - \Delta_- P_I = \frac{\sum_{i=1}^{n} W_i}{\sum_{i=1}^{n} \dfrac{W_i}{X_i}} \quad (i = 1, 2;\ t \geq 1)$$

$$= \frac{W_h + W_s}{\frac{W_h}{X_h} + \frac{W_s}{X_s}} \qquad (7\text{-}35)$$

and $$t = INT[\beta / \varphi] \qquad (\beta \geq t\varphi) \qquad (7\text{-}36)$$

where:

Min [···] = The minimum of the terms within the brackets;

$\Delta_+$ and $\Delta_-$ = Positive and negative effects on Playing Quality Index respectively;

$M_I(t)$ = Daily maintenance effect, reflecting combined effects from all daily maintenance practices (e.g. mowing, rolling, irrigating, fertilizing, pesticides and wetting agent application) with the exception of effects from cultivation/aeration treatments at time t. Under the maintenance practices used, the value of $M_I(t)$ is set to 0.50 (Table 7-1);

$\Upsilon$ = Scaling factor, reflecting how overall management practices (including cultivation/aeration treatments) and seasonal climate change affect surface playing quality of golf greens; here the value is set to 0.37 for sand-based rootzones and 0.40 for soil-based rootzones (Table 7-1);

$h_c$ = Scaling factor, reflecting how playing quality is influenced by a given type of cultivation/aeration treatment applied at known frequency. It is 1.5 times more sensitive than the effect of daily maintenance practice (Table 7-1);

$h_m$ = Scaling factor, reflecting how surface playing quality is influenced by the overall management practices (including cultivation/aeration treatments). It is 37.5 times more sensitive than effects of seasonal climate change (Table 7-1);

$C_n$ = Frequency of a cultivation/aeration treatment applied per year;

$C_f$ = Effect of a cultivation/aeration treatment (for sand-based rootzones, the value for Verti-drain is set to 0.98, HydroJect = 0.98, scarification = 0.82, the control = 0.89; for soil-based rootzones, the value for Verti-drain is set to 1.00, HydroJect = 0.98, scarification = 0.81, the control = 0.87) (Table 7-1);

$S_w$ = Reflects how seasonal climate change affects the overall playing quality; here if the value in the winter is set to 0.50, then the value in the summer is 0.51 (Table 7-1);

$\int d[G_I(t)]/dt$ = Natural diminishing integral equation computed by plot fitting (Table 7-1);

t = Runs of simulation;

$\Phi$ = Simulation time step in months; here the value is given as 6;

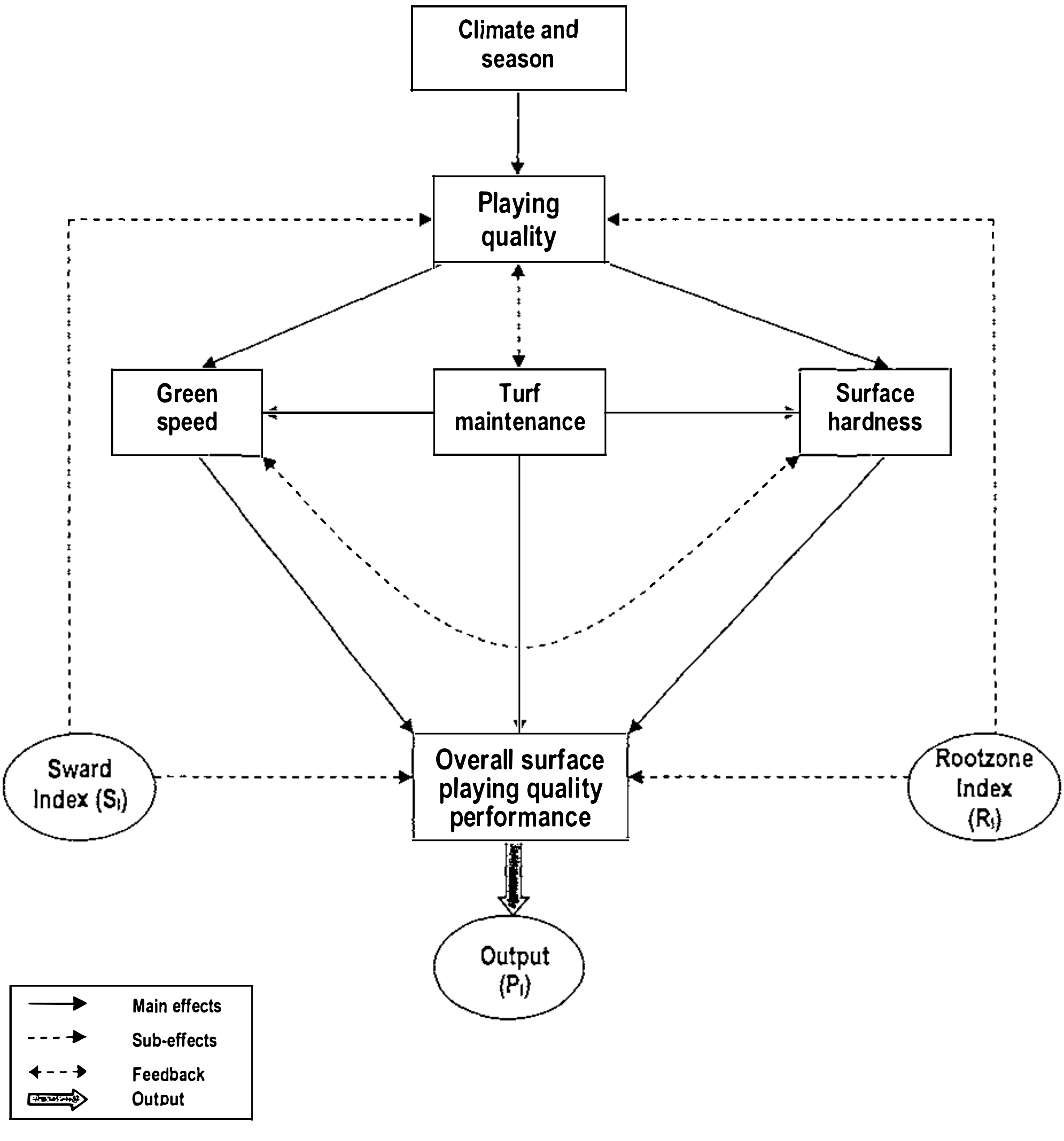


**Fig. 7-4 A conceptual Playing Quality sub-model for a golf green ecosystem**

Green speed: corrected ball roll distance (m) measured by the Stimpmeter; Surface hardness: golf green surface hardness (10 × impact unit) measured by the Clegg Impact Soil Tester by using 0.5 kg hammer at the first drop from a height of 300 mm.

$\beta$ = Months following turf establishment;

INT [$\beta$ / $\varphi$] = The largest integer less than or equal to $\beta$ / $\varphi$;

$X_h$ = Normalized surface hardness of golf greens, scaled from 0 to 1;

$X_s$ = Normalized green speed of golf greens, scaled from 0 to 1;

$W_h$ and $W_s$ = weighting factors for surface hardness and green speed respectively (Table 7-2), which are determined directly by solving the Eq. 7-16 (Wu *et al.* 1994). For details of development of the Eq.7-37 to 7-38, please refer to Table 7-1.

where

$$\begin{cases} X_h = 9.5681E\text{-}05G_h^2 - 1.4480E\text{-}03G_h + 1.0727E\text{-}05 & (G_h \leq 110) \\ X_h = \text{Min}\,[1, 0.00009G_h^2 - 0.03924G_h + 4.20795] & (G_h > 110) \end{cases} \quad \textbf{(7-37)}$$

$$\begin{cases} X_s = 0.0001 & (3.75 \leq G_s \leq 0.75) \\ X_s = \dfrac{G_s - 0.75}{1.5} & (0.75 \leq G_s \leq 2.25) \\ X_s = \dfrac{3.75 - G_s}{1.5} & (2.25 \leq G_s \leq 3.75) \end{cases} \quad \textbf{(7-38)}$$

where:

Max [···] = The maximum of the terms within the brackets;

$G_h$ : Surface hardness measured by the 0.5 kg CIT hammer at the first drop from a height of 300 mm; the acceptable surface hardness range for golf green is set at 80-140 (10 × impact unit) (Table 3-6);

$G_s$ : Corrected ball roll distance (m) measured by the Stimpmeter; the acceptable ball roll distance range is set at 1.50-3.00 m (Table 3-6);

### *7.3.4.1 Determination of factor weightings*

For the two-factor case, a reference factor (e.g. $X_{12}$) is arbitrarily chosen and its weighting ($W_{10}$) is set to 1. The weighting for factor two ($W_{11}$) with respect to that reference is a constant; hence, $W_{13}$ can be estimated by the above Eq. 7-16 (Wu *et a*l. 1994).

## Table 7-2 Factor weightings of the IRM model for golf green ecosystems

| Factors of golf green performance† | Symbol in the model | Factor weightings (%) | | |
|---|---|---|---|---|
| | | Calculated | Adjusted‡ | Comments on the adjustment |
| **Water infiltration rate**; the minimum acceptable infiltration rate for golf greens is set as ≥ 20 (mm $h^{-1}$). | $W_1$ | 9 | 35 | Based on previous studies (Schmidt 1980; Hind *et al.* 1995) |
| **Air-filled porosity** at -3kPa in the 35-70 mm depth; the acceptable air-filled porosity range at -3kPa in the 35-70 mm depth for golf greens is 10-30 (%,v/v). | $W_2$ | 22 | 15 | Based on results of present study and expert validation |
| **Organic matter content in the top 35 mm** of the rootzone; the acceptable organic matter content (%, w/w) at the top 35 mm depth for golf greens is set as ≤ 6 (%, w/w). | $W_3$ | 15 | 35 | Based on previous studies (Habeck & Christians 2000; Curtis & Pulis 2001; Carrow *et al.* 2002) |
| **Organic matter content at the 35-70 mm** rootzone depth; the acceptable organic matter content (%, w/w) at the 35-70 mm depth for golf greens is set as ≤ 3 (%, w/w). | $W_4$ | 22 | 5 | Based on results of present study and expert validation |
| **Water-filled porosity** at -3kPa in the 35-70 mm rootzone depth; the acceptable water-filled porosity range at -3kPa in the 35-70 mm depth for golf greens is set as 20-35 (%, v/v). | $W_5$ | 32 | 10 | Based on results of present study and expert validation |
| **Root distribution**; the minimum acceptable dry root-mass percentage at the 50-250 mm rootzone depth in total profile for golf greens is set as ≥ 3.50%. | $W_6$ | 16 | 40 | Based on previous studies (Parr *et al.* 1984; Carrow 1989; Hannaford & Baker 2000) |
| **Dry patch severity** (0-5); the acceptable dry patch score range for golf greens is set as 0-2. | $W_7$ | 27 | 25 | Based on results calculated (left column) and expert validation |
| **Turf quality (uniformity + density)** (0-9); the acceptable turf quality scores range for golf greens is set as 7-9. | $W_8$ | 36 | 15 | Based on results of present study and expert validation |
| **Species composition**; the minimum acceptable turfgrass cover for golf greens is 85%, while the acceptable relative balance index of the two sown turfgrass species for golf greens is set as 0.03-0.40. | $W_9$ | 21 | 20 | Based on results calculated and expert validation |
| **Green surface hardness** (10 × impact unit); the acceptable surface hardness range for golf greens is set as 80-140. | $W_{10}$ | 52 | 50 | Based on results calculated and expert validation |
| **Ball roll distance** (m); the acceptable range of ball roll distance for golf greens is set as 1.50-3.00. | $W_{11}$ | 48 | 50 | Based on results calculated and expert validation |

† Determination of acceptable range values and justifications for these modeling factors are given in Table 3-6.

‡ Adjusted according to results of present and previous studies, or expert validation (Gibbs, *pers. comm.*).

as $(X_{10})_{1/2} = (X_h)_{1/2} = 0.73$;

and $(X_{11})_{1/2} = (X_s)_{1/2} = 0.67$.

So, $W_{10} = 1.00$, $W_{11} = 0.92$. All factor weightings (%) from both calculations based on the above Eq. 7-14, 7-15, 7-16 and adjustments based on contributions of each factor to overall golf green performance were listed in Table 7-2. In this thesis, the adjusted factor weightings were used instead of the calculated values because of the partial inconsistency between the calculated values and the common opinions on the contributions of each factor to the overall golf green performance. Reasons for this inconsistency are not clear. Further study and validation may be required on this aspect.

## 7.4 RESULTS

### 7.4.1 Rootzone Index ($R_I$)

Rootzone Index ($R_I$), which was simulated based on measured data during the first six years after sowing and based on predicted data during the period between the 6$^{th}$ and the 30$^{th}$ year after sowing, increased during the first two years after sowing for the four sand-based rootzones. After that, there was an overall progressive decrease in the $R_I$ for the four sand-based rootzones during the remainder of the 30 years simulated. As a result, the $R_I$ values decreased below the '0.5' of the minimum threshold by the 28$^{th}$ year, and after the 30$^{th}$ year following sowing for the partially amended sand rootzone (T1) and other sand-based rootzones (i.e. the pure sand rootzone, the fully amended sand rootzone and partially amended sand + zeolite rootzone) respectively. In contrast, the $R_I$ of the soil rootzone remained well below the '0.5' of the minimum threshold and changed less throughout the 30 years simulated (Fig. 7-5).

The effects of rootzone type on $R_I$ were significant (Fig. 7-5). For example, the $R_I$ values of the soil rootzone were significantly lower than those of the four sand-based rootzones throughout the 30 years simulated, though the differences in the $R_I$ values between the soil rootzone and the four sand-based rootzones diminished over time. The pure sand rootzone also showed significantly lower $R_I$ values than the three amended sand rootzones during the first two years after sowing. However, no consistent and significant differences in the $R_I$ values were measured between the pure sand rootzone,

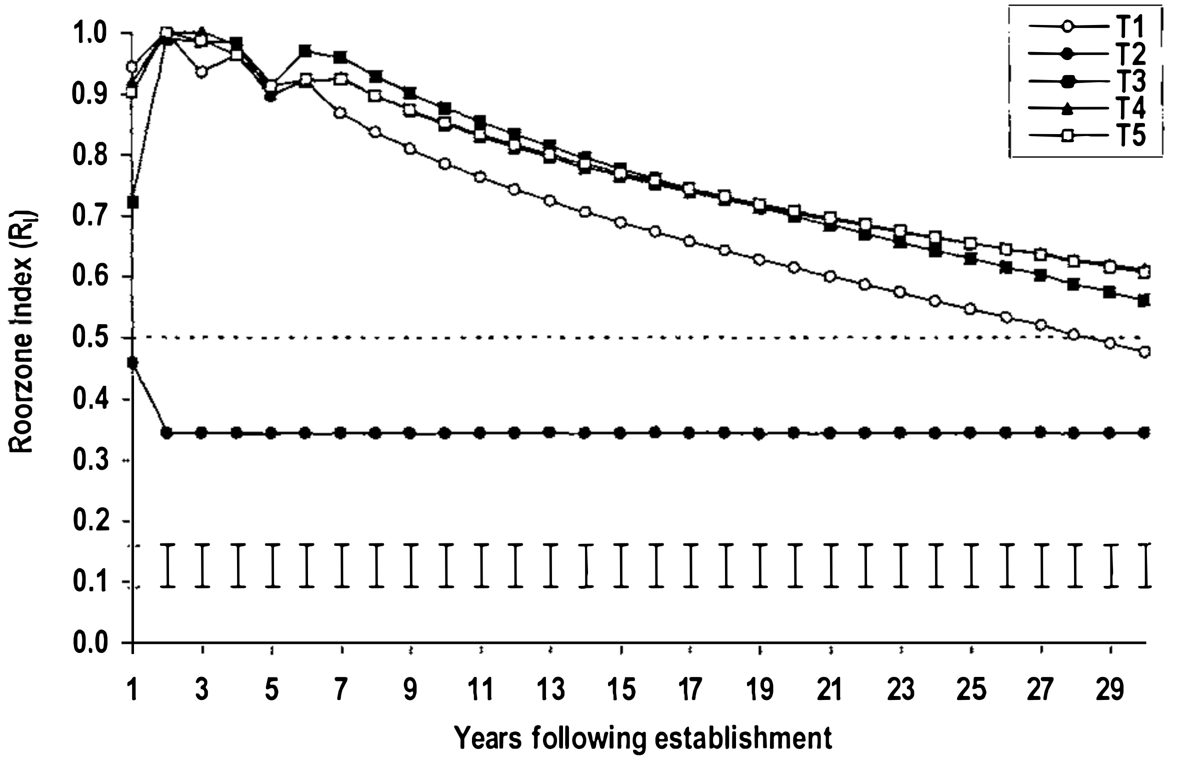


**Fig. 7-5 Changes in the Rootzone Index with time in relation to each rootzone type**

***The dotted line represents a Rootzone Index value of 0.5, the recommended minimum acceptable value for New Zealand golf green turf. The error bar represents the LSD value of the rootzones on each predicted occasion; T1---Partially amended sand rootzone; T2---Soil rootzone; T3---Pure sand rootzone; T4---Fully amended sand rootzone; T5---Partially amended sand + zeolite rootzone.***

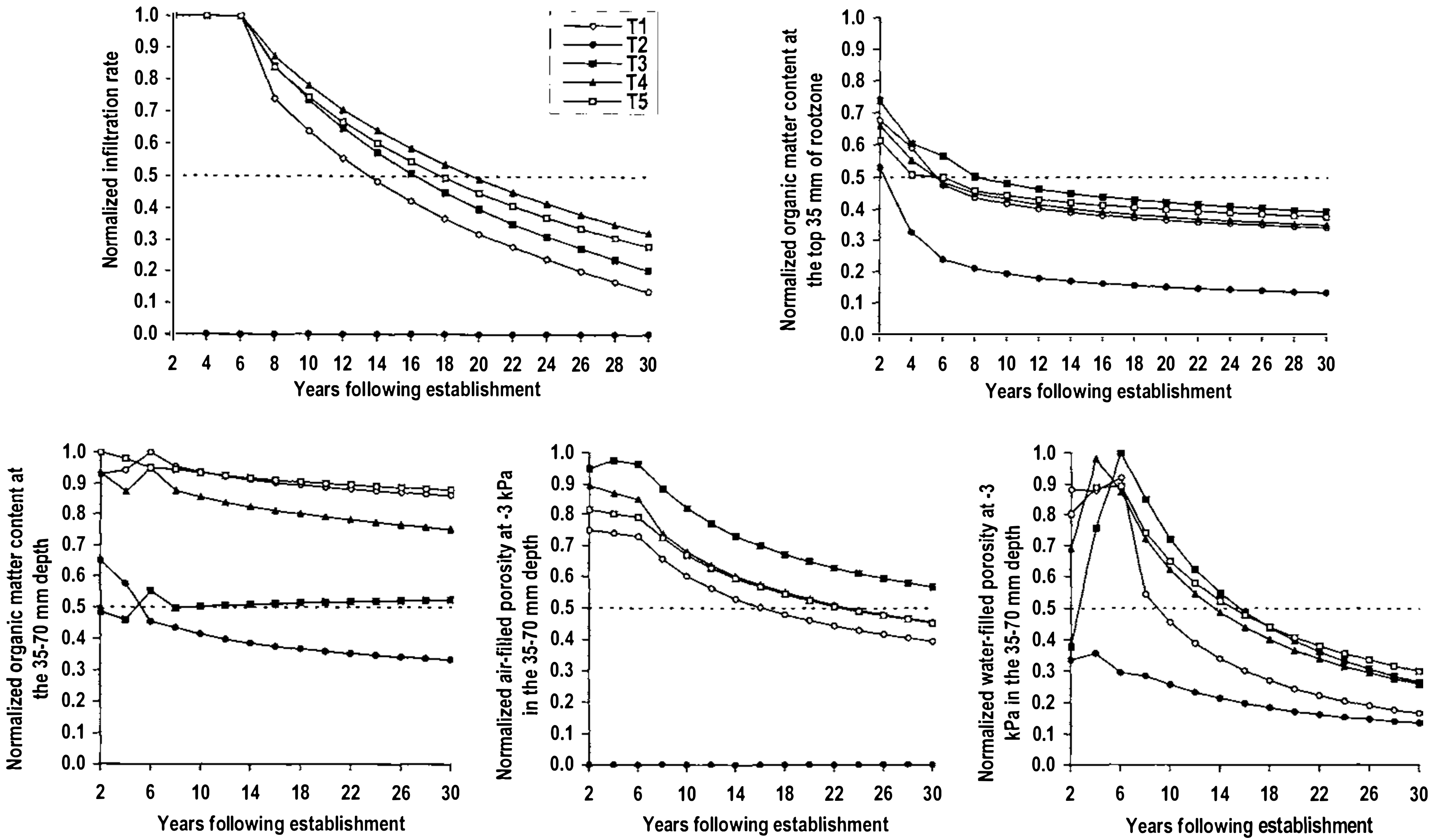


**Fig. 7-6 Changes in the normalized values of rootzone physical factors with time in relation to each rootzone type**

***The dotted line represents a normalized value of 0.5, the recommended minimum acceptable value for New Zealand golf green turf. T1---Partially amended sand rootzone; T2---Soil rootzone; T3---Pure sand rootzone; T4---Fully amended sand rootzone; T5---Partially amended sand + zeolite rootzone.***

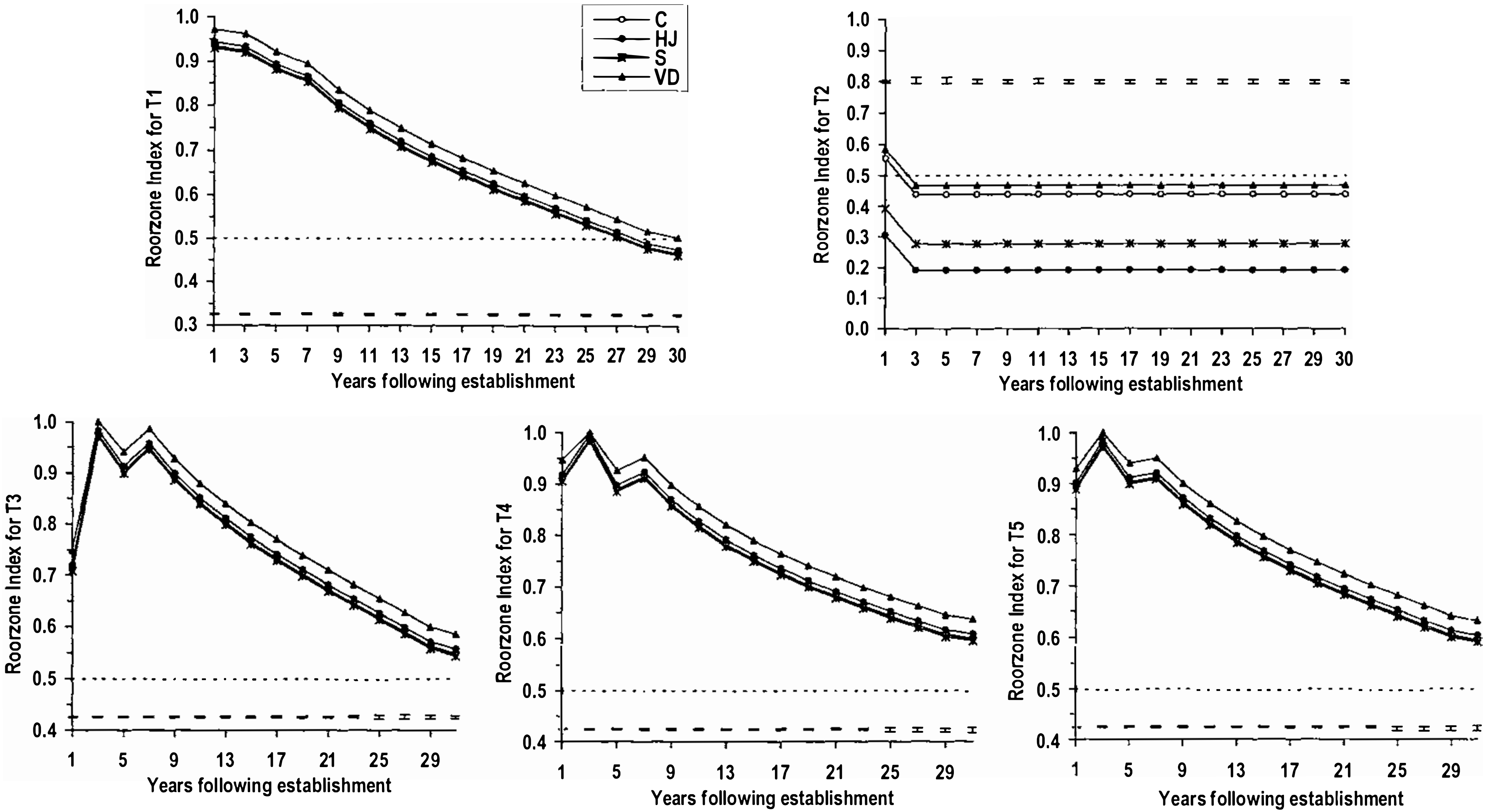


**Fig. 7-7 Changes in the Rootzone Index with time in relation to each rootzone type managed under different cultivation/aeration treatment**

*The dotted line represents a Rootzone index value of 0.5, the recommended minimum acceptable value for New Zealand golf green turf. The error bar represents the LSD value of the rootzone treatments on each predicted occasion. T1---Partially amended sand rootzone; T2---Soil rootzone; T3---Pure sand rootzone; T4---Fully amended sand rootzone; T5---Partially amended sand + zeolite rootzone. C---Control; HJ---HydroJect; S---Scarification; VD---Verti-drain.*

fully amended sand rootzone and partially amended sand + zeolite rootzone on all simulation occasions after the second year following sowing. Nevertheless, an evident and consistent pattern occurred between the partially amended sand rootzone (T1) and the other sand rootzones after the sixth year, with the T1 possessing significantly lower $R_I$ values than the other three sand rootzones on most of the simulation occasions.

The trends over time in normalized water infiltration rate and water-filled porosity at -3 kPa in the 35-70 mm depth followed a similar time-trend as that of $R_I$ for all rootzones. Most importantly, the normalized organic matter content in the surface 35 mm remained below the '0.5' minimum acceptable value after the third year, sixth year and eighth year for the soil rootzone, three amended sand rootzones and pure sand rootzone respectively (Fig. 7-6).

The influence of cultivation/aeration treatment on $R_I$ was significant for all rootzones, especially for the soil rootzone (Fig. 7-7). For example, Verti-drain treatment resulted in statistically the highest $R_I$ values for each rootzone throughout the 30 years simulated. In contrast, scarification treatment resulted in statistically the lowest $R_I$ values on all simulation occasions for the four sand-based rootzones. On the soil rootzone, HydroJect treatment resulted in statistically the lowest $R_I$ values on all simulation occasions.

## 7.4.2 Sward Index ($S_I$)

There was an overall progressive decrease in the Sward Index ($S_I$), which was simulated based on measured data during the first six years after sowing and based on predicted data during the period between the $6^{th}$ and the $30^{th}$ year after sowing, for the four sand-based rootzones throughout the 30 years simulated (Fig 7-8). This general trend was particularly pronounced for the three amended sand rootzones. For example, by the ninth year after sowing, the $S_I$ values of the three amended sand rootzones decreased below the '0.5' minimum threshold and tended to merge with values of the soil rootzone. However, for the pure sand rootzone, the decrease with time in the $S_I$ appeared significantly slower, and the $S_I$ values always remained above the '0.5' minimum value up to the $30^{th}$ year after sowing. In contrast, for the soil rootzone, $S_I$ values greatly increased during the first three years after sowing. After that, the $S_I$ of the soil rootzone gradually decreased throughout the remaining 30 years simulated, and

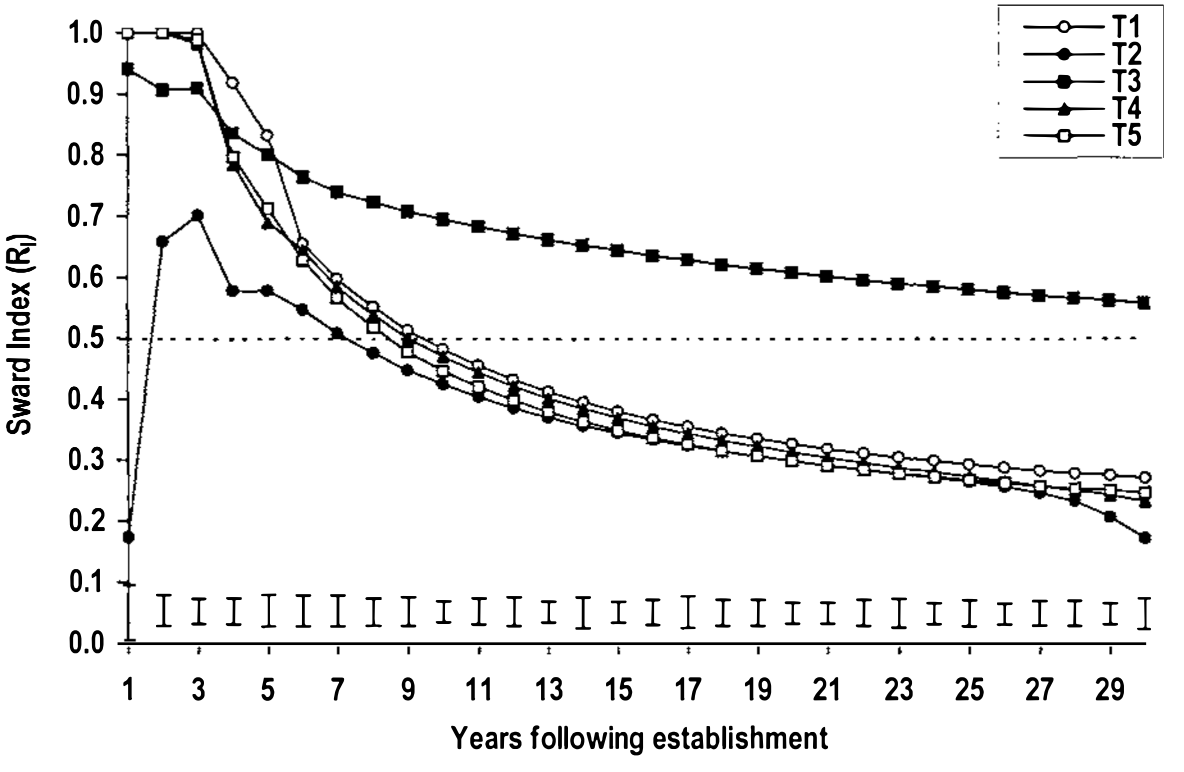


**Fig. 7-8 Changes in the Sward Index with time in relation to each rootzone type**

***The dotted line represents a Sward Index value of 0.5, the recommended minimum acceptable value for New Zealand golf green turf. The error bar represents the LSD value of the rootzone types on each predicted occasion. T1---Partially amended sand rootzone; T2---Soil rootzone; T3---Pure sand rootzone; T4---Fully amended sand rootzone; T5---Partially amended sand + zeolite rootzone.***

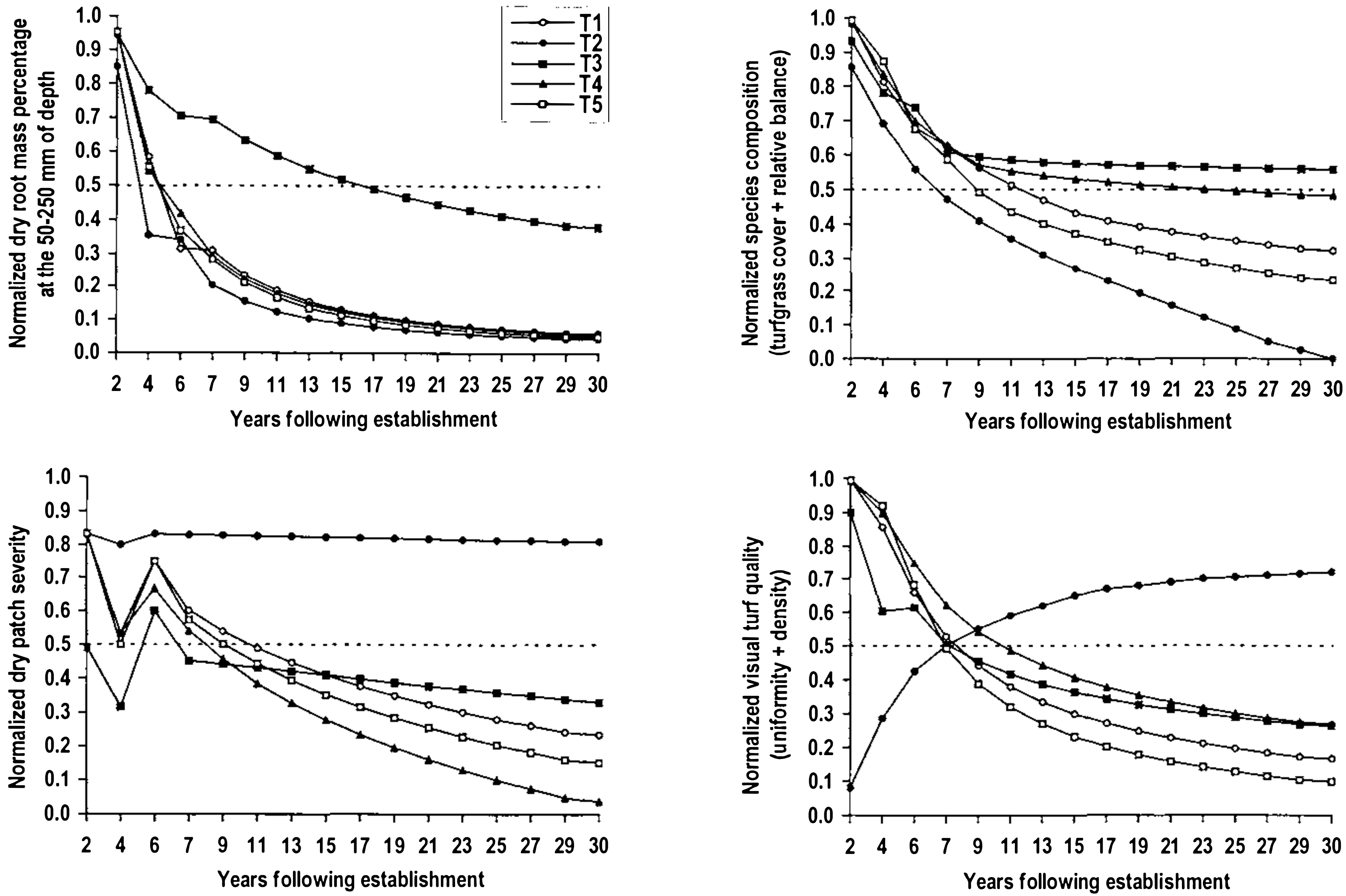


**Fig. 7-9 Changes in the normalized values of each sward factor with time in relation to each rootzone type**

***The dotted line represents a normalized value of 0.5, the recommended minimum acceptable value for New Zealand golf green turf. T1---Partially amended sand rootzone; T2---Soil rootzone; T3---Pure sand rootzone; T4---Fully amended sand rootzone; T5---Partially amended sand + zeolite rootzone.***

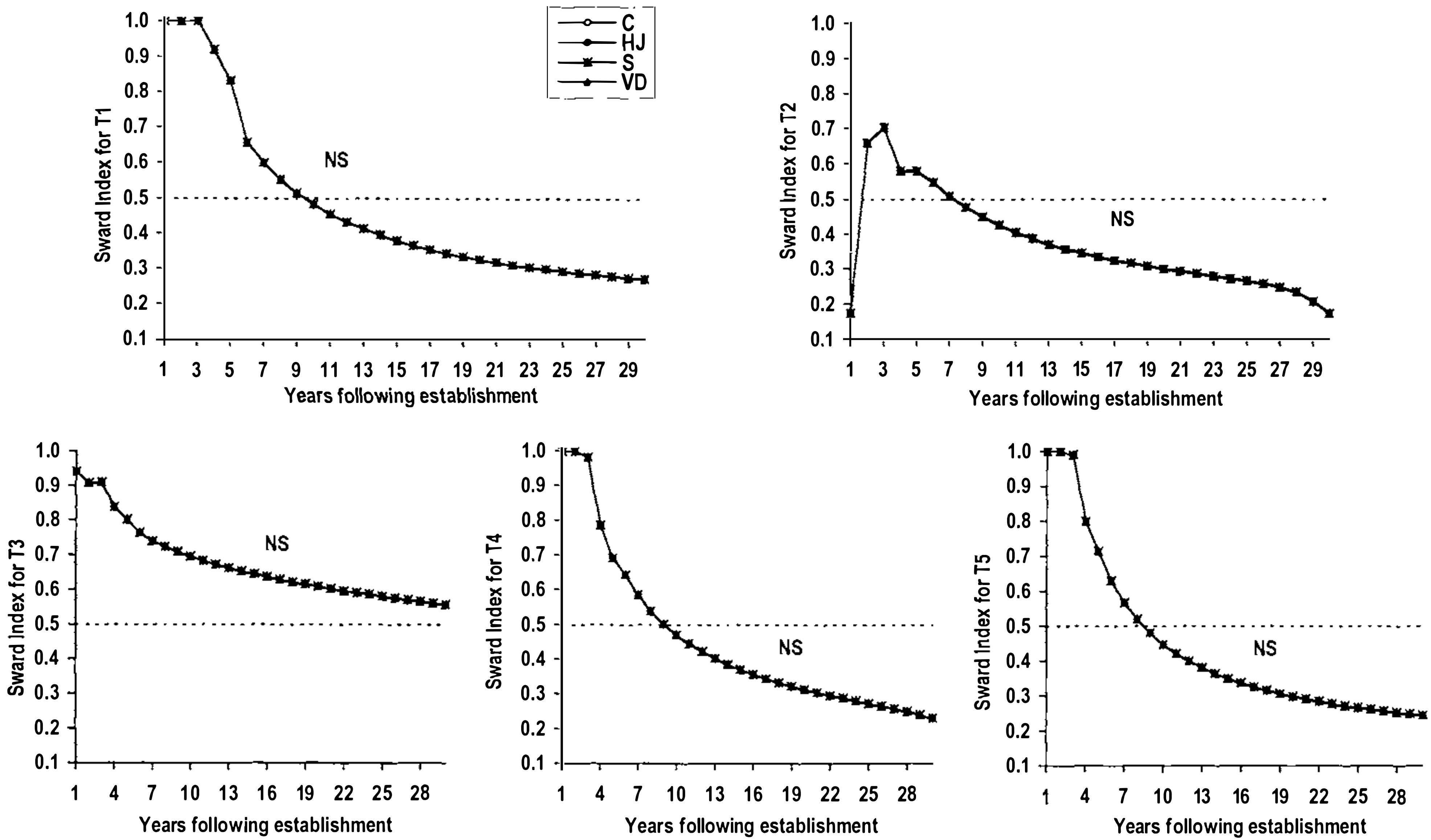


**Fig. 7-10 Changes in the Sward Index with time in relation to each rootzone type managed under different cultivation/aeration treatment**

*The dotted line represents a Sward Index value of 0.5, the recommended minimum acceptable value for New Zealand golf green turf. NS--Not significant between the four cultivation/aeration treatments on most of the predicted occasions. T1---Partially amended sand rootzone; T2---Soil rootzone; T3---Pure sand rootzone; T4---Fully amended sand rootzone; T5---Partially amended sand + zeolite rootzone. C---Control; HJ---HydroJect; S---Scarification; VD---Verti-drain.*

decreased below the'0.5' minimum acceptable value by the seventh year after sowing (Fig. 7-8).

The effects of rootzone type on $S_I$ were significant on each simulation occasion (Fig. 7-8). For example, though the $S_I$ values of the pure sand rootzone were significantly lower than that of the three amended sand rootzones during the first five years after sowing, $S_I$ values were significantly higher than those of all other rootzones throughout the remainder of the 30 years simulated. Differences in the $S_I$ values between the pure sand rootzone and other rootzones also became larger over time. For the three amended sand rootzones, though they had statistically the highest $S_I$ values during the first five years, their $S_I$ values decreased very quickly over time and remained significantly lower than the pure sand rootzone on all simulation occasions after the sixth year. However, there were no consistent and significant differences in the $S_I$ values between either the three amended sand rootzones throughout the 30 years simulated, or the three amended sand rootzones and the soil rootzone after the $10^{th}$ year following sowing.

The trend over time in normalized root mass percentage in the 50-250 mm depth was similar to that of the $S_I$. For example, the normalized root percentage values decreased below the '0.5' minimum value by the fourth year, sixth year and $16^{th}$ year after sowing for the soil rootzone, three amended sand rootzones and pure sand rootzone, respectively (Fig. 7-9). However, the trend over time in normalized dry patch severity and visual turf quality of the soil rootzone was opposite to that of the four sand-based rootzones on all simulation occasions.

None of the cultivation/aeration treatments showed any consistent and significant influences on $S_I$ under the frequency of the treatment used (Fig. 7-10).

### 7.4.3 Playing Quality Index ($P_I$)

There was an overall gradual decrease in the Playing Quality Index ($P_I$), which was simulated based on measured data during the first six years after sowing and based on predicted data during the period between the $6^{th}$ and the $30^{th}$ year after sowing, for all rootzones throughout the 30 years simulated, especially for the fully amended sand rootzone (Fig. 7-11). For example, the $P_I$ values of the fully amended sand rootzone

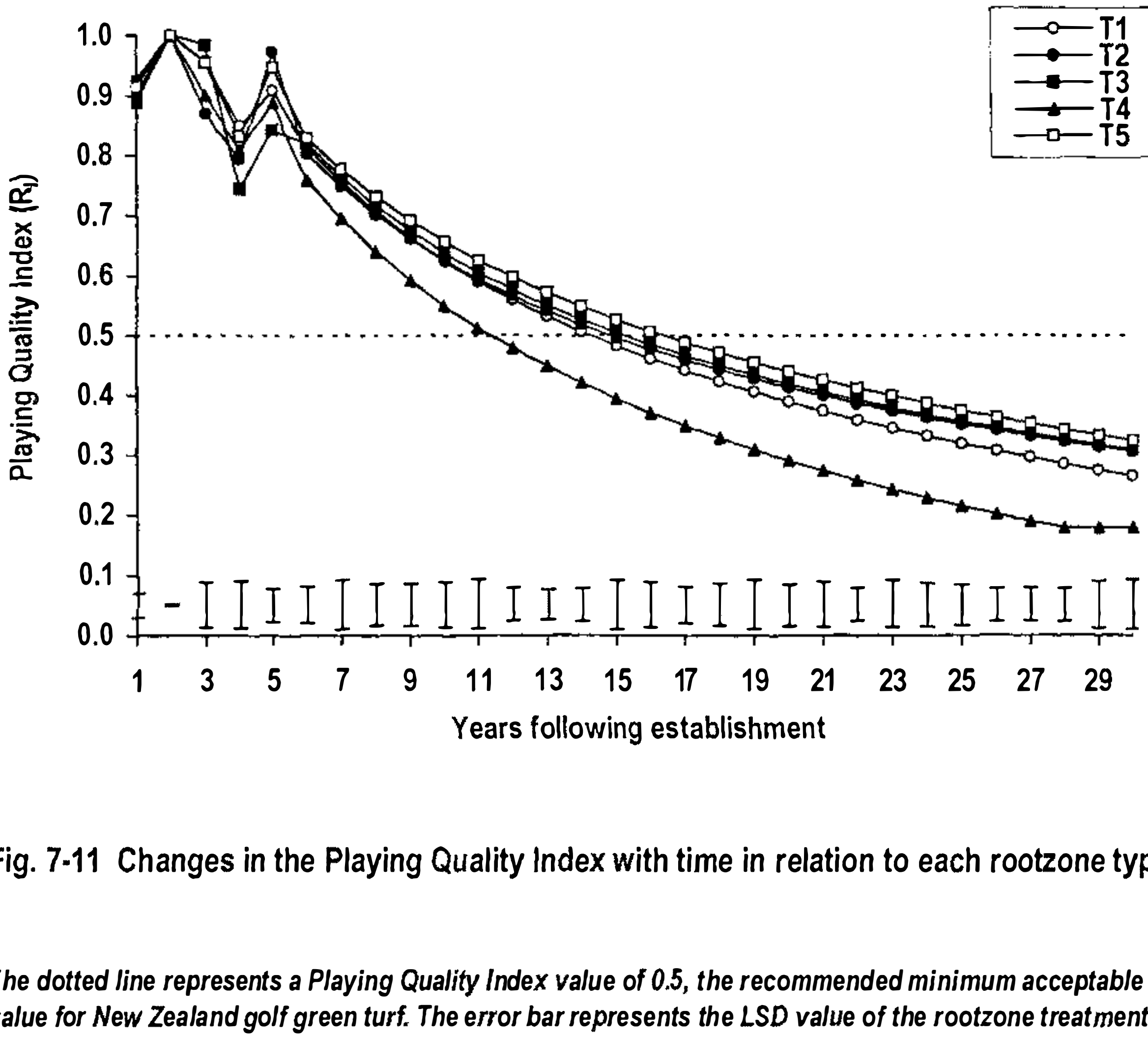


Fig. 7-11 Changes in the Playing Quality Index with time in relation to each rootzone type

*The dotted line represents a Playing Quality Index value of 0.5, the recommended minimum acceptable value for New Zealand golf green turf. The error bar represents the LSD value of the rootzone treatments on each predicted occasion. T1---Partially amended sand rootzone; T2---Soil rootzone; T3---Pure sand rootzone; T4---Fully amended sand rootzone; T5---Partially amended sand + zeolite rootzone.*

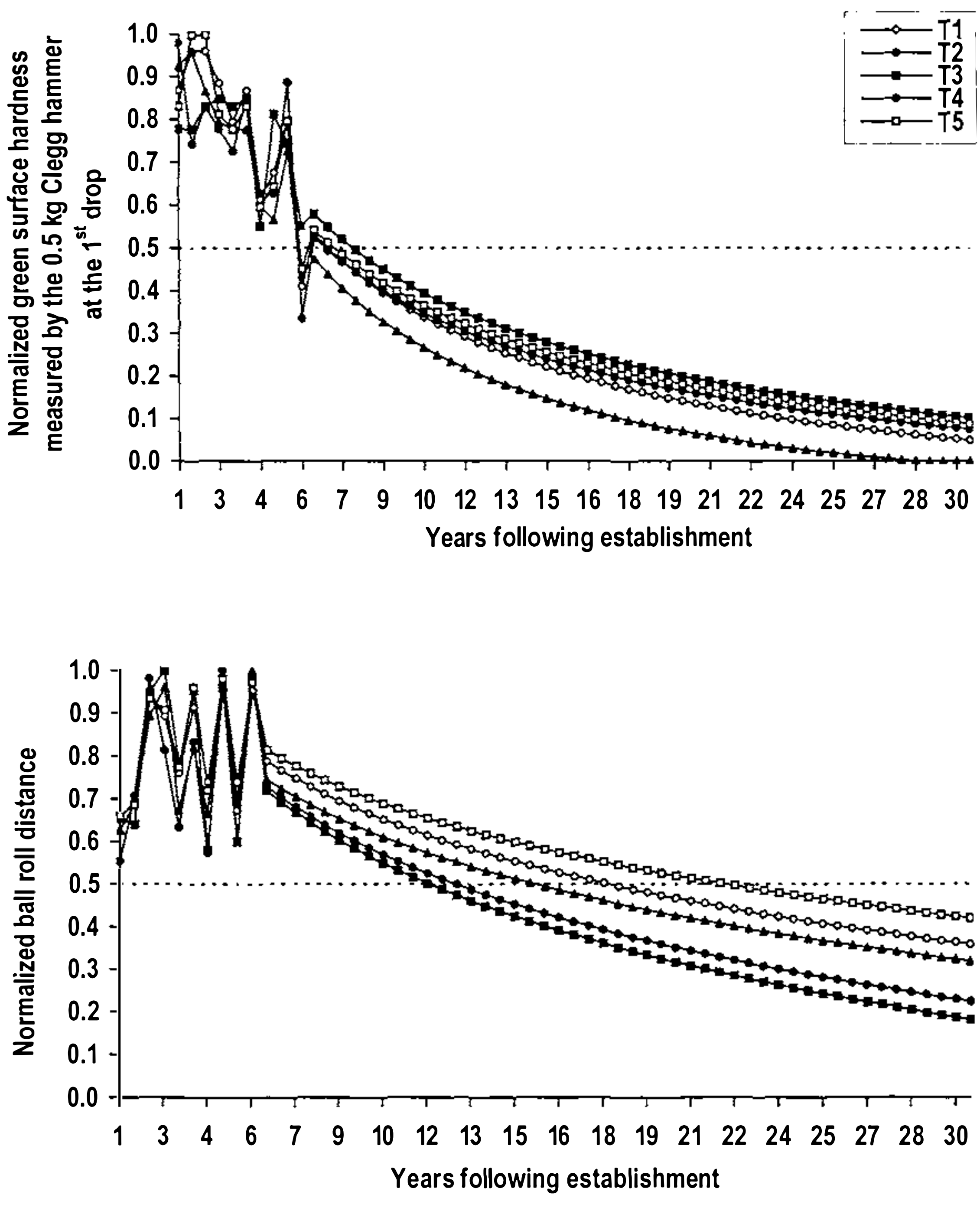


**Fig. 7-12 Changes in the normalized values of each Playing Quality factor with time in relation to each rootzone type**

***The dotted line represents a normalized value of 0.5, the recommended minimum acceptable ball roll distance or the green surface hardness value for New Zealand golf green turf. T1---Partially amended sand rootzone; T2---Soil rootzone; T3---Pure sand rootzone; T4---Fully amended sand rootzone; T5---Partially amended sand + zeolite rootzone.***

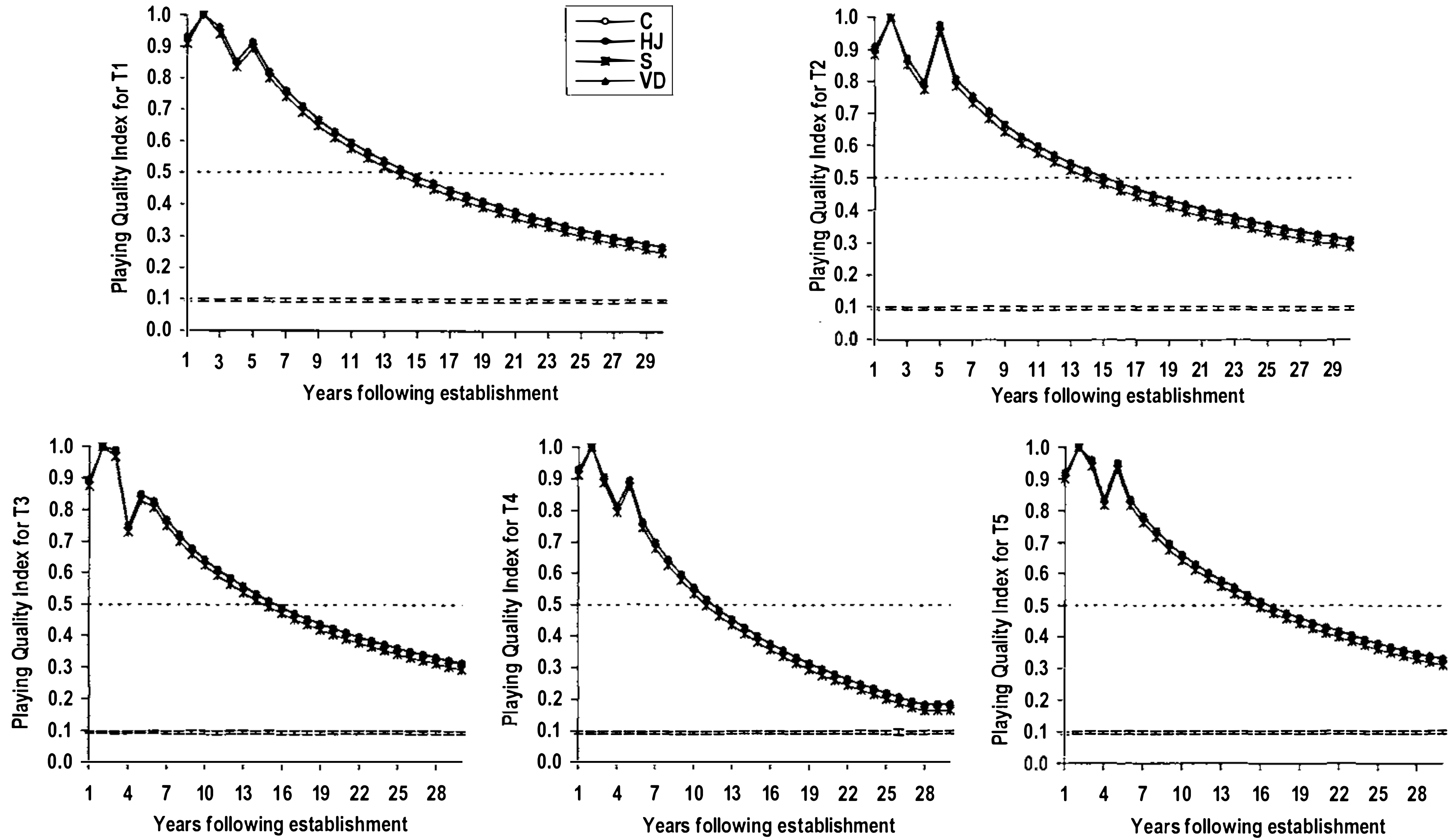


**Fig. 7-13 Changes in the Playing Quality Index with time in relation to each rootzone type managed under different cultivation/aeration treatment**

*The dotted line represents a Playing Quality Index value of 0.5, the recommended minimum acceptable value for New Zealand golf green turf. The error bar represents the LSD value of the rootzone types on each predicted occasion. T1---Partially amended sand rootzone; T2---Soil rootzone; T3---Pure sand rootzone; T4---Fully amended sand rootzone; T5---Partially amended sand + zeolite rootzone. C---Control; HJ---HydroJec; S---Scarification; VD---Verti-drain.*

(T4) decreased below the '0.5' minimum value by the 11$^{th}$ year after sowing, while the $P_I$ values of all other rootzones still remained above the '0.5' minimum value between 14 and 16 years after sowing.

There were significant effects of rootzone type on $P_I$ (Fig. 7-11). For example, although no consistent and significant influences of rootzone type on $P_I$ could be found during the first five years after sowing, the $P_I$ values of the fully amended sand rootzone remained significantly lower than that of the other rootzones after the seventh year. Differences in the $P_I$ values between the fully amended sand rootzone and other rootzones also became larger over time. However, there were no consistent and significant differences in the $P_I$ values between other rootzones (i.e. T1, T2, T3 and T5) throughout the 30 years simulated.

The pattern in normalized values of green surface hardness was similar to that of $P_I$ irrespective of its large fluctuation with seasons during the first five years after sowing. For example, the normalized hardness values of the fully amended sand rootzone were the lowest of all rootzones on most simulation occasions throughout the 30 years. By the eighth year after sowing, normalized hardness values of all rootzones decreased below the '0.5' minimum value (Fig. 7-12).

Cultivation/aeration treatments showed small, but significant influences on $P_I$ (Fig. 7-13). For example, the control, Verti-drain and HydroJect treatments resulted in significantly higher $P_I$ values than scarification treatment on all simulation occasions. However, there were no significant differences in the $P_I$ values between Verti-drain and HydroJect treatments throughout the 30 years simulated for each rootzone type.

### 7.4.4 The Comprehensive Golf Green Performance Index ($CGGP_I$)

The Comprehensive Golf Green Performance Index ($CGGP_I$), which was simulated based on measured data during the first six years after sowing and based on predicted data during the period between the 6$^{th}$ and the 30$^{th}$ year after sowing, increased during the first two years for all rootzones. After that time, there was an overall progressive decrease in the $CGGP_I$ values for all rootzones throughout the remainder of the 30 years simulated. This general trend was particularly pronounced for the three amended

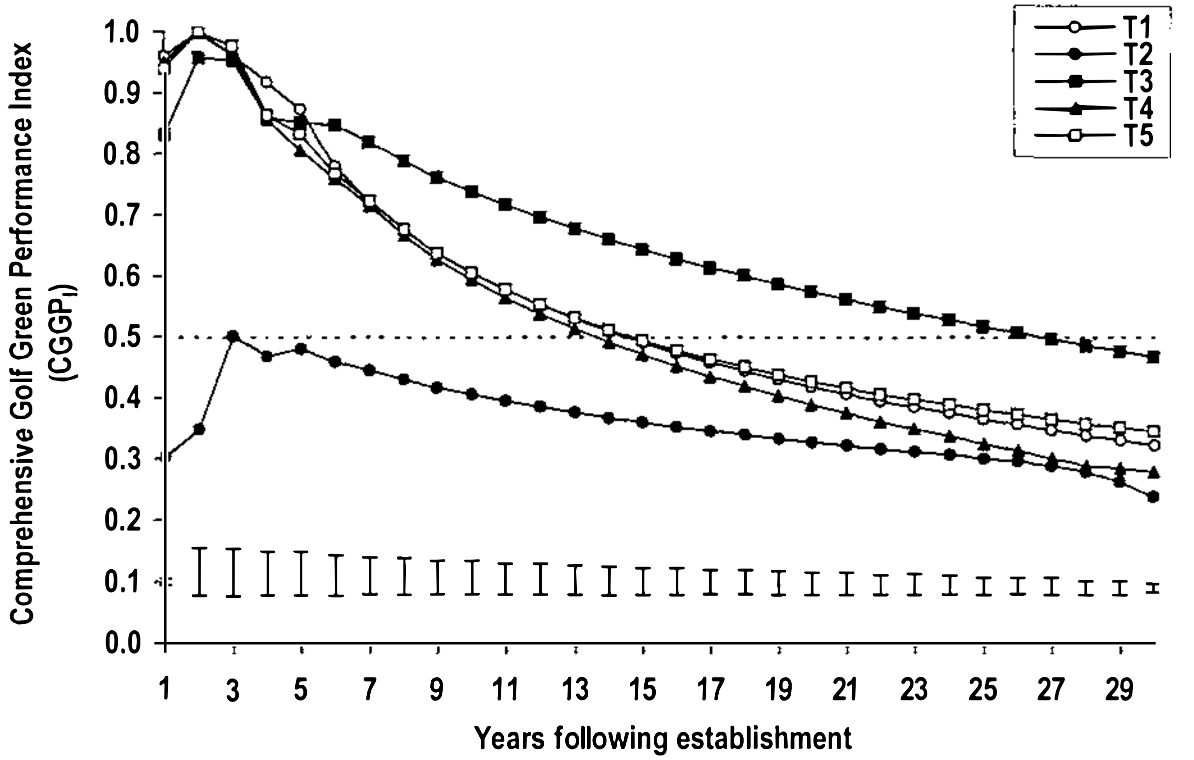


**Fig. 7-14 Changes in the Comprehensive Golf Green Performance Index with time in relation to each rootzone type**

***The dotted line represents a Comprehensive Golf Green Performance Index value of 0.5, the recommended minimum acceptable value for New Zealand golf green turf. Error bar represents the LSD value of the rootzones on each predicted occasion. T1---Partially amended sand rootzone; T2---Soil rootzone; T3---Pure sand rootzone; T4---Fully amended sand rootzone; T5---Partially amended sand + zeolite rootzone.***

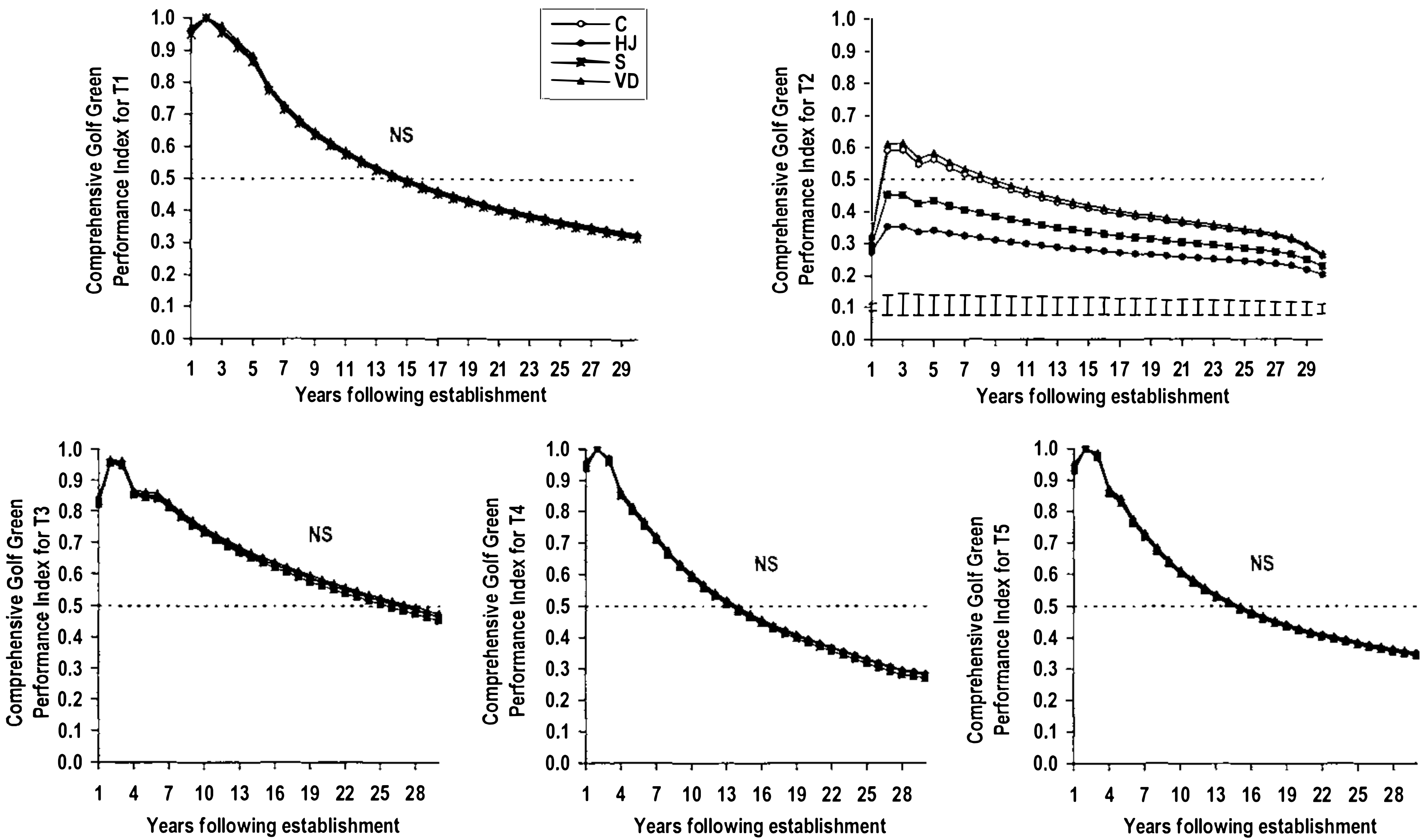


**Fig. 7-15 Changes in the Comprehensive Golf Green Performance Index with time in relation to each rootzone type managed under different cultivation/aeration treatment**

***The dotted line represents a Comprehensive Golf Green Performance Index value of 0.5, the recommended minimum acceptable value for New Zealand golf green turf. Error bar represents the LSD value of the rootzones on each predicted occasion. NS--Not significant between rootzone types on majority of the predicted occasions. T1---Partially amended sand rootzone; T2---Soil rootzone; T3---Pure sand rootzone; T4---Fully amended sand rootzone; T5---Partially amended sand + zeolite rootzone. C---Control; HJ---HydroJect; S---Scarification; VD---Verti-drain.***

sand rootzones (Fig. 7-14). For example, the $CGGP_I$ values decreased below the '0.5' minimum value by the14th year and 27th year after sowing for the three amended sand rootzones and pure sand rootzone, respectively. However, for the soil rootzone, $CGGP_I$ values changed less and remained below the '0.5' minimum value throughout the 30 years simulated.

The effects of rootzone type on $CGGP_I$ were significant (Fig. 7-14). For example, the $CGGP_I$ values of the soil rootzone remained the lowest of the five rootzones throughout the 30 years simulated. This result was significant on most of the simulation occasions. In contrast, the $CGGP_I$ values of the pure sand rootzone were statistically the highest during the period from the sixth year to the 30th year after sowing, although its $CGGP_I$ values were significantly lower than the three amended sand rootzones during the first three years after sowing. However, the $CGGP_I$ values of the three amended sand rootzones decreased quickly so that they tended to merge with that of the soil rootzone by the 25th year after sowing. No significant differences in the $CGGP_I$ values could be found between the three amended sand rootzones on all simulation occasions throughout the first 20 years, although the CGGPI values of the fully amended sand rootzones appeared to become significantly lower than the two partially amended sand rootzones after that time.

The influence of cultivation/aeration treatment on $CGGP_I$ was not significant on all sand-based rootzones throughout the 30 years under the frequency of treatment used. A consistent and significant influence of cultivation/aeration treatments on the $CGGP_I$ was found only for the soil rootzone. This result was reflected by the control and Verti-drain treatments having statistically the highest, scarification treatment the intermediate and HydroJect treatment the lowest $CGGP_I$ values throughout the 30 years simulated. However, these effects diminished with time (Fig. 7-15).

## 7.5 DISCUSSION

### 7.5.1 Rootzone Index ($R_I$)

The initial increase in the simulated $R_I$ for the four sand-based rootzones over the first two years after sowing reflected the physical maturing process of sand-based rootzones following establishment as reported by Curtis and Pulis (2001). However, the progressive decrease in the simulated $R_I$ of the four sand-based rootzones throughout the remainder of the 30 years illustrated well the typical deterioration in overall rootzone physical performance of sand-based rootzones under sports turf conditions that has been reported in many previous studies (Baker & Richards 1993; Lodge & Baker 1993; Baker *et al.* 1999a). Despite the decrease, $R_I$ was not considered limiting to the greens' performance by the $28^{th}$ year and $30^{th}$ year after sowing for the partially amended sand rootzone (T1) and three other sand-based rootzones (i.e. pure sand rootzone, the fully amended sand rootzone and partially amended sand + zeolite rootzone), respectively under current maintenance conditions. In contrast, the $R_I$ of the soil rootzone remained well below the minimum acceptable value on all simulation occasions throughout the 30 years, suggesting that the soil rootzone might not be suitable for construction of intensively used golf greens under conventional management conditions.

The pure sand rootzone showed no long-term and significant differences in the $R_I$ compared with the other sand-based rootzones throughout the 30 years simulated. However, it is difficult to give a satisfactory explanation on why overall physical performance of the partially amended sand rootzone (T1) was significantly poorer than three other sand-based rootzones after the sixth year following sowing. More study may be required on this aspect.

Results of the rootzone sub-modeling showed that organic matter content in the upper portion of the profile was probably the principal factor limiting the $R_I$ of sand-based rootzones (Fig. 7-6). This result was consistent with other previous studies (Carrow 2004a, b, c; O'Brien & Hartwiger 2003). Model simulations demonstrated that accumulation of organic matter in the upper portion of the sand-based rootzones over the first few years after sowing resulted in a quick improvement in water holding capacity of the sand-based rootzones that were originally very poor. This improvement further increased the $R_I$ of the sand-based rootzones (Fig. 7-6). However, subsequent excess accumulation (e.g. beyond 6% at the 0-35 mm depth) of organic matter in the upper portion of the profiles resulted in a progressive decrease in the $R_I$ values of the four sand-based rootzones (Fig. 7-6). This result was similar to that of previous studies (Habeck & Christians 2000; Snow 1992; Curtis & Pulis 2001; O'Brien & Hartwiger 2003). Based on the literature review (refer to section 2.2.2.4 of Chapter two in this thesis) and model simulation, organic matter content should be maintained below 6% in the surface 35 mm or below 3% at the 35-70 mm depth, respectively, for sand-based rootzones under golf green conditions. However, for the soil rootzone, its poor soil physical properties (e.g. poor infiltration rate and air-filled porosity) was mainly a result of the rapid buildup of soil compaction after sowing as reported by other studies (Schmidt 1980; Thien 1994), rather than excess accumulation of organic matter near the surface (Fig. 7-6).

The above results imply that regular monitoring of organic matter content in the upper portion of the profile is crucial for managing physical deterioration of sand-based rootzones in order to prevent excess accumulation of organic. Regular mini-coring, Verti-draining with hollow tines or HydroJecting + dethatching operations would be suitable choices of organic matter removal. However, maintenance of soil-based rootzones should be based on both surface removal of organic matter and deep relieving of soil compaction to improve rootzone drainage capacity. For example, regular mini-coring and deep Verti-drain treatment may be suitable choices for soil-based rootzones used for golf greens.

Although the effects of HydroJect and scarification treatment on $R_I$ were relatively limited under the treatment conditions used (twice per year), the increase in $R_I$ following twice-yearly Verti-drain treatment was significant on all simulation occasions for all rootzones, especially for the soil rootzone. The larger increase in $R_I$ following Verti-drain treatment was consistent with findings of other studies (Carrow 1992; Shim & Carrow 1997). However, none of the cultivation/aeration treatment was able to halt the overall decrease in $R_I$ throughout the 30 year period predicted at the frequency of treatment used.

### 7.5.2 Sward Index ($S_I$)

The progressive decrease in the simulated $S_I$ for all rootzones during the first 30 years after sowing (after the third year for the soil rootzone) reflected not only the typical deterioration in root growth over time as reported by several previous studies (Carrow 1995; Hannaford & Baker 2000), but also the typical succession in species composition of a *Agrostis/Fescue* golf green sward with age and usage reported by Lodge and Lawson (1993) and Baker *et al.* (1997, 1999b). This decrease also mirrored the deterioration with time in rootzone physical performance taking place within the underlying rootzone media.

Although it was difficult to establish turf on pure sand rootzone (Gibbs *et al.* 2000) and although the $S_I$ values of the pure sand rootzone were significantly lower than the three amended sand rootzones during the first five years after sowing, the pure sand rootzone showed large benefits in overall sward performance over the conventional soil rootzone and the three amended sand rootzones after the fifth year following sowing. For example, overall sward performance of the three amended sand rootzones deteriorated more quickly over time than that of the pure sand rootzone. By the ninth year after sowing, their $S_I$ values decreased below the minimum acceptable threshold, while that of the pure sand rootzone was still acceptable by the 30$^{th}$ year after sowing. However, the two modified USGA rootzones (T1 and T5) did not show any disadvantages in terms of overall sward performance compared with a standard USGA rootzone throughout the 30 years simulated.

Results of the sward sub-model showed that dry patch disorder and visual turf quality were factors limiting overall sward performance of the pure sand rootzone during the first five years after sowing. However, factor limiting overall sward performance of all amended sand rootzones was dry root mass percentage at the 50-250 mm depth. This result was consistent with several previous studies (Hannaford & Baker 2000) (Fig. 7-9).

The response of each sward factor (e.g. species composition, root growth, dry patch severity and visual turf quality) to cultivation/aeration treatment was not as sensitive as each soil physical factor. This is probably due to that the response of the root mass and distribution, which was identified as the key modeling factor in this study, to cultivation/aeration treatment was not sensitive during five years of the trial period.

### 7.5.3 Playing Quality Index ($P_I$)

The progressive decrease in the simulated $P_I$ of all rootzones during the 30 years was a result of gradual and excess increases in green speed and surface hardness, which were likely associated with the regular use of the heavy roller wear treatment. For example, the $P_I$ values decreased below the minimum acceptable value by the 11$^{th}$ year and between the 14th and 16th year after sowing for the standard USGA profile and other four rootzones under the maintenance conditions used.

It appears that $P_I$ was relatively insensitive to rootzone composition. This result agrees with findings obtained in previous studies (Baker & Richards 1991; Baker *et al.* 1999c). For example, there were no measurable differences in overall playing quality performance between the pure sand rootzone, the two partially amended sand rootzones, and the conventional soil rootzone on all simulation occasions throughout the 30 years. However, the standard USGA profile (T4) showed significantly poorer playing quality when compared with all other rootzones on most simulation occasions after the seventh year following sowing. Model simulation showed that this result was caused mainly by an excessively hard playing surface produced by the standard USGA profile after fifth year following sowing (Fig. 7-12). It is difficult to suggest a reason for this result.

Cultivation/aeration treatments (i.e. HydroJect, scarification and Verti-drain) had only slight, but significant influences on the $P_I$. As with the rootzone physical performance, none of the cultivation/aeration treatment was able to halt the overall decrease in $P_I$ throughout the 30 year period predicted at the frequency of treatment used.

### 7.5.4 Comprehensive Golf Green Performance Index ($CGGP_I$)

The large increase in the simulated $CGGP_I$ during the first two years after sowing was consistent with the general trend in the Rootzone Index ($R_I$) for all rootzones, which basically reflected the physical 'maturing' process of rootzones after sowing under sports turf conditions as reported by Curtis and Pulis (2001). The results showed that the initial increase in $CGGP_I$ was due mainly to a progressive improvement in water-holding capacity for sand-based rootzones, or due to a gradual increase in turf density and cover for soil rootzone during the first two years after sowing. However, the progressive decrease in $CGGP_I$ for all rootzones during the remainder of the 30 years simulated was a combined result of the general deterioration in rootzone physical properties, sward characteristics and playing quality as reported in a series of the previous studies (Schmidt 1980; Gibbs & Baker 1989; Lodge & Baker 1993; Carrow 1995; Hannaford & Baker 2000).

The considerable and consistent differences in the $CGGP_I$ values between the sand-based rootzones and soil rootzone throughout the 30 years simulated highlighted the benefits of upgrading from a soil-based to a sand-based medium. For example, the $CGGP_I$ values of the conventional soil rootzone remained well below the minimum acceptable value throughout the 30 years simulated, indicating that the conventional soil rootzone might be unsuitable for construction of intensively used golf greens in most cases, even though the soil-based golf greens had good visual turf quality and low incidence of dry patch disorder and disease damage.

The pure sand rootzone performed significantly worse than the three amended sand rootzones during the first two years after sowing. This shortcoming of the pure sand rootzone was reflected mainly by severe dry patch disorder, large fluctuation in visual turf quality (refer to chapter five), poor water-holding capacity (refer to chapter four) and difficulties in achieving a uniform establishment (Gibbs *et al.* 2000). This result was consistent with previous studies (Tucker *et al.* 1990; York & Baldwin 1992; Snow 1992; Baker *et al.* 1999a). Nevertheless, the $CGGP_I$ of the pure sand rootzone was still considered not limiting to greens' performance during the first few years after sowing under standard New Zealand putting green maintenance conditions. Most importantly, during the remainder of the 30 years simulated, the $CGGP_I$ of the pure sand rootzone remained significantly higher than that of the three amended sand rootzones. Therefore, in the long run, the pure sand rootzone system could be used for golf green construction instead of a standard, fully amended USGA profile if the practice of the partially amended sand rootzones is impractical, providing the early establishment growth could be managed successfully.

Compared with the pure sand rootzone, the three amended sand rootzones had obvious advantages in rootzone physical and sward performance during the first few years after sowing. These advantages were reflected mainly by the ease of establishment and low occurrence of dry patch disorder and take-all disease, although the performance of the three amended sand rootzones deteriorated more quickly over time than the pure sand rootzone and the conventional soil rootzone. However, there was no evidence to show any measurable disadvantage of the two modified USGA profiles recommended in New Zealand (Gibbs *et al.* 1997, 2000; Yang *et al.* 1998; Myer *et al.* 2003) compared with a fully amended USGA-type profile on all simulation occasions throughout the 30 years. The implication of this result is that the two modified USGA profiles can be used successfully for golf green rootzone construction instead of a fully amended, standard USGA-type profile.

Reverse pursuit of the modeling indicated that the principal factor causing the general decrease in the $CGGP_I$ of the sand-based rootzones was excess accumulation of organic matter over time in the upper portion of the profiles (Fig. 7-6). This result was consistent with a series of previous studies (Curtis & Pulis 2001; Carrow 2004a, b, c; O'Brien & Hartwiger 2003). However, the key factor causing the relatively quicker decrease over time in the $CGGP_I$ of the three amended sand rootzones, compared with the pure sand rootzone, was the faster shift of rooting depth towards the surface profile (Fig. 7-9), similar to that found by by Carrow (1995) and Hannaford and Baker (2000). The present study showed that under the frequency of treatment used (twice yearly), the improvement from cultivation/aeration treatments on golf green performance was not significant on all rootzones.

Model simulation indicated that the optimum improvement in $CGGP_I$ could be achieved from cultivation/aeration treatment (e.g. Verti-drain and scarification) at a frequency of up to six times per year on sand-based rootzones (Appendix Fig. 7-5). This merits validation by further field studies.

## 7.6 SUMMARY AND CONCLUSIONS

The Integrated Rate Methodology (IRM) model is able to give an objective, quantitative and comprehensive assessment of the long-term performance of golf greens at both the surface and the rootzone level under changeable field conditions by computing a Comprehensive Golf Green Performance Index ($CGGP_I$). The IRM model has the potential to be used as an effective decision-making tool in consultancy, performance assessment and monitoring, and seasonal management of golf greens.

Quantitative benefits of upgrading from a soil-based to a sand-based golf green were initially large. However, deterioration over time in golf green performance was considerable for all sand-based rootzones, particularly for the three amended sand rootzones. Advantages of the sand-based rootzones over the conventional soil rootzone diminished with time. Under the management conditions used, greens' performance was considered unacceptable by the $14^{th}$ year and $27^{th}$ year after establishment for the three amended sand rootzones and pure sand rootzone, respectively. The key factor that resulted in such a general deterioration in greens' performance of sand-based rootzones was considered to be excess accumulation of organic matter in the upper portion of the profile. However, the controlling factor causing the relatively faster deterioration rate in greens' performance of the three amended sand rootzones compared with the pure sand rootzone was a faster reduction in rooting depth of the amended sand profiles.

The performance of the pure sand rootzone was worse than the three amended sand rootzones during the first two years after sowing. However, from the second year onwards, the pure sand rootzone showed significant advantages in terms of the simulated $CGGP_I$ over the three amended sand rootzones.

There was little indication that the New Zealand practice of constructing only the top 100 mm of the sand rootzone with organic-amended sand (with or without an underlying zeolite layer) was a disadvantage in terms of greens' performance compared with a fully amended USGA-type profile.

None of the cultivation/aeration treatments effectively controlled the general deterioration in golf green performance over time under the twice-yearly treatment frequency. Model simulation indicated that cultivation/aeration treatments (e.g. Verti-drain and scarification) should theoretically be used on sand-based rootzones at a frequency of up to six times per year under New Zealand conditions.

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# 8. GENERAL DISCUSSION

## 8.1 GENERAL TREND OVER TIME IN GOLF GREEN PERFORMANCE

There was a general, progressive deterioration for all rootzones in golf green performance in terms of rootzone physical properties, sward characteristics and playing quality, measured over the first five years or predicted over the first 30 years following establishment by computing a Comprehensive Golf Green Performance Index ($CGGP_I$) using an Integrated Rate Methodology (IRM) model. This general trend indicated that green's performance of the conventional soil rootzone was not acceptable on all occasions measured or predicted, while that of the three amended sand rootzones and pure sand rootzone remained above the minimum acceptable threshold by the first 14 and 27 years after sowing, respectively. None of the cultivation/aeration treatments could effectively halt this general deterioration rate in golf green performance for all the rootzones under the maintenance conditions used (twice yearly HydroJect, scarification and Verti-drain). This study indicated the requirement of commencing an earlier and more frequent cultivation/aeration programme (e.g. up to six times per year for Verti-drain and scarification treatments on sand-based golf greens) after establishment on both soil-based and sand-based rootzones in order to maintain the long term sustainability of golf green performance.

## 8.2 KEY FACTORS CAUSING THE GENERAL DETERIORATION TREND IN GOLF GREEN PERFORMANCE

The general trend of deterioration in greens' performance, either measured over the first five years or predicted over the first 30 years following establishment, was more pronounced on sand-based rootzones, especially on the three amended sand rootzones. Results showed that the principal factor causing this general deterioration of sand-based rootzones was excess accumulation of organic matter in the upper portion of profiles. Similar results have been reported in a series of other studies (Schmidt 1980; Adams 1981; Carrow 1995, 2004a, b, c; Habeck & Christians 2000; Curtis & Pulis 2001; O'Brien & Hartwiger 2003). However, for a soil rootzone, which has inherently poor resistance to soil compaction (Elliot 1971; Baker 1988), the key factor causing this general deterioration could be a rapid development of soil compaction as well as an excess accumulation of organic matter in the surface of the profile. This result is also consistent with previous studies (Schmidt 1980; Thien 1994).

The results of previous studies and this thesis imply that monitoring organic matter content in the upper portion of a profile is of crucial importance in the management of sand-based rootzones. "It is the manipulation of this layer by aerification that is perhaps of the greatest safeguard in ensuring the long-term integrity of the root zone" (Curtis & Pulis 2001). For example, regular mini-coring, Verti-draining with hollow tines or a combination of aeration + scarification-type treatments are suitable choices for this purpose. However, quantitative information on effectiveness and relative frequency of these cultivation/aeration treatments in controlling organic matter accumulation and resultant performance deterioration of sand-based rootzones is still limited. This area warrants further studies. Furthermore, the present study suggested that maintenance of soil-based rootzones should be based on both controlling organic matter accumulation in the surface of the profiles (e.g. dethatching) and relieving soil compaction by using some deep penetration equipment (e.g. Verti-drain).

## 8.3 EFFECT OF ROOTZONE TYPE ON GOLF GREEN PERFORMANCE

This study indicated that advantages of upgrading from a conventional soil-based to a sand-based rootzone were significant in terms of increased water and air transmission capacity, a deeper and more balanced root distribution, a more stable sward and less fluctuation in playing quality with seasons. Although the conventional soil rootzone had lower incidence of both dry patch disorder and pest damage, it was not considered suitable for the construction of intensively used golf greens in most cases because its green's performance, either measured over the first five years after sowing or predicted over the long-term, consistently remained well below the minimum acceptable threshold.

No measurable disadvantages of the two partially amended sand rootzones in terms of greens' performance could be determined when compared with the fully amended sand rootzone on all occasions measured or predicted, with the only exception of the oxygen diffusion rate. Furthermore, the predicted long-term greens' performance of the two partially amended sand rootzones was better than that of the fully amended sand rootzone in some cases. The implication of this result is that the two modified USGA-type rootzones recommended for New Zealand golf green constructions (Gibbs *et al.*

1997, 2000; Yang *et al.* 1998; Myer *et al.* 2003) could be used successfully for golf green construction instead of the standard USGA profile (USGA 1993, 2004).

The poor green's performance of the pure sand rootzone measured at earlier stages after sowing was caused mainly by poor sward establishment and severe dry patch disorder during the first two years after sowing. This result can be explained partially by poor water-holding capacity caused by low organic matter content in the medium-coarse, pure sand rootzone at sowing. Nevertheless, the measured green's performance of the pure sand rootzone was still acceptable during the first two years after sowing under the standard putting green management used. More importantly, either the measured or predicted long-term green's performance of the pure sand rootzone remained significantly superior to all amended sand rootzones throughout the remaining evaluation period. This advantage of the pure sand rootzone over the three amended sand rootzones appeared mainly because of a deeper and more balanced root distribution in the profile, which is considered a pre-requirement of sports turf management by Hannaford and Baker (2000). A similar result was found by Baker and Richards (1993). Better root development in the present study may in part have resulted from poor moisture and nutrition retention levels in the pure sand rootzone, requiring roots to grow deeper (Adams & Gibbs 1994). The above results imply that in the long run, a simple pure sand rootzone system, which is a preferred practice in golf green construction by golf superintendents in many countries (Gibbs *et al.* 2000, 2001), could also be used for golf green construction instead of the standard USGA profile where the use of the partially amended sand rootzone is impractical, provided the establishment period can be managed successfully.

On a few occasions, some unexpected results were recorded in relation to effects of the rootzone type. For example, the proposed advantages of amended sand with zeolite, ostensibly for encouraging deep rooting (Ferguson *et al.* 1986), was not observed under the experimental conditions used. This result is possibly because the plots were not maintained under potentially harsh growth conditions, and the potential benefits of the zeolite might have been masked. Moreover, the partially amended sand rootzone (T1) showed poorer physical performance [reflected by a lower Rootzone Index ($R_I$)] after the fifth year following sowing, compared with other sand-based rootzones. Furthermore, the fully amended sand rootzone generally produced a green's surface with poorer playing quality [reflected by lower Playing Quality Index ($P_I$)] compared with all other sand-based rootzones. It is difficult to give satisfactory explanations for these effects, and more studies may be required on these aspects.

## 8.4 EFFECT OF CULTIVATION/AERATION TREATMENT ON GOLF GREEN PERFORMANCE

Verti-drain treatment tended to increase infiltration rate and air-filled porosity, decrease root growth and organic matter accumulation in the surface of the profile, and reduce green speed and surface hardness. The HydroJect treatment, which is usually associated with a higher incidence of certain diseases, had less beneficial influences on rootzone physical properties compared with the Verti-drain treatment. The HydroJect treatment also appeared particularly effective in minimizing the occurrence of dry patch disorder on sand-based rootzones when used in conjunction with a proprietary wetting agent. In contrast, the scarification treatment showed that whilst it was effective in significantly reducing organic matter accumulation near the surface of the profile, it also caused significant reductions in infiltration rate and visual turf quality at all simulated frequencies.

Nevertheless, the influence of cultivation/aeration treatment (e.g. HydroJect, scarification and Verti-drain) on golf green performance, either measured over the first five years or predicted over the first 30 years following establishment, was negligible under the treatment frequency used (i.e. twice yearly) for all the sand-based rootzones. Consistent and significant beneficial effects of twice yearly HydroJect and Verti-drain treatments were apparent only on rootzone physical performance. However, the significant effect of these treatments on rootzone physical performance lasted only about two months under the golf green conditions of this trial. The short-lived nature of these cultivation/aeration treatments has been observed under sports turf conditions in several other studies (Lodge & Baker 1993; McAuliffe *et al.* 1993).

Increased frequency (e.g. up to six times per year) of these cultivation/aeration treatments (Verti-drain and scarification) in the IRM model led to a significant increase in golf green performance predicted by $CGGP_I$. The implication of this result is the twice-yearly frequency of cultivation/aeration treatment is inadequate for sustainable management of sand-based golf greens under New Zealand ecological conditions, and these aspects deserve further field studies.

## 8.5 POTENTIAL APPLICATIONS OF THE IRM MODEL IN GOLF GREEN MANAGEMENT PRACTICES

The IRM model is able to quantitatively integrate the components of a complicated and dynamic golf green ecosystem into a mathematical model through strict factor linkage, by using a system analysis approach (Wu *et al.* 1994, 1996). If supported by an appropriate computer software package, this method can potentially become a convenient and effective decision-making tool for rootzone upgrading, surface preparation, performance assessment and monitoring, professional consultancy and seasonal planning of golf green management.

If the model was combined with a national computer web system, it would have the potential to link different sections of the golf industry (e.g. consultants, turf managers and club members) through an updateable database-modeling-web platforn, greatly enhancing national cooperation in standards establishment and seasonal planning of golf course management. For example, if a national database for each golf club was available, an IRM model could be developed for each participating golf club (Note: this may be a limitation for some golf clubs because twice-yearly measurement on the eleven key factors of six selected golf greens over three years will cost each club approximately NZ$1000-2000 per year) (Fig. 8-1). Potentially, a national benchmarking system could be developed for golf course management, provided the sensitive issue of how the system would be used in respect of superintendents' performance being adequately addressed. Under such a system, performance of each golf course could be assessed comprehensively, and compared or ranked quantitatively in relation to other golf courses according to one single quantitative index, the $CGGP_I$. The long-term performance of each golf course could be monitored on computer by consultants through a built-in IRM model. Relying on reverse pursuit functions of the IRM model, limiting factors (e.g. organic matter content at the top 35 mm of rootzone), which can potentially cause a problem in green performance, could be predicted and examined beforehand, and the most cost-effective solutions (e.g. mini-core treatment) to reverse this performance could be determined through model simulation by consultants well before symptoms occurred (Fig. 8-1).

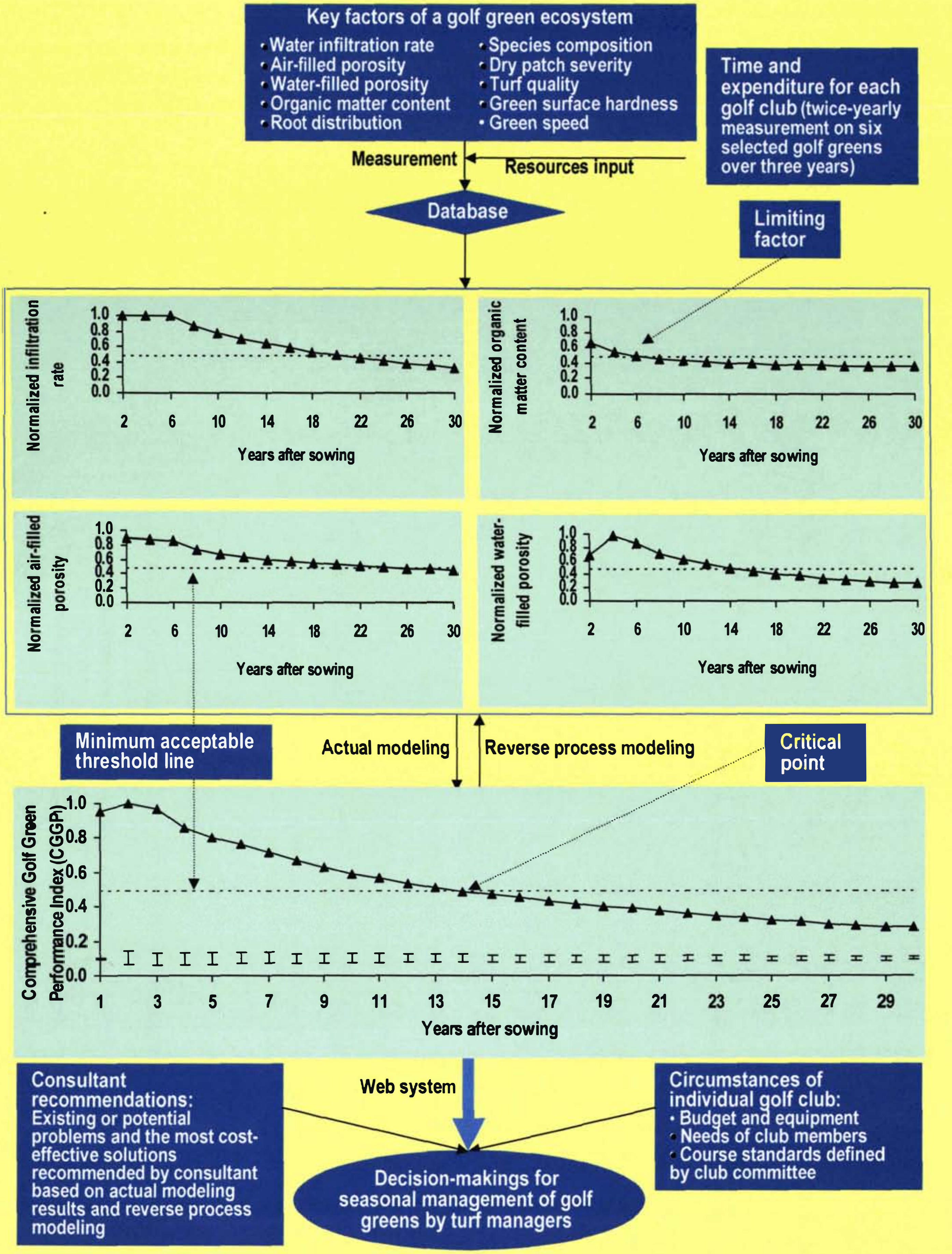


**Fig. 8-1** A schematic representation of the decision-making process using an IRM model for seasonal management of golf greens

Modeling results would be regularly delivered through a web system to each registered golf club based on updated database and renewed modeling results. Then, turf managers would be able to review, adjust and arrange a suitable management programme, according to the modeling results (i.e. threshold figures in Fig. 8-1), recommendations from consultants and changeable circumstances of a golf club (e.g. budget, equipment, needs of club members and course standards defined by the club committee). Therefore, an automatic, national golf course benchmarking and seasonal management system based on modern information technology and system analysis knowledge could be achieved (Fig. 8-1).

According to published information, it appears that little research has been conducted on this aspect in the turf industry compared with recent significant developments in ecological modeling in other branches of agriculture. The present study is only a first-step investigation and concept demonstration. The full development of the model and its application to management practice in the sports turf industry deserves further validation and field research.

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# 9. CONCLUSIONS

# 9. CONCLUSIONS

The research presented in this thesis provides the following conclusions.

1. A key factor causing progressive deterioration over time in golf green performance of sand-based greens is the excess accumulation of organic matter in the upper portion of the profile. Management of sand-based golf greens should focus on control of excess accumulation of organic matter in the surface profile, starting within 12 months from establishment.

2. Cultivation/aeration treatments for control of organic matter accumulation in the surface of the profile need to commence immediately after full turf establishment, and be applied more than twice per year on both sand-based and soil-based golf greens under New Zealand conditions if appropriate performance is to be sustained in the long term.

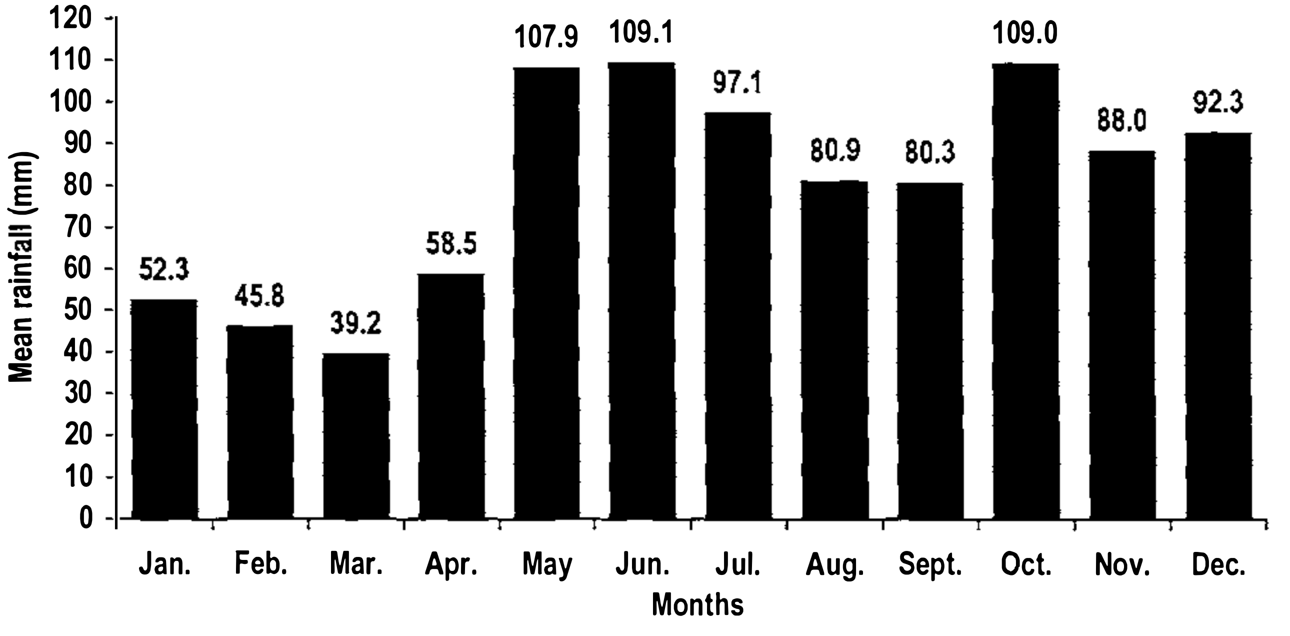
3. Regular use of HydroJect appears to be an effective management tool for prevention of dry patch disorder on sand-based golf greens. However, the variable responses of scarification treatment, indicating scarification should not be used in isolation of other physical cultivation.

4. Upgrading from a conventional soil rootzone to a high-grade sand-based rootzone will greatly improve golf green performance. Limitations of a conventional soil rootzone can be suitably identified using the integrated rate modeling approach.

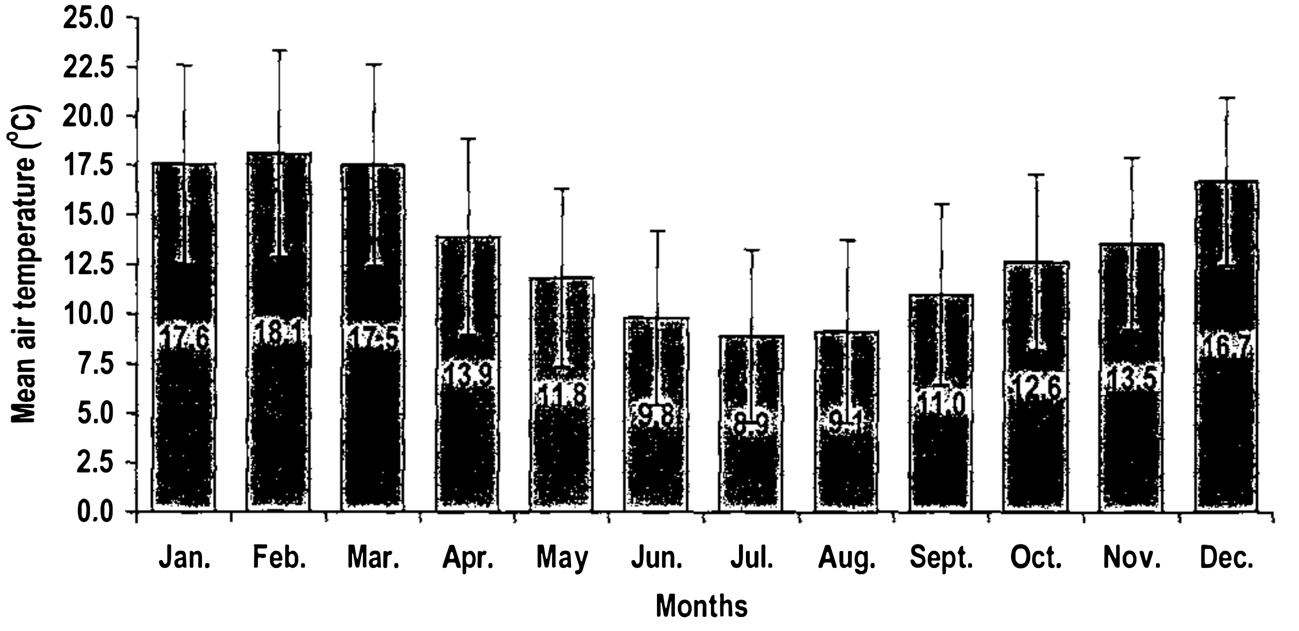
5. Negligible difference in golf green performance between the three amended sand rootzones on all measurement/prediction occasions, or between the amended sand rootzones and the pure sand rootzone after three years from sowing indicate that: (a) the New Zealand practice of constructing only the top 100 mm of the sand rootzone with organic-amended sand can be used successfully for golf green construction instead of a fully amended USGA-type profile; (b) the pure sand rootzone system is also an appropriate alternative for rootzone construction of golf greens where the use of the partially amended sands is impractical, provided early establishment can be managed successfully.

6. The integrated rate modeling approach is a potentially effective decision-making tool that can be used for rootzone upgrading justification, surface preparation, performance assessment and monitoring, professional consultancy and long-term management of golf greens. It is strongly recommended that a national benchmarking scheme should be set up for golf course management in New Zealand.

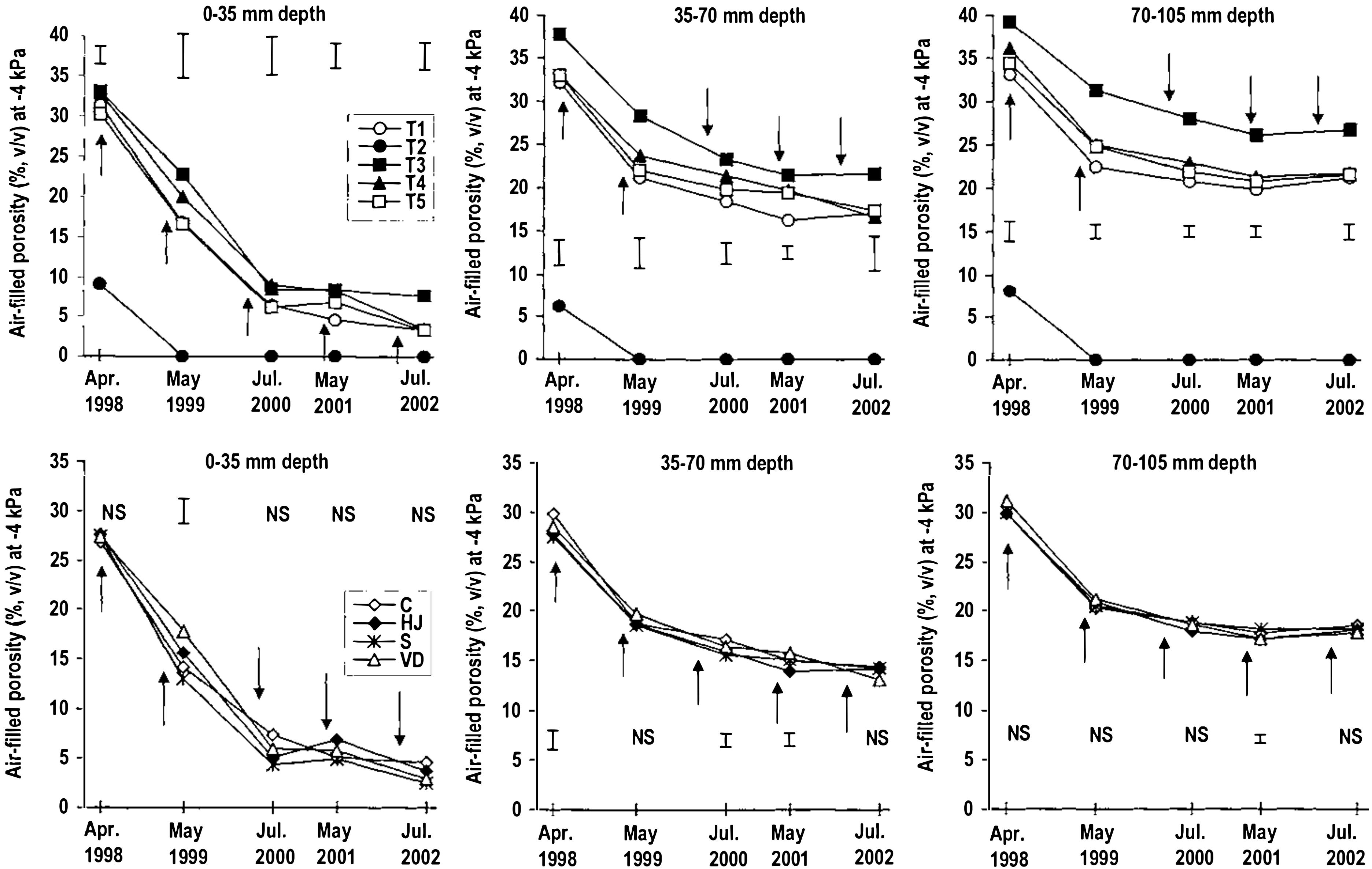
# APPENDICES




**Appendix Fig. 3-1 Mean rainfall during the experimental period (1998-2003) for Palmerston North region; Number at the top of each bar represents the mean rainfall (mm) for each month.**

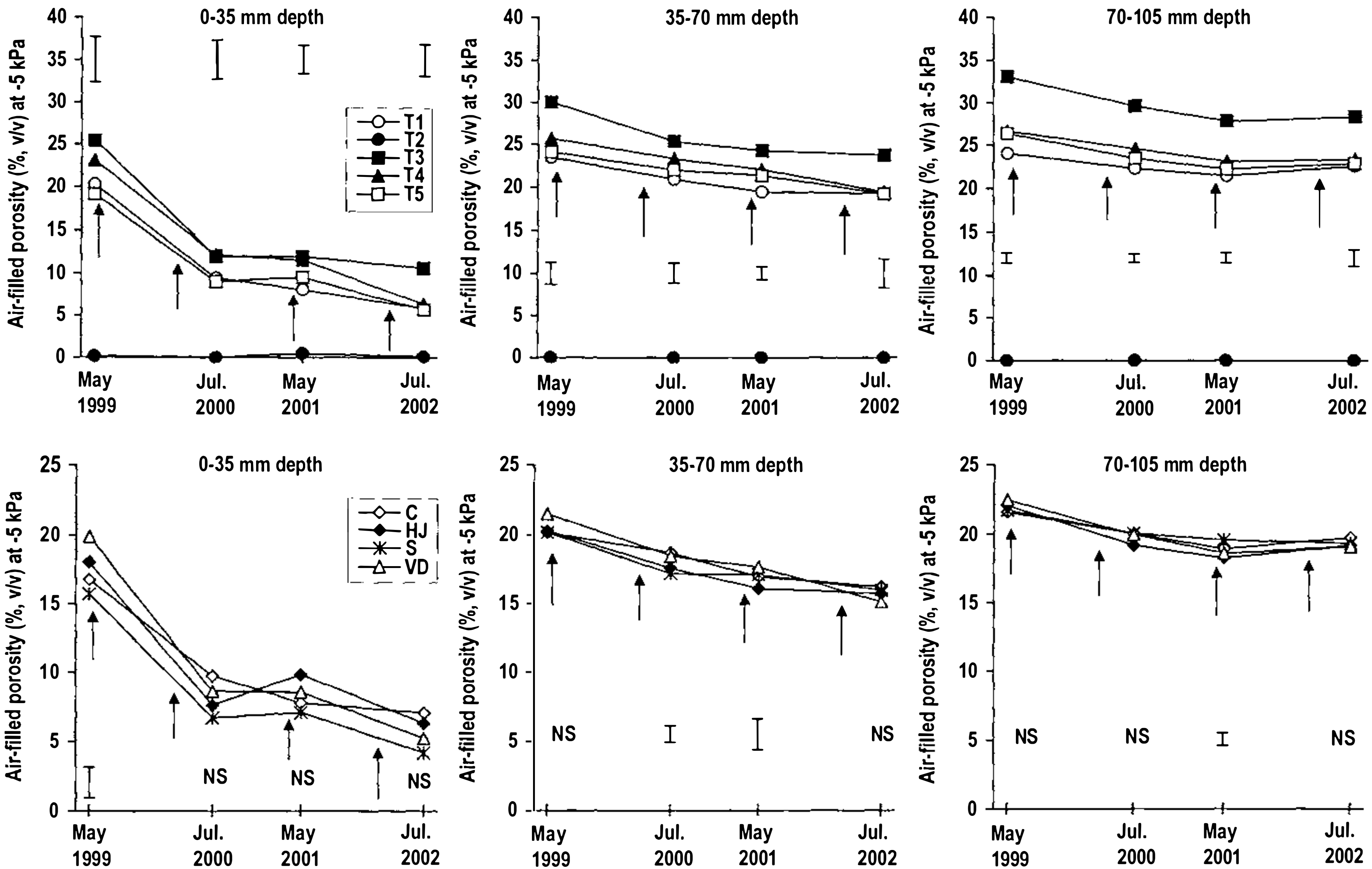



**Appendix Fig. 3-2 Mean air temperature during the experimental period (1998-2003) for Palmerston North region; Numbers within the bars represent the mean air temperature (°C) for each month; Error bars represent the value range between the mean maximum and mean minimum air temperature (°C) for each month.**



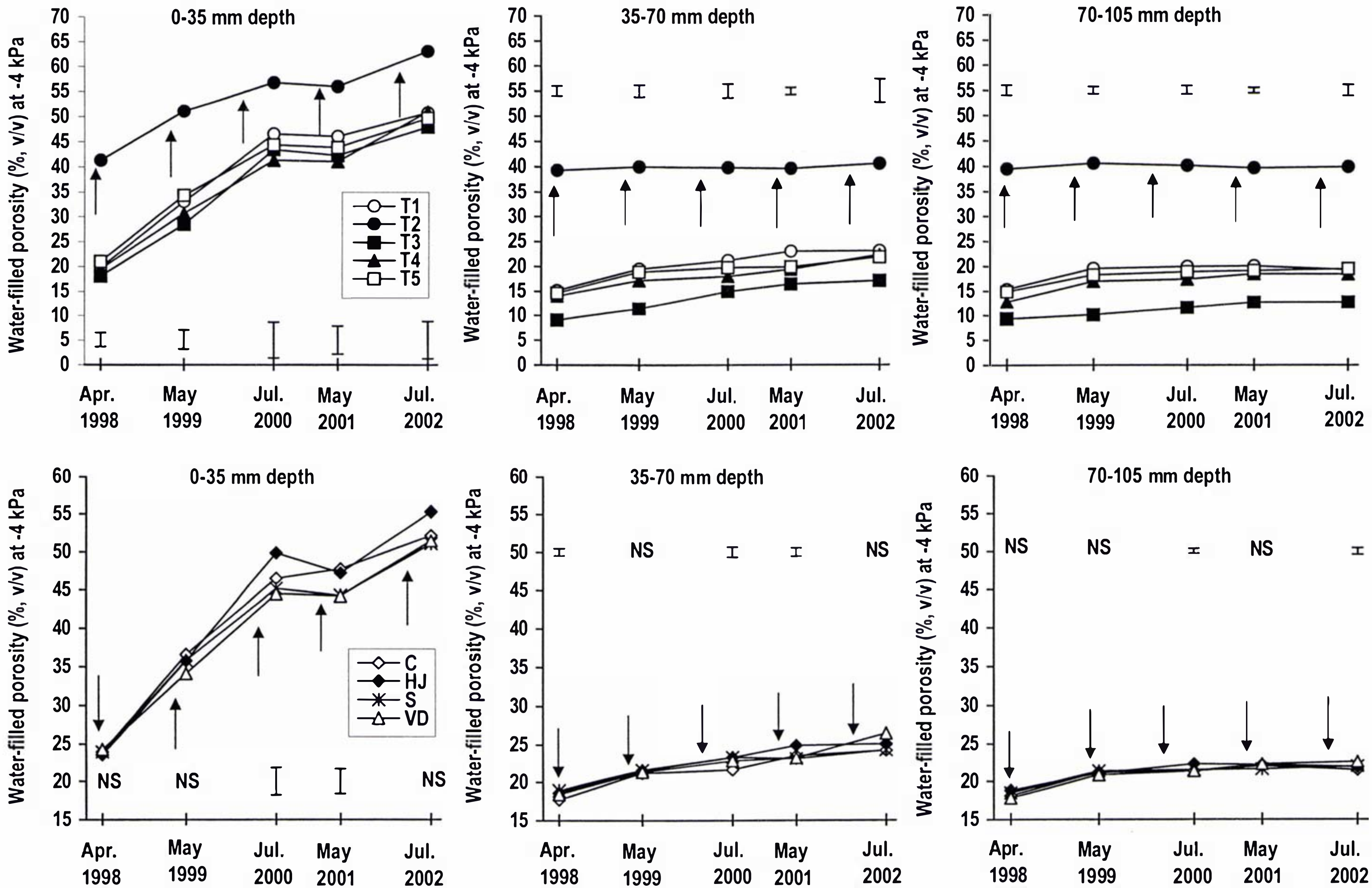

**Appendix Fig. 4-1 Changes in air-filled porosity at -4 kPa with time in relation to each rootzone type and cultivation/aeration treatment**

*NS---not significantly different at the 0.05 level of probability. Error bars represent the LSD value for each group of treatments on each period of measurement. Arrows show the application time of the cultivation/aeration treatment. T1---Partially amended sand rootzone, T2---Soil rootzone, T3---Pure sand rootzone, T4---Fully amended sand rootzone, T5---Partially amended sand + zeolite rootzone. C---Control, HJ---HydroJect, S---Scarification, VD---Verti-drain.*



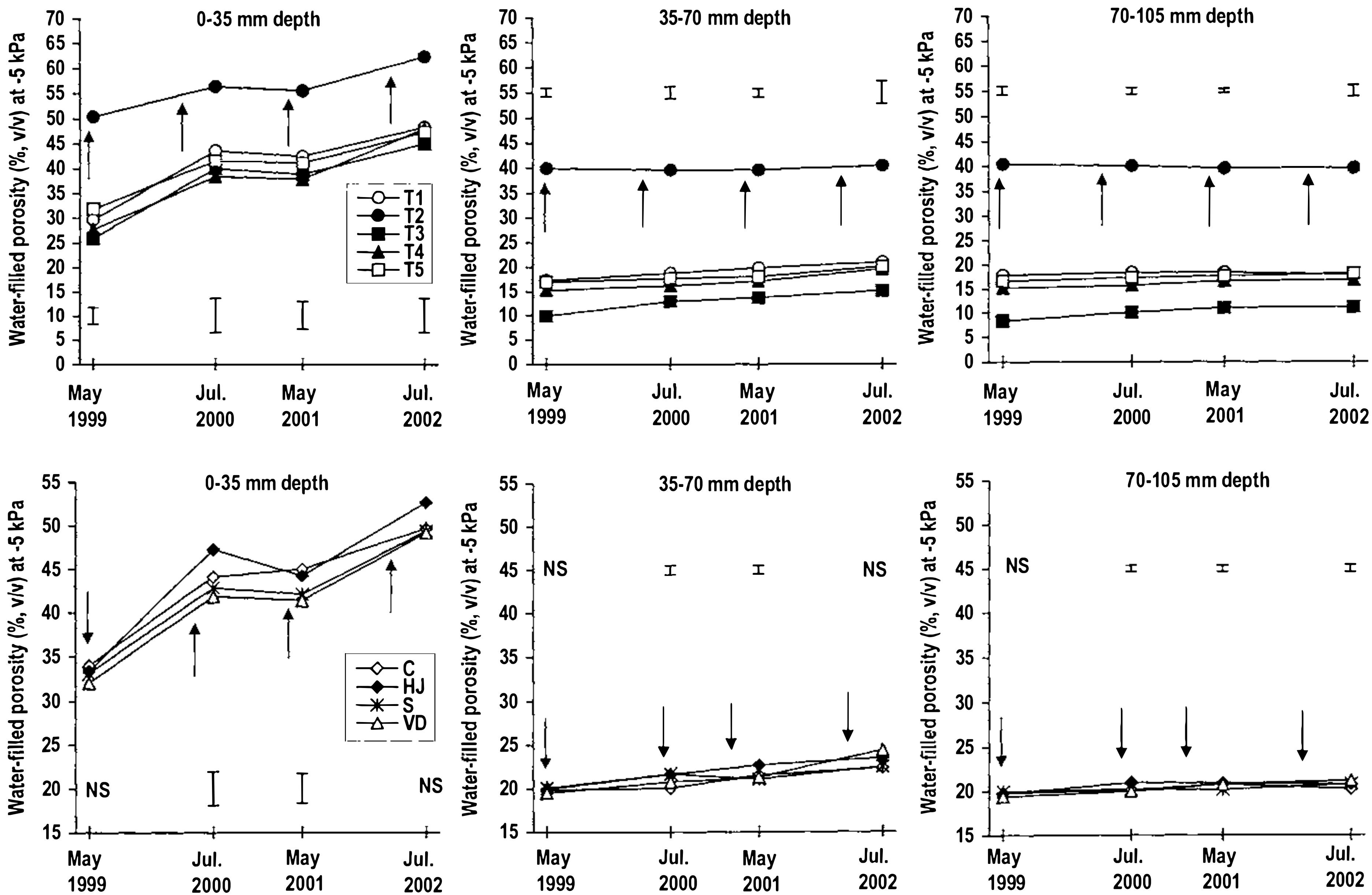

**Appendix Fig. 4-2 Changes in air-filled porosity at -5 kPa with time in relation to each rootzone type and cultivation/aeration treatment**

*NS---not significantly different at the 0.05 level of probability. Error bars represent the LSD value for each group of treatments on each period of measurement. Arrows show the application time of the cultivation/aeration treatment. T1---Partially amended sand rootzone, T2---Soil rootzone, T3---Pure sand rootzone, T4---Fully amended sand rootzone, T5---Partially amended sand + zeolite rootzone. C---Control, HJ---HydroJect, S---Scarification, VD---Verti-drain.*




**Appendix Fig. 4-3 Changes in water-filled porosity at -4 kPa with time in relation to each rootzone type and cultivation/aeration treatment**

*NS---not significantly different at the 0.05 level of probability. Error bars represent the LSD value for each group of treatments on each period of measurement. Arrows show the application time of the cultivation/aeration treatment. T1---Partially amended sand rootzone, T2---Soil rootzone, T3---Pure sand rootzone, T4---Fully amended sand rootzone, T5---Partially amended sand + zeolite rootzone. C---Control, HJ---HydroJect, S---Scarification, VD---Verti-drain.*




**Appendix Fig. 4-4 Changes in water-filled porosity at -5 kPa with time in relation to each rootzone type and cultivation/aeration treatment**

*NS---not significantly different at the 0.05 level of probability. Error bars represent the LSD value for each group of treatments on each period of measurement. Arrows show the application time of the cultivation/aeration treatment. T1---Partially amended sand rootzone, T2---Soil rootzone, T3---Pure sand rootzone, T4---Fully amended sand rootzone, T5---Partially amended sand + zeolite rootzone. C---Control, HJ---HydroJect, S---Scarification, VD---Verti-drain.*

**Appendix Table 7-1 Calculation of weighting factors of the general IRM model for a golf green ecosystem**

| IRM model factor | | | | Sub-models | | |
|---|---|---|---|---|---|---|
| Name | | Symbol | Calculated weightings (Wu *et al*. 1994) | Symbol | Accumulated weightings for each sub-model | Calculated weightings for each sub-model |
| Rootzone sub-model | Water infiltration rate | $W_1$ | 1.00 | a | 11.30 | 0.39 |
| | Air-filled porosity | $W_2$ | 2.50 | | | |
| | Organic matter content in the top 35 mm of rootzone | $W_3$ | 1.67 | | | |
| | Organic matter content in the 35-70 mm depth | $W_4$ | 2.50 | | | |
| | Water-filled porosity | $W_5$ | 3.64 | | | |
| Sward sub-model | Root distribution | $W_6$ | 1.75 | b | 10.92 | 0.37 |
| | Dry patch severity | $W_7$ | 3.00 | | | |
| | Turf quality | $W_8$ | 3.89 | | | |
| | Species composition | $W_9$ | 2.28 | | | |
| Playing Quality sub-model | Green surface hardness | $W_{10}$ | 3.64 | c | 6.97 | 0.24 |
| | Green speed | $W_{11}$ | 3.33 | | | |
| Sum | | | 29.19 | | 29.19 | 1.00 |

**Appendix Table 7-2a Effects of season and climate on the infiltration rate of rootzones for golf greens**

| Seasons and climate | Temperature ( °C) | Ptest | Ptest/P10 (P10=1.307) |
|---|---|---|---|
| Summer | 20.19 | 1.02 | 0.78 |
| | 22.83 | 0.95 | 0.73 |
| | 21.28 | 0.99 | 0.76 |
| | 23.10 | 0.94 | 0.72 |
| **Mean** | **21.85** | **0.98** | **0.75** |
| Winter | 10.38 | 1.30 | 0.99 |
| | 11.38 | 1.27 | 0.97 |
| | 11.63 | 1.26 | 0.97 |
| **Mean** | **11.13** | **1.28** | **0.98** |

If the value in the winter is set to 0.5, then the value in the summer can be calculated using the following equation:

0.75/0.5 = 0.98/X

then, X = 0.5 * 0.98/0.75 = 0.65, so, the value in summer should be 0.65 (i.e. 0.15 more than the value in winter).

**Appendix Table 7-2b Effects of season and climate on sward characteristics of rootzones for golf greens**

| Seasons and climate | Turf uniformity | Turf density | Dry patch severity | Root distribution (%) | Normalized turf uniformity | Normalized turf density | Normalized dry patch severity | Normalized root distribution (%) | weighted average |
|---|---|---|---|---|---|---|---|---|---|
| Summer | 7.72 | 7.71 | 1.96 | 12.00 | **0.66** | 0.66 | 0.51 | 0.95 | |
| | 7.63 | 7.47 | 0.78 | 9.30 | **0.64** | 0.61 | 0.70 | 0.89 | |
| | | | 0.71 | 4.30 | | | 0.71 | 0.58 | |
| | | | 1.40 | 3.50 | | | 0.60 | 0.50 | |
| | | | | 3.00 | | | | 0.44 | |
| **Mean** | **7.68** | **7.59** | **1.21** | **6.42** | **0.65** | **0.63** | **0.63** | **0.67** | **0.65** |
| Winter | 7.73 | 7.98 | 0.00 | 14.60 | **0.67** | 0.73 | 0.83 | 0.95 | |
| | 7.96 | 7.91 | 0.00 | 12.60 | **0.72** | 0.71 | 0.83 | 0.95 | |
| | 7.43 | 7.71 | 0.00 | 7.10 | **0.60** | 0.66 | 0.83 | 0.80 | |
| | | | 0.00 | 4.60 | | | 0.83 | 0.61 | |
| | | | 0.00 | 3.80 | | | 0.83 | 0.53 | |
| **Mean** | **7.71** | **7.87** | **0.00** | **8.54** | **0.66** | **0.70** | **0.83** | **0.77** | **0.76** |

If the value in the summer is set to 0.5, then the value in the winter can be calculated by the following equation:

0.65/0.5 = 0.76/X

then, X = 0.5 * 0.76/0.65 = 0.59, so, the value in winter should be 0.59 (i.e. 0.09 more than the value in summer).

**Appendix Table 7-2c Effects of season and climate on the playing quality of rootzones for golf greens**

| Seasons and climate | Green speed (m) | Green surface hardness (gravity) | Normalized green speed | Normalized green surface hardness | weighted average |
|---|---|---|---|---|---|
| Summer | 1.78 | 118 | **0.69** | 0.83 | |
| | 2.13 | 118 | **0.92** | 0.83 | |
| | 2.41 | 128 | **0.89** | 0.66 | |
| | 2.27 | 143 | **0.99** | 0.44 | |
| | 2.23 | | **0.99** | | |
| **Mean** | **2.16** | **127** | **0.89** | **0.69** | **0.79** |
| Winter | 2.34 | 108 | **0.94** | 0.96 | |
| | 2.67 | 102 | **0.72** | 0.85 | |
| | 2.77 | 121 | **0.65** | 0.78 | |
| | 2.73 | 132 | **0.68** | 0.60 | |
| | | 121 | | 0.78 | |
| **Mean** | **2.63** | **117** | **0.75** | **0.79** | **0.77** |

**If the value in the winter is set to 0.5, then the value in the summer can be calculated by the following equation:**

**0.77/0.5 = 0.79/X**

**then, X = 0.5 * 0.79/0.77 = 0.51, so, the value in summer should be 0.51 (i.e. 0.01 more than the value in winter).**

**Appendix Table 7-3a Scaled effects of each cultivation/areation treatment on each factor of the physical performance of the golf green rootzones**

| Rootzone type | Cultivation /aeration treatment | Infiltration rate (mm $h^{-1}$) | | Air-filled porosity (%, v/v) at the -3 kPa in the 35-70 mm of the rootzone depth | | | Organic matter content (%, w/w) at the top 35 mm of the rootzone | | | Organic matter content (%, w/w) at the 35-70 mm of the rootzone depth | | | Water-filled porosity (%, v/v) at the -3 kPa in the 35-70 mm of the rootzone depth | | | Scaled factor for each cultivation /aeration treatment |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Meaured means | Normalized values | Meaured means | Normalized values | Normalized values | Meaured means | Normalized values | Normalized values | Meaured means | Normalized values | Normalized values | Meaured means | Normalized values | Normalized values | |
| Sand-based rootzones | C | 255 | 0.74 | 16.9 | 0.85 | 1.00 | 6.1 | 0.49 | 0.79 | 1.7 | 0.85 | 1.00 | 23.7 | 0.73 | 0.90 | **0.81** |
| | HJ | 294 | 0.85 | 16.2 | 0.81 | 0.96 | 6.1 | 0.49 | 0.79 | 1.7 | 0.85 | 1.00 | 24.7 | 0.80 | 0.99 | **0.86** |
| | S | 212 | 0.62 | 16.1 | 0.81 | 0.95 | 5.1 | 0.59 | 0.94 | 1.7 | 0.85 | 1.00 | 24.5 | 0.79 | 0.97 | **0.80** |
| | VD | 345 | 1.00 | 16.5 | 0.83 | 0.98 | 4.8 | 0.63 | 1.00 | 1.7 | 0.85 | 1.00 | 24.8 | 0.81 | 1.00 | **1.00** |
| Soil-based rootzones | C | 1.9 | 0.39 | 2.0 | 1.00 | 1.00 | 9.9 | 0.30 | 0.87 | 2.9 | 0.53 | 0.95 | 39.6 | 0.36 | 1.00 | **0.62** |
| | HJ | 1.3 | 0.27 | 0.1 | 0.10 | 0.10 | 10.4 | 0.29 | 0.83 | 2.9 | 0.53 | 0.95 | 40.7 | 0.32 | 0.89 | **0.29** |
| | S | 1.4 | 0.29 | 0.6 | 0.30 | 0.30 | 8.6 | 0.35 | 1.00 | 2.8 | 0.56 | 1.00 | 39.8 | 0.35 | 0.98 | **0.45** |
| | VD | 4.9 | 1.00 | 1.4 | 0.70 | 0.70 | 9.3 | 0.32 | 0.92 | 3.0 | 0.50 | 0.90 | 41.0 | 0.31 | 0.86 | **0.90** |

If the value of daily maintenance practice [$M_l(t)$] varies between 0.3-0.7 (Wu *et al*. 1996), and the value of current maintenance practice is set to 0.50, then the scaling factor (r) for sand-based rootzones = cultivation/aeration effects + daily maintenance effect + season effect = $H_c + M_l(t) + S_w = 0.2 + 0.2 + 0.15 = 0.55$; Similarly, the scaling factor (r) for soil-based rootzones = 0.61 + 0.2 + 0.15 = 0.96.

As $h_m : S_w = (0.4 + 0.81)/2 : 0.15 = 0.605 : 0.15 = 4.0$, so in the equation 7-3, the $h_m$ is four times more sensitive than the $S_w$.

Similarly, $h_c : M_l(t) = (0.2 + 0.61)/2 : 0.20 = 0.405 : 0.20 = 2.0$, as the twice-yearly treatment is considered as a standard putting green management practice in New Zealand, and the value is set to 0.50, so in the equation 7-4, the $h_c$ is four times more sensitive than the $M_l(t)$.

**Appendix Table 7-3b Scaled effects of each cultivation/areation treatment on each factor of the sward characteristics of the golf green rootzones**

| Rootzone type | Cultivation/ aeration treatment | Root percentage (%) at the 50-250 mm depth in the total rootzone | | Species composition index (total turfgrass coverage + stability) | | | Dry patch severity | | | Turf quality (uniformity + density) | | | Scaled factor for each cultivation/ aeration treatment |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Meaured means | Normalized values | Meaured means | Normalized values | Normalized values | Meaured means | Normalized values | Normalized values | Meaured means | Normalized values | Normalized values | |
| Sand-based rootzones | C | 7.56 | 0.82 | 0.94 | 0.94 | 0.96 | 1.50 | 0.58 | 0.77 | 0.81 | 1.00 | 1.00 | **0.88** |
| | HJ | 7.54 | 0.82 | 0.98 | 0.98 | 1.00 | 0.44 | 0.76 | 1.00 | 0.80 | 1.00 | 1.00 | **0.92** |
| | S | 9.21 | 1.00 | 0.91 | 0.91 | 0.93 | 1.11 | 0.65 | 0.85 | 0.69 | 0.86 | 0.86 | **0.93** |
| | VD | 8.76 | 0.95 | 0.94 | 0.94 | 0.96 | 1.28 | 0.62 | 0.82 | 0.73 | 0.90 | 0.90 | **0.93** |
| Soil-based rootzones | C | 3.87 | 0.81 | 0.96 | 0.96 | 0.96 | 0.01 | 0.832 | 1.00 | 0.45 | 1.00 | 1.00 | **0.90** |
| | HJ | 4.43 | 0.92 | 1.00 | 1.00 | 1.00 | 0.00 | 0.833 | 1.00 | 0.43 | 0.96 | 0.96 | **0.96** |
| | S | 4.80 | 1.00 | 0.91 | 0.91 | 0.91 | 0.01 | 0.832 | 1.00 | 0.36 | 0.82 | 0.82 | **0.93** |
| | VD | 4.26 | 0.89 | 0.95 | 0.95 | 0.95 | 0.03 | 0.828 | 0.99 | 0.38 | 0.85 | 0.85 | **0.91** |

If the value of daily maintenance practice [$M_l(t)$] varies between 0.3-0.7 (Wu *et al*. 1996), and the value of current maintenance practice is set to 0.50, then the scaling factor (r) for sand-based rootzones = cultivation/aeration effects + daily maintenance effect + season effect = $H_c + M_l(t) + S_w = 0.05 + 0.20 + 0.09 = 0.34$; Similarly, the scaling factor (r) for soil-based rootzones = 0.06 + 0.20 + 0.09 = 0.35.

As $h_m : S_w = (0.25 + 0.26)/2 : 0.09 = 0.255 : 0.09 = 2.83$, so in the equation 7-18, the $h_m$ is three times more sensitive than the $S_w$.

Similarly, $h_c : M_l(t) = (0.05 + 0.06)/2 : 0.20 = 0.055 : 0.20 = 0.275$, as the twice-yearly treatment is considered as a standard putting green management practice in New Zealand, and the value is set to 0.50, so in the equation 7-19, the $M_l(t)$ is 1.5 times more sensitive than the $h_c$.

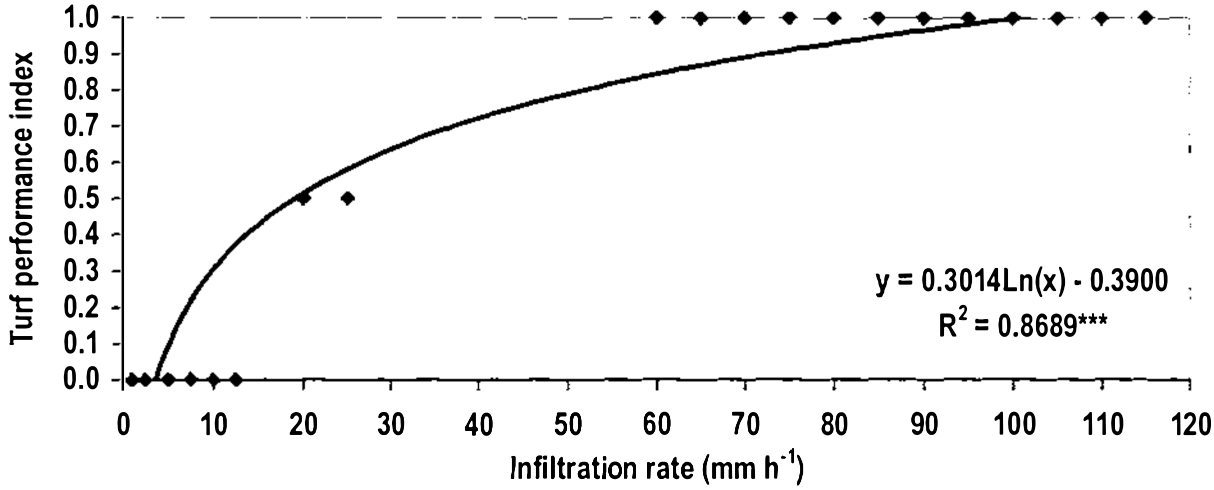
**Appendix Table 7-3c Scaled effects of each cultivation/areation treatment on each factor of the playing quality of the golf green rootzones**

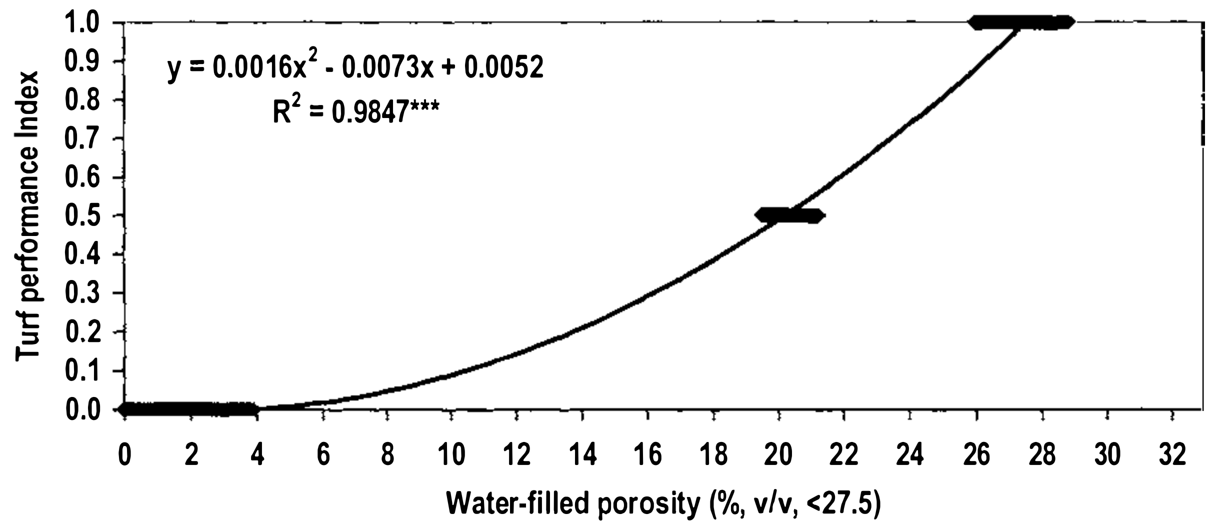
| Rootzone type | Cultivation/ aeration treatment | Surface green hardness measured by 0.5 kg Clegg hammer at the 1st drop | | | Ball roll distance (green speed) | | | Scaled factor for each cultivation/ aeration treatment |
|---|---|---|---|---|---|---|---|---|
| | | Meaured means | Normalized values | Normalized values | Meaured means | Normalized values | Normalized values | |
| Sand-based rootzones | C | 123 | 0.74 | 0.84 | 2.39 | 0.91 | 0.94 | **0.89** |
| | HJ | 117 | 0.85 | 0.96 | 2.31 | 0.96 | 1.00 | **0.98** |
| | S | 129 | 0.64 | 0.73 | 2.38 | 0.91 | 0.95 | **0.82** |
| | VD | 115 | 0.89 | 1.00 | 2.37 | 0.92 | 0.96 | **0.98** |
| Soil-based rootzones | C | 127 | 0.68 | 0.78 | 2.37 | 0.92 | 1.00 | **0.87** |
| | HJ | 117 | 0.85 | 0.98 | 2.40 | 0.90 | 0.98 | **0.98** |
| | S | 131 | 0.61 | 0.71 | 2.40 | 0.90 | 0.98 | **0.81** |
| | VD | 116 | 0.87 | 1.00 | 2.38 | 0.91 | 0.99 | **1.00** |

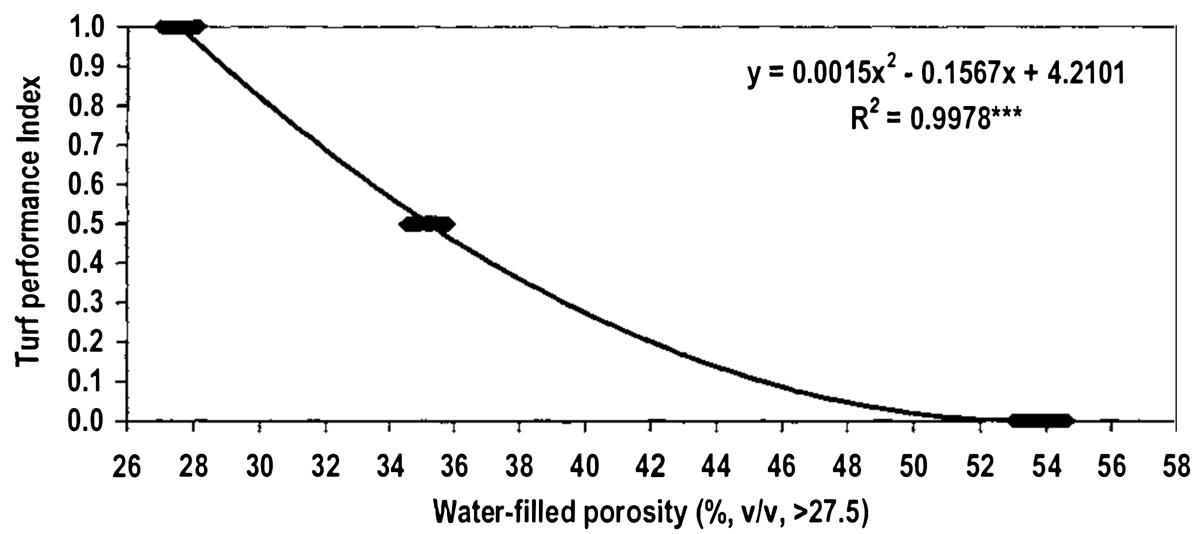
If the value of daily maintenance practice [$M_l(t)$] varies between 0.3-0.7 (Wu *et al*. 1996), and the value of current maintenance practice is set to 0.50, then the scaling factor (r) for sand-based rootzones $\approx$ cultivation/aeration effects + daily maintenance effect + season effect $\approx$ $H_c + M_l(t) + S_w = 0.16 + 0.20 + 0.01 \approx 0.37$; Similarly, the scaling factor (r) for soil-based rootzones = 0.19 + 0.20 + 0.01 = 0.40.

As $h_m : S_w \approx (0.36 + 0.39)/2 : 0.01 \approx 0.375 : 0.01 = 37.5$, so in the equation 7-31, the $h_m$ is 37.5 times more sensitive than the $S_w$.

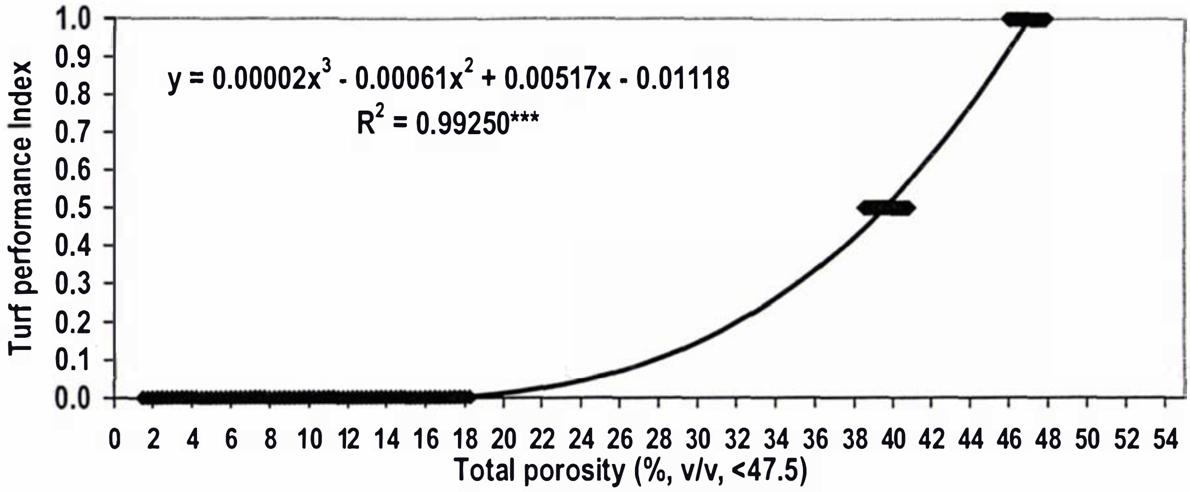
Similarly, $h_c : M_l(t) = (0.16 + 0.19)/2 : 0.20 = 0.175 : 0.20 = 0.875$, as the twice-yearly treatment is considered as a standard putting green management practice in New Zealand, and the value is set to 0.50, so in the equation 7-32, the $h_c$ is 1.5 times more sensitive than the $M_l(t)$.

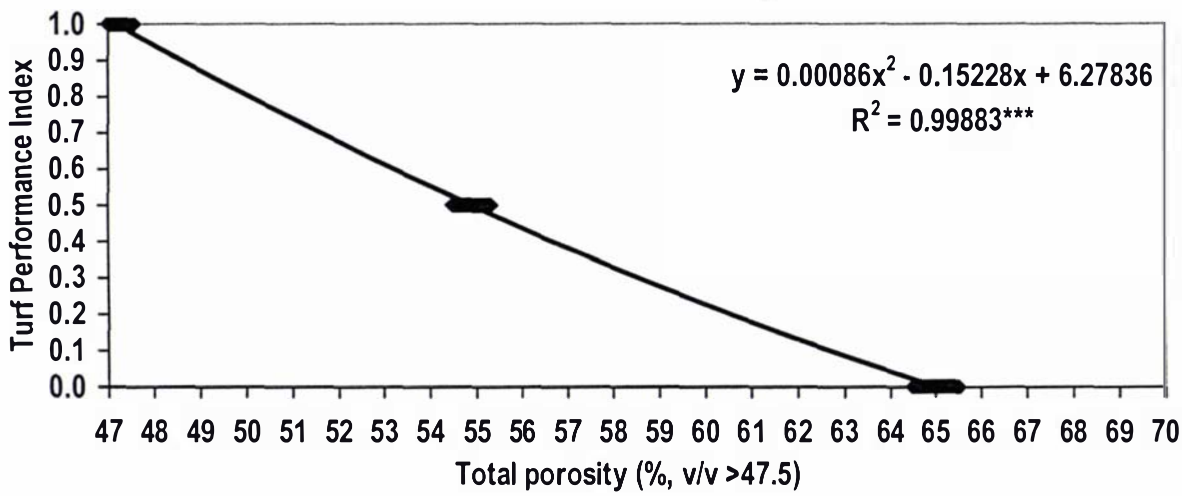


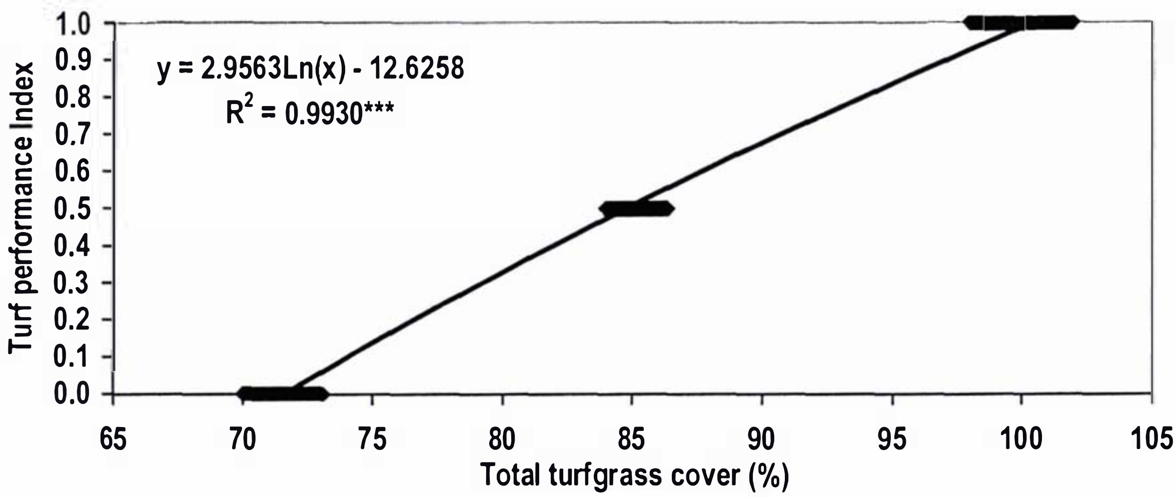



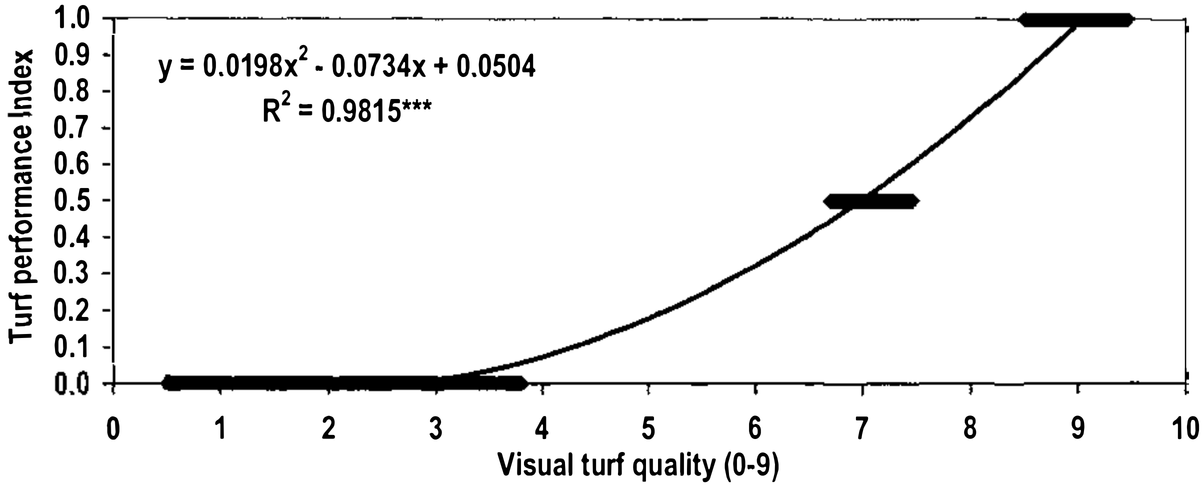

**Appendix Fig. 7-1a Development of statistical models for normalization of measurement values of each modeling factor**

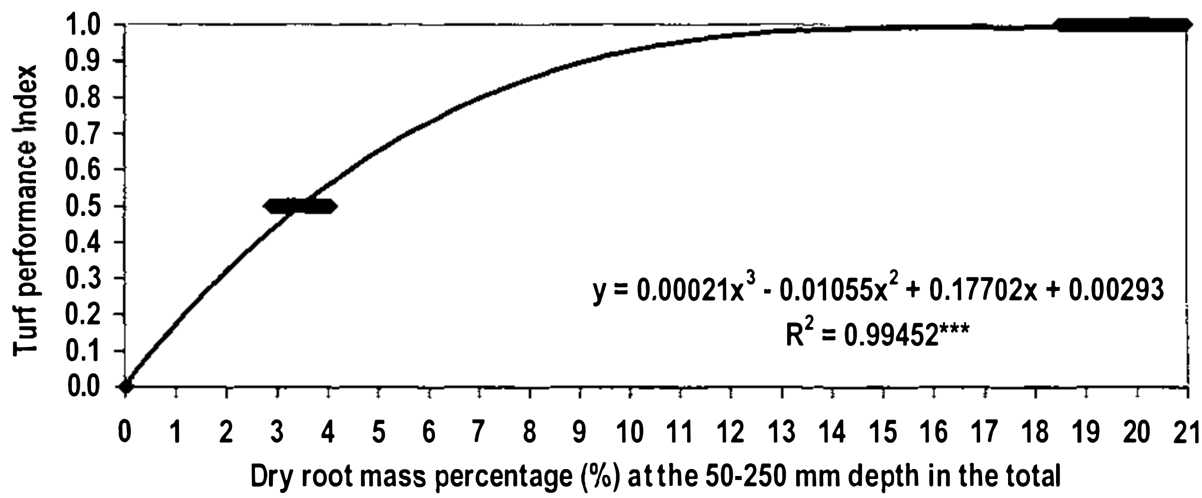


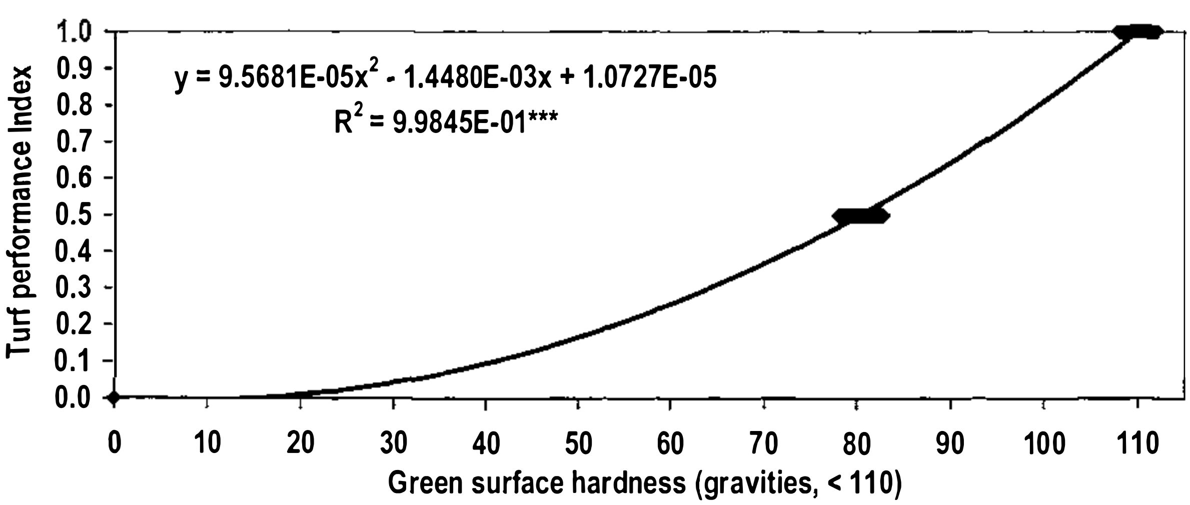



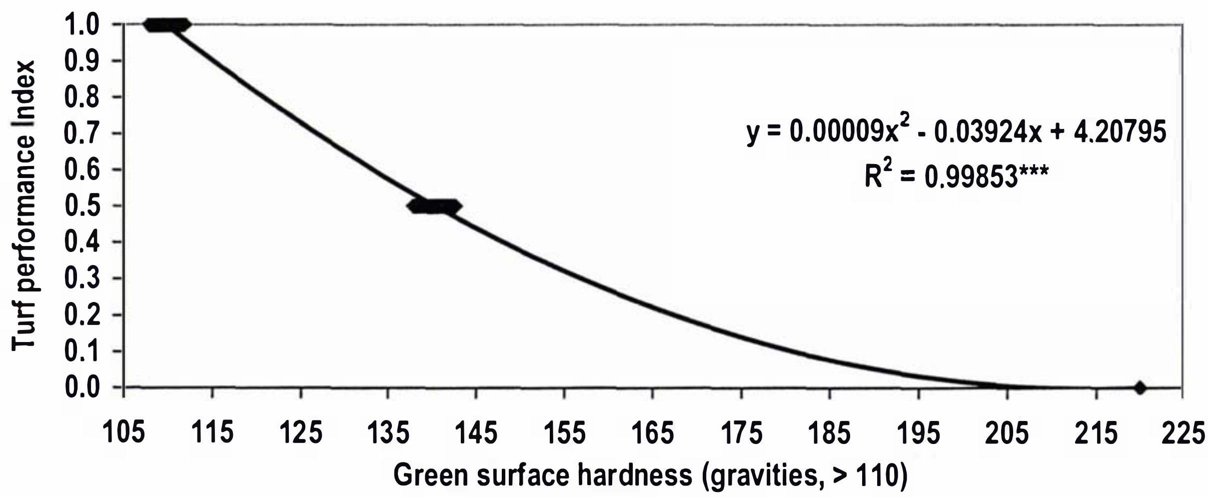

**Appendix Fig. 7-1b Development of statistical models for normalization of measurement values of each modeling factor**



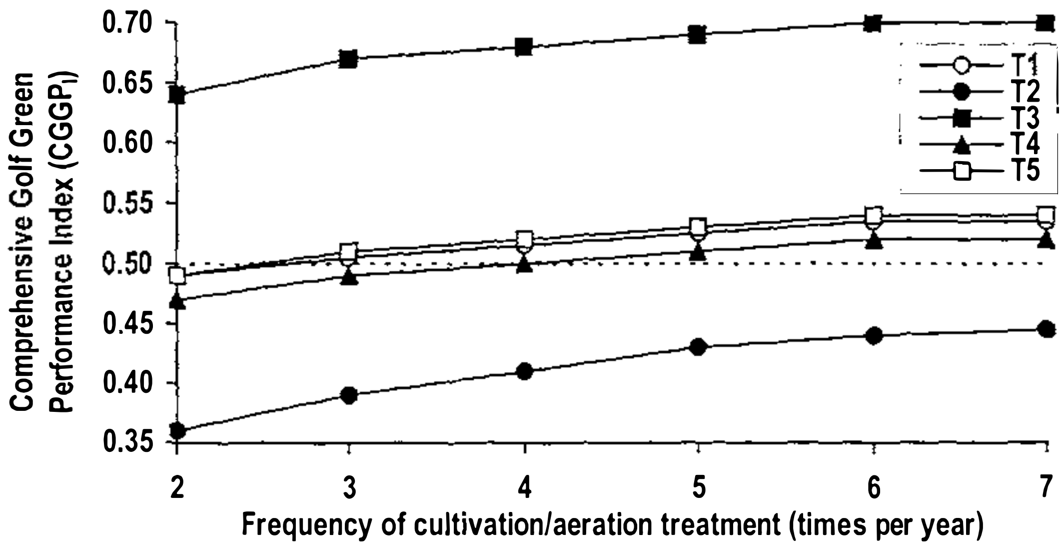



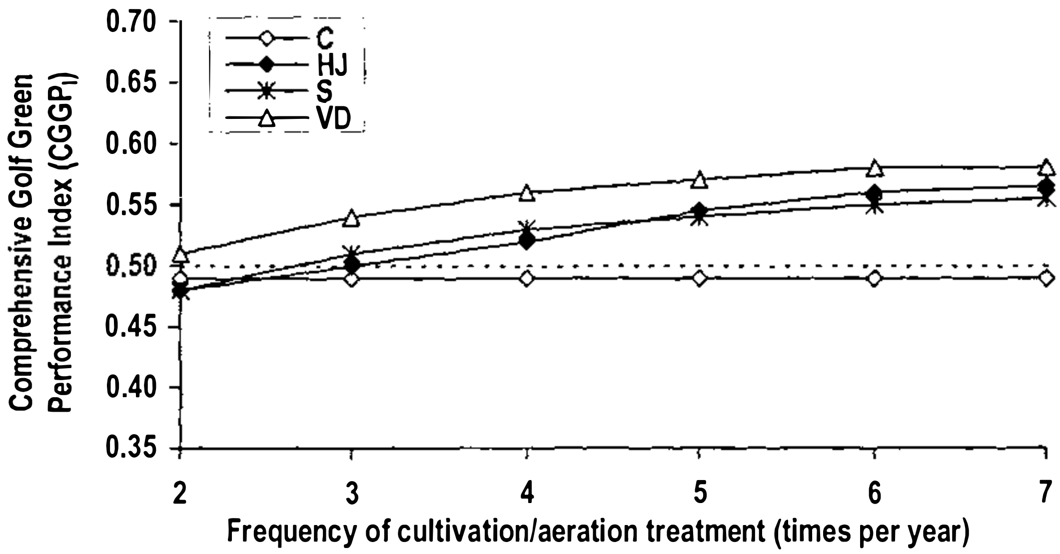




**Appendix Fig. 7-1c Development of statistical models for normalization of measurement values of each modeling factor**



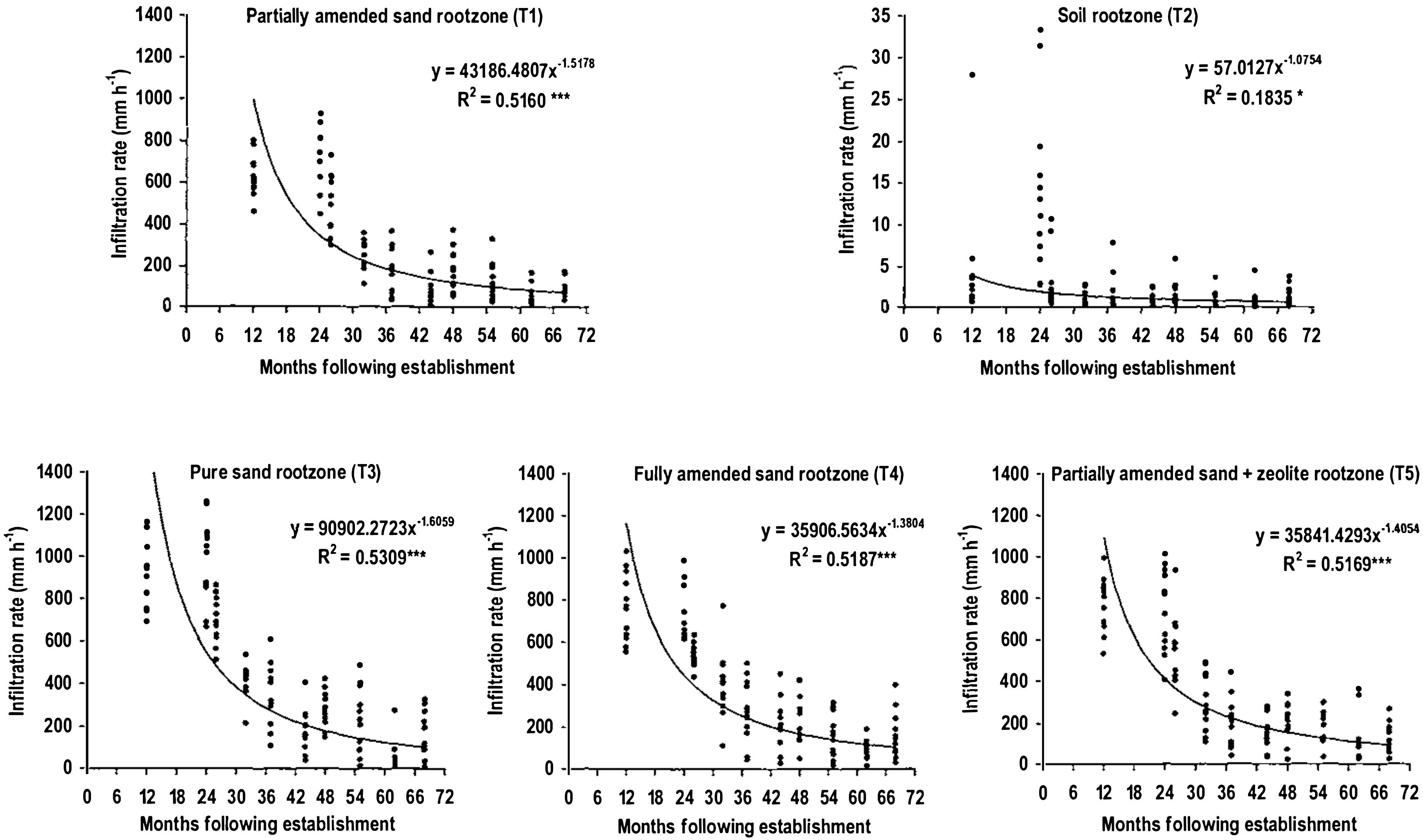

**Appendix Fig. 7-1d Development of statistical models for normalization of measurement values of each modeling factor**



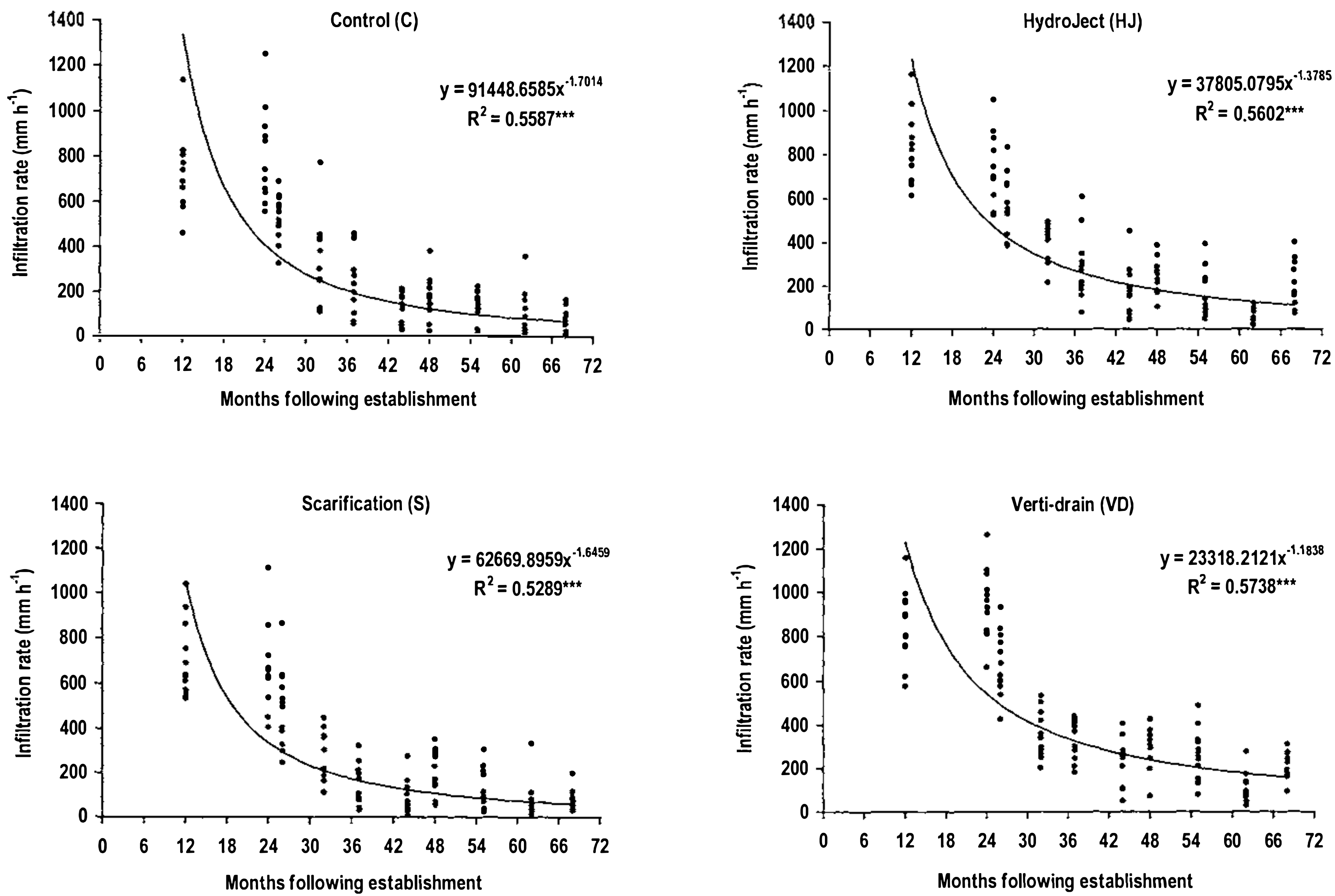




**Appendix Fig. 7-2 Changes in Comprehensive Golf Green Performance Index with frequency of cultivation/aeration treatment in relation to each rootzone type and cultivation/aeration treatment by the 15$^{th}$ year after sowing**

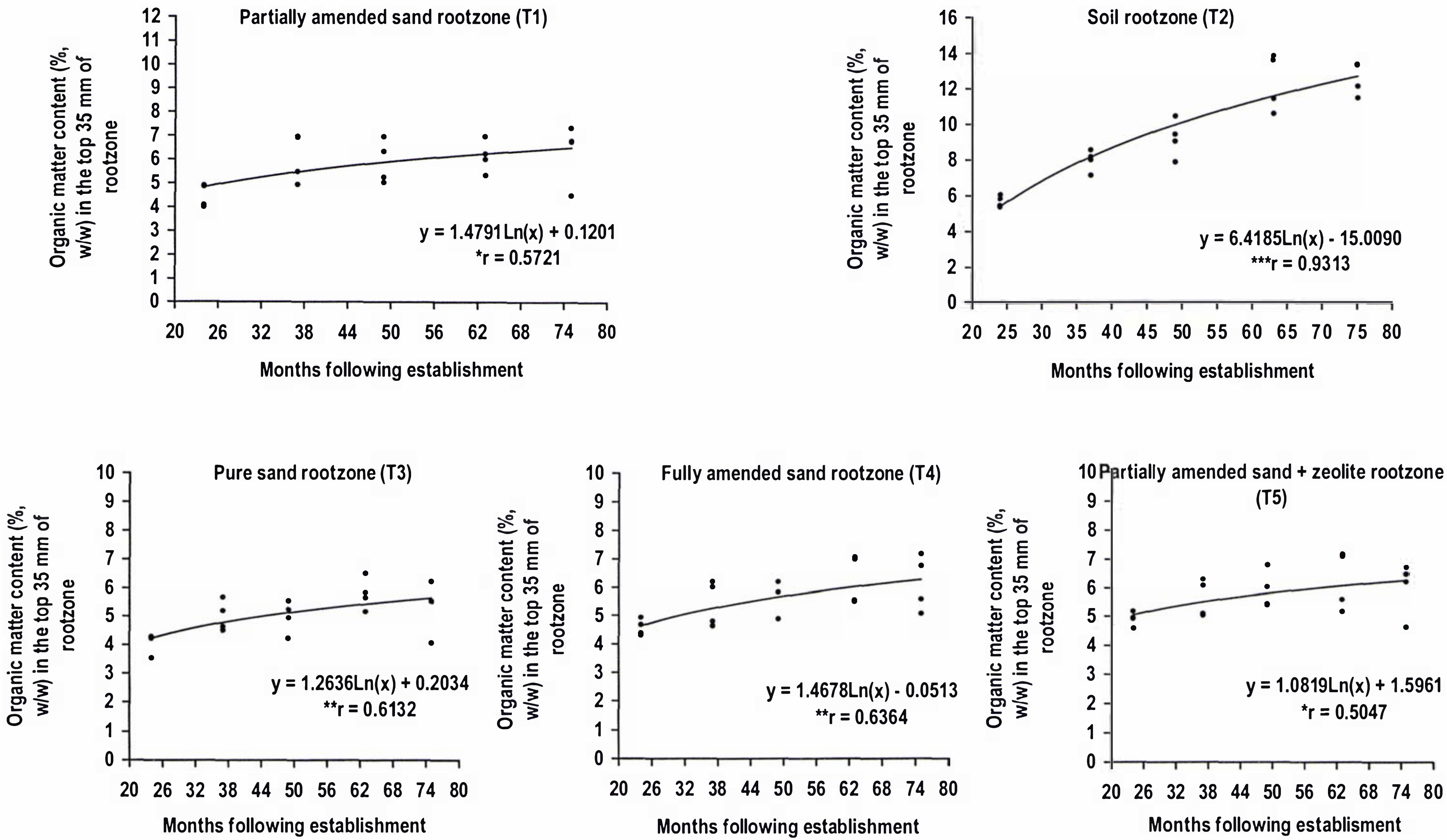
*The dotted line represents a Comprehensive Golf Green Performance Index value of 0.5, the recommended minimum acceptable value for New Zealand golf green turf. T1---Partially amended sand rootzone; T2---Soil rootzone; T3---Pure sand rootzone; T4---Fully amended sand rootzone; T5---Partially amended sand + zeolite rootzone. C---Control; HJ---HydroJect; S---Scarification; VD---Verti-drain.*



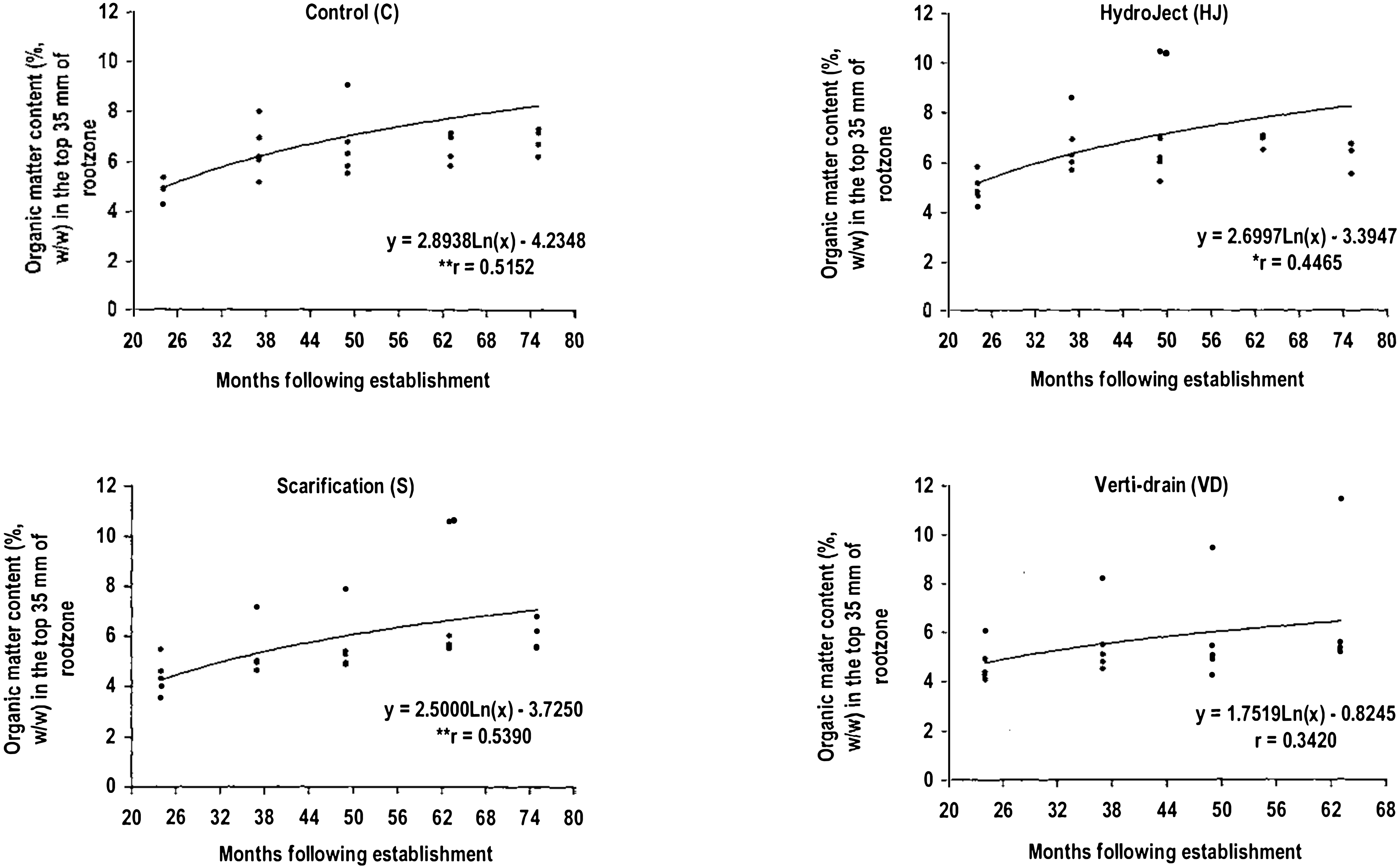

**Appendix Fig. 7-3a Natural diminishing equations for water infiltration rate after sowing in relation to each rootzone type and cultivation/aeration treatment**



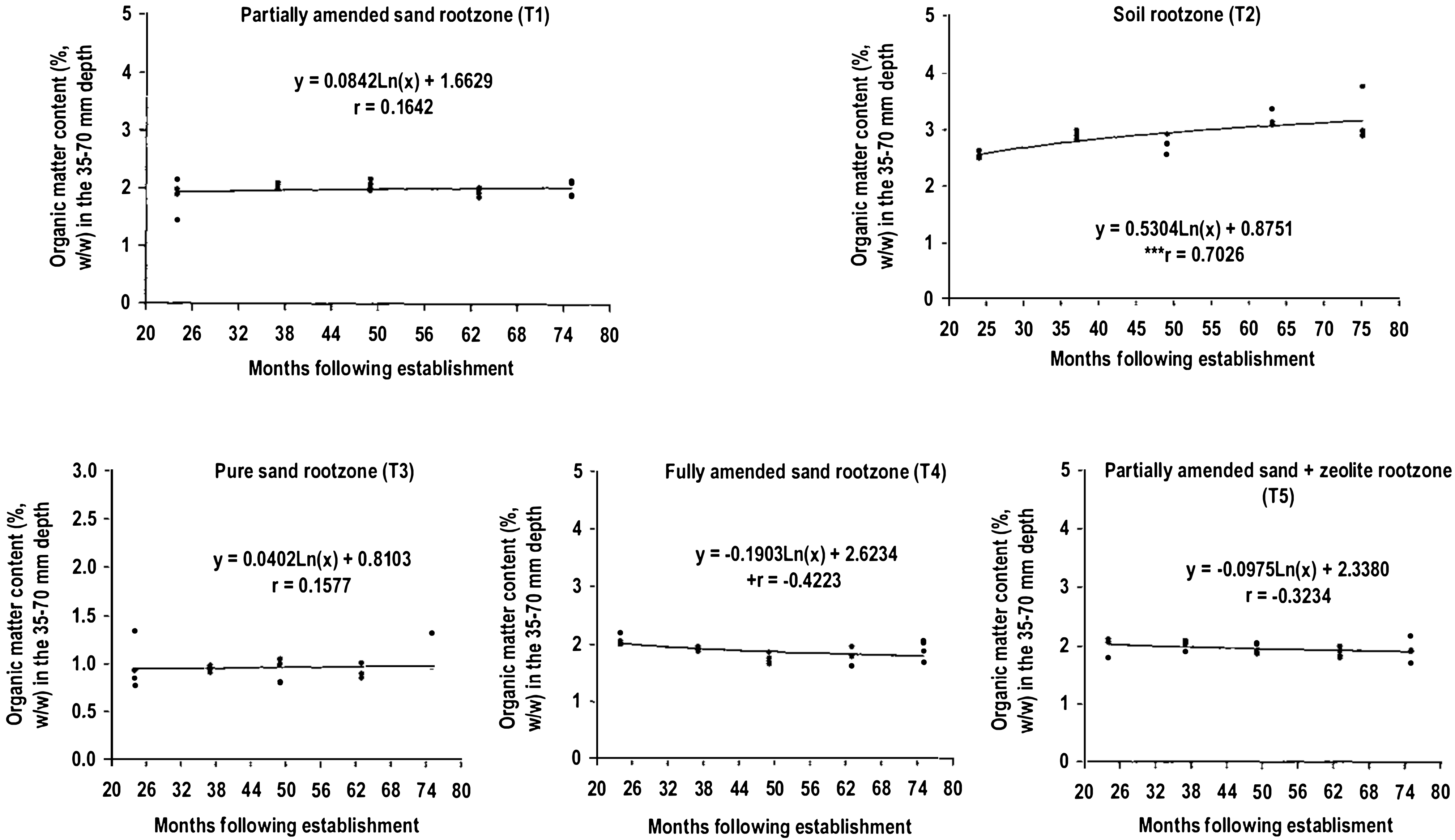

**Appendix Fig. 7-3b Natural diminishing equations for water infiltration rate after sowing in relation to each rootzone type and cultivation/aeration treatment**



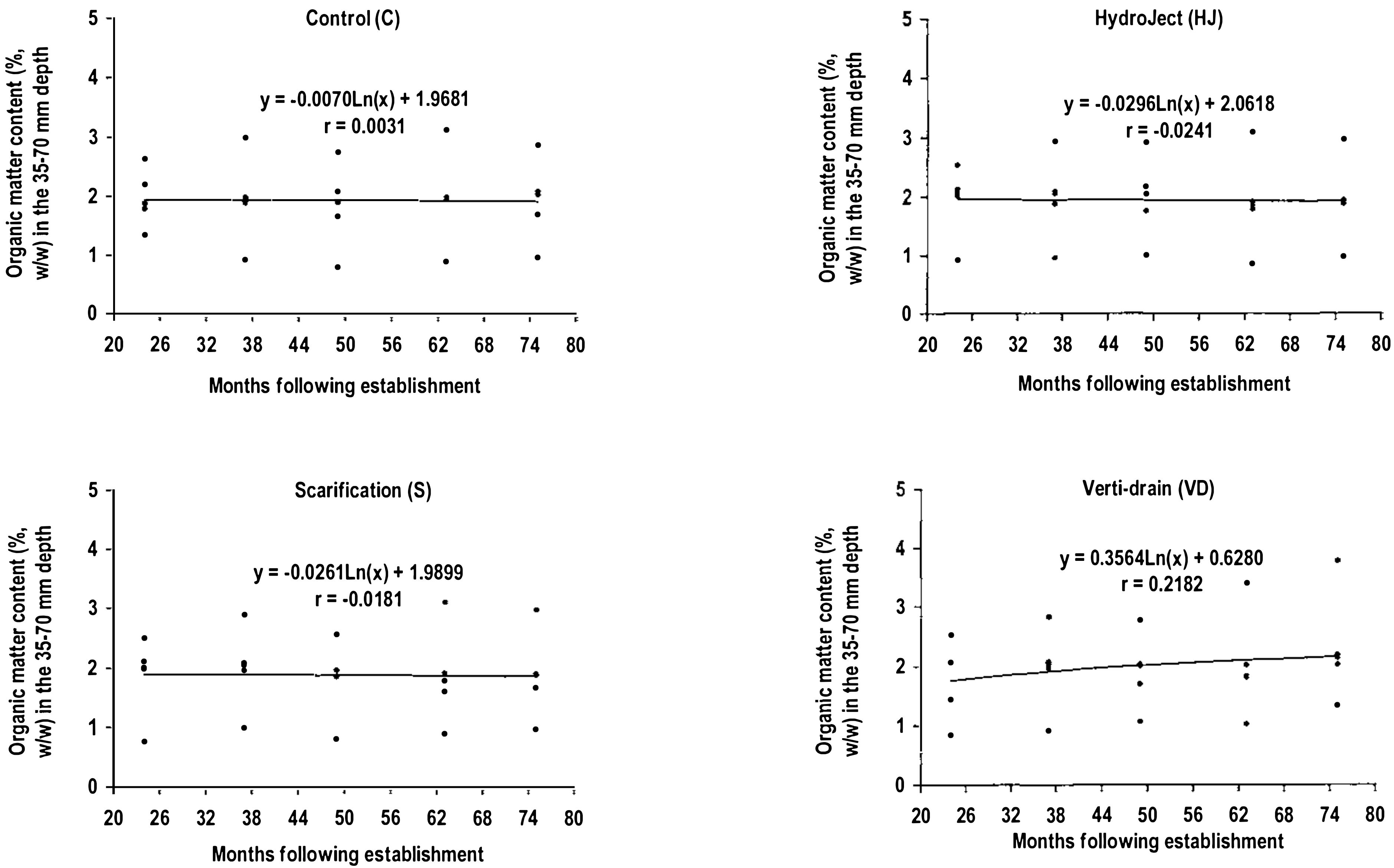

**Appendix Fig. 7-4a Natural diminishing equations for organic matter content (measured in the top 35 mm of rootzone) after sowing in relation to each rootzone type**



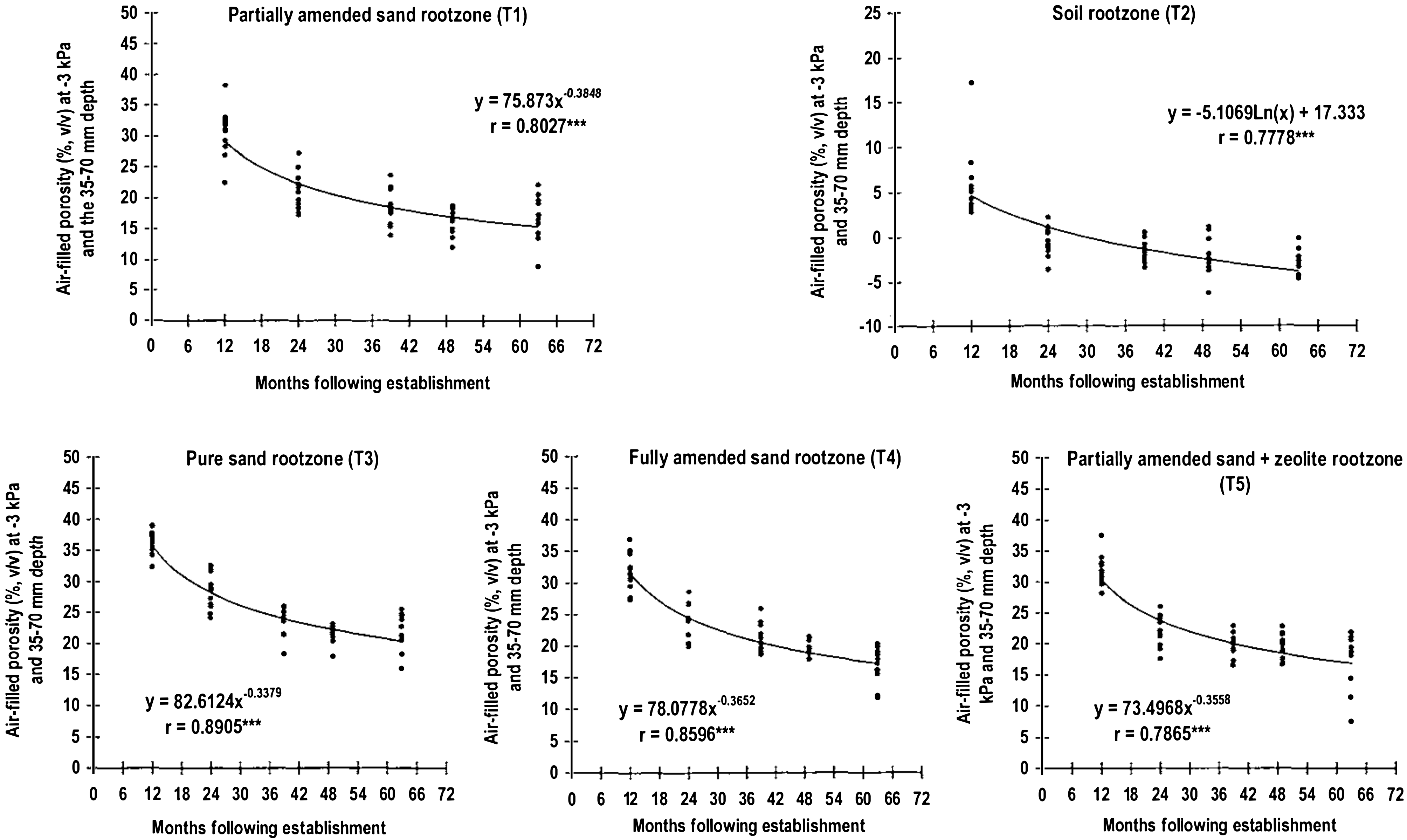

**Appendix Fig. 7-4b Natural diminishing equations for organic matter content (measured in the top 35 mm of rootzone) after sowing in relation to each cultivation/aeration treatment**



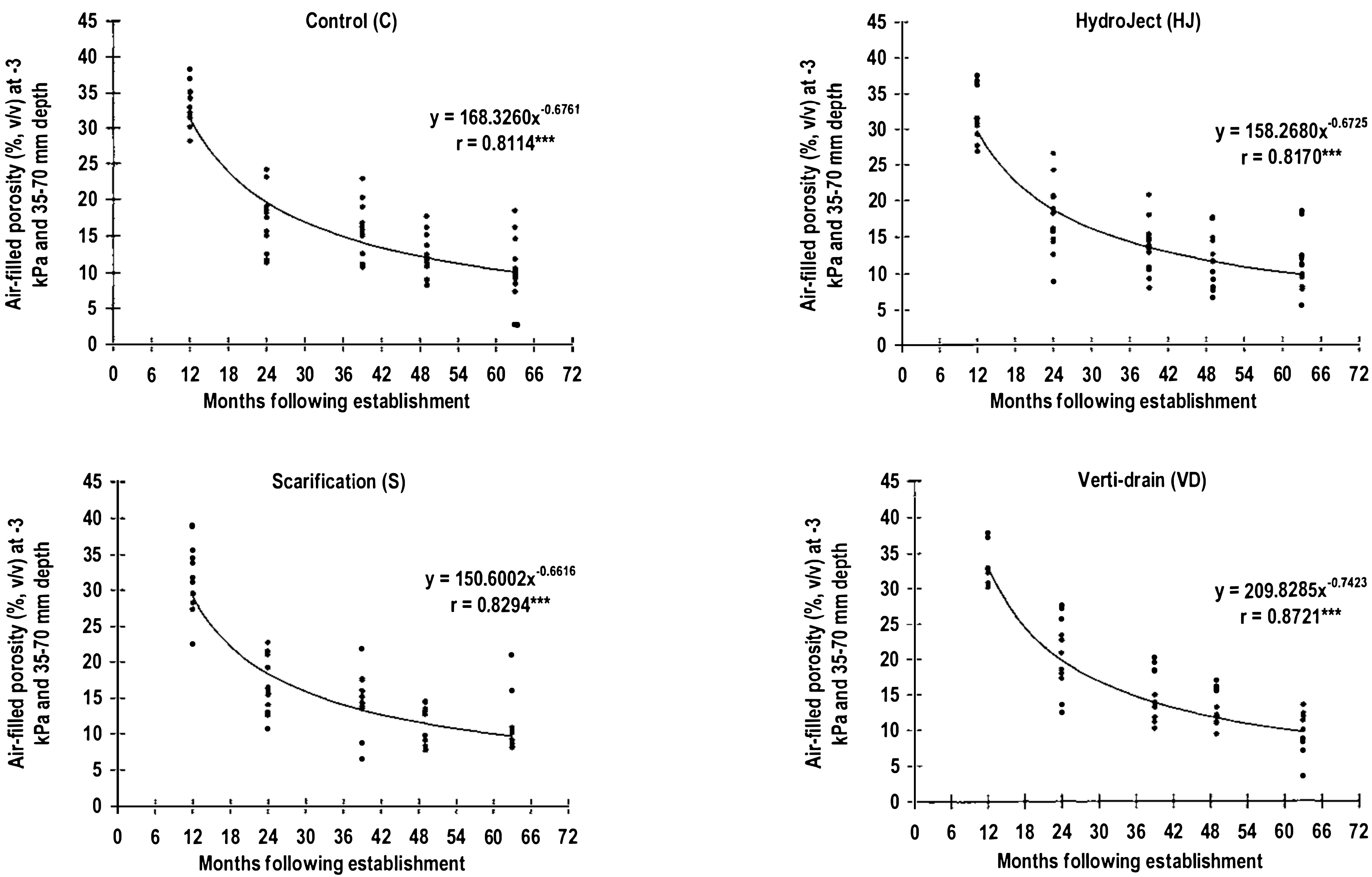

**Appendix Fig. 7-4c Natural diminishing equations for organic matter content (measured in the 35-70 mm of rootzone depth) after sowing in relation to each rootzone type**



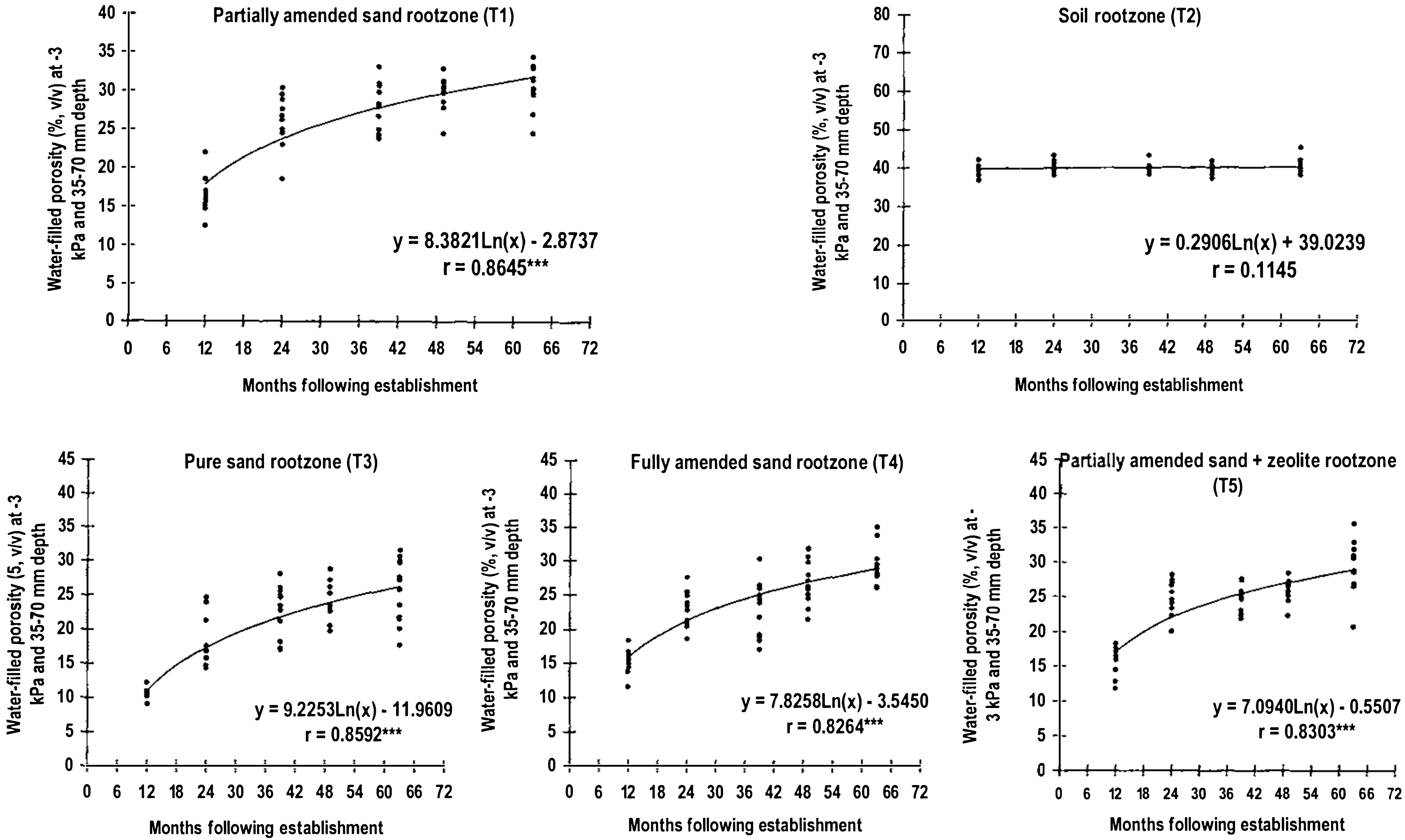

**Appendix Fig. 7-4d Natural diminishing equations for organic matter content (measured in the 35-70 mm of rootzone depth) after sowing in relation to each cultivation/aeration treatment**



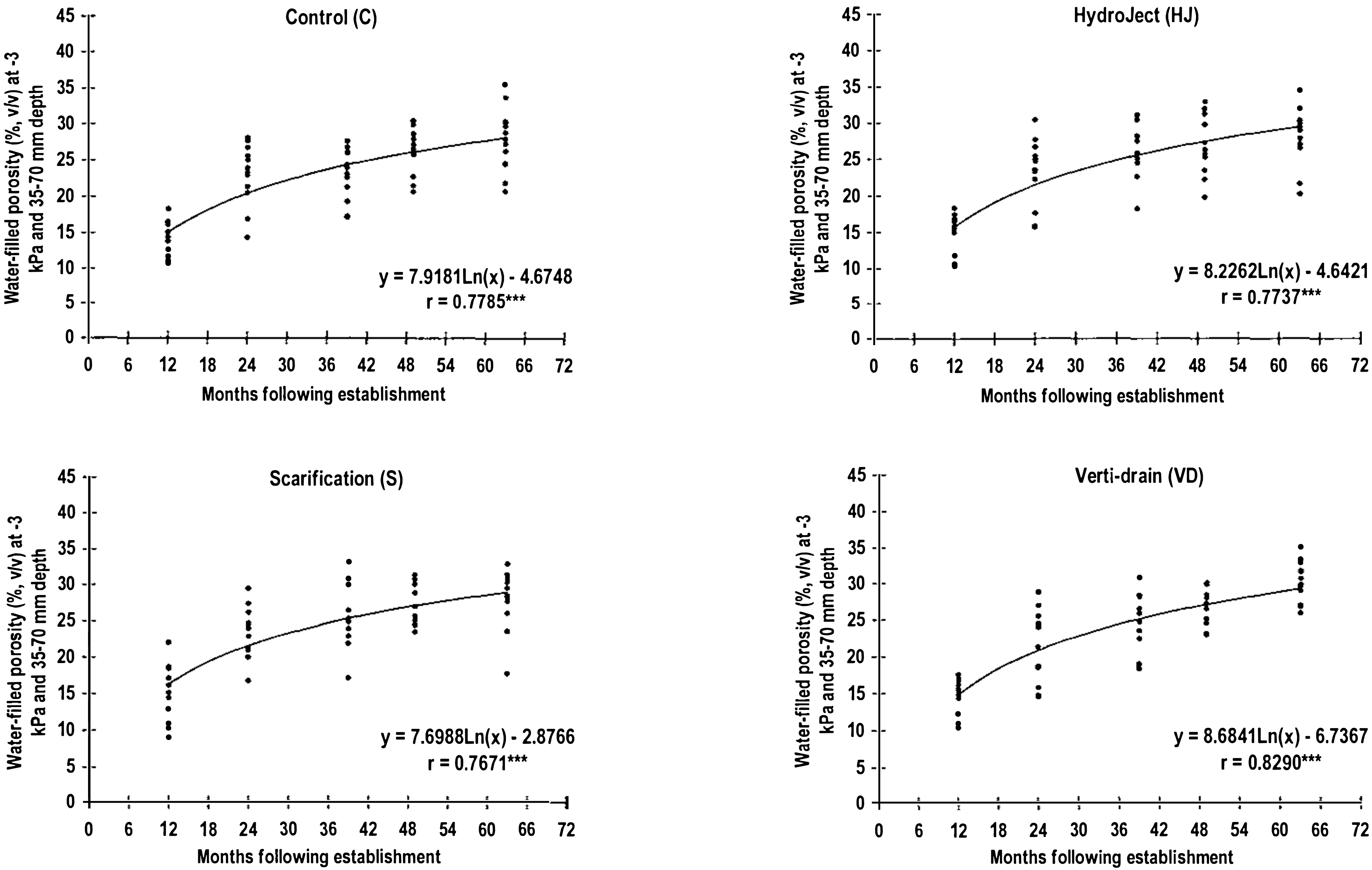

**Appendix Fig. 7-5a Natural diminishing equations for air-filled porosity (measured at -3 kPa in 35-70 mm rootzone depth) after sowing in relation to each rootzone type**



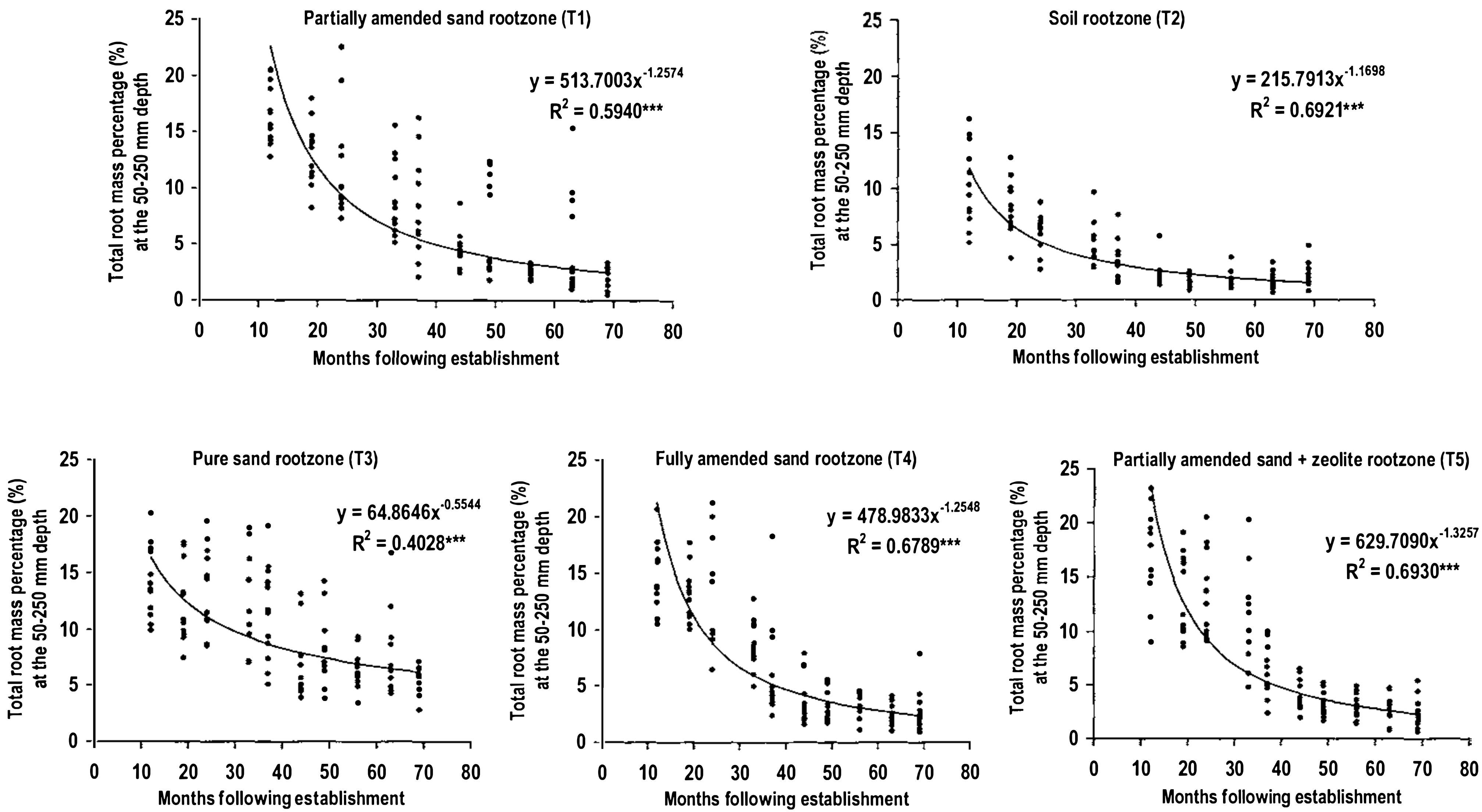

**Appendix Fig. 7-5b Natural diminishing equations for air-filled porosity (measured at -3 kPa in 35-70 mm rootzone depth) after sowing in relation to each cultivation/aeration treatment**



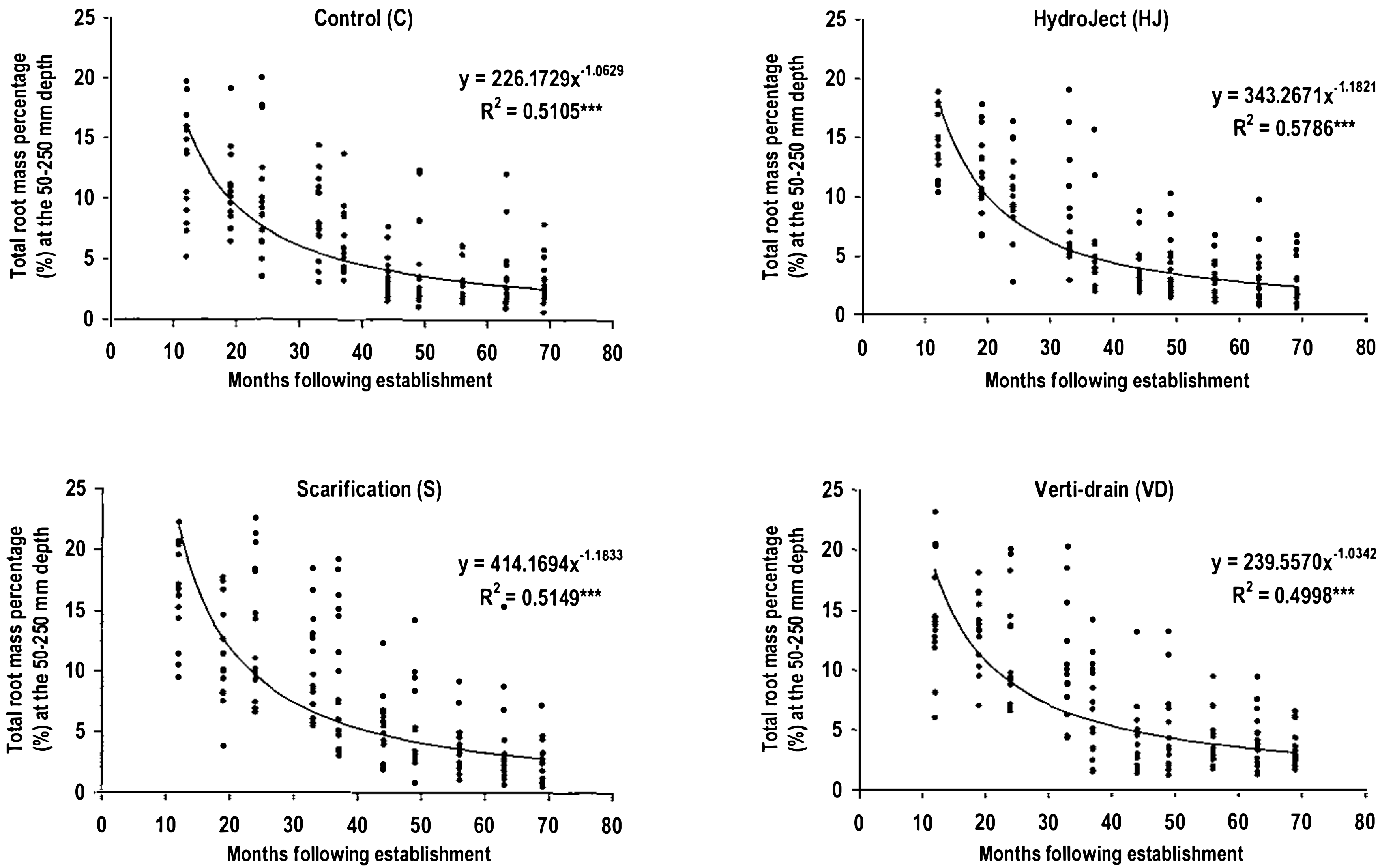

**Appendix Fig. 7-6a Natural diminishing equations for water-filled porosity (measured at -3 kPa in 35-70 mm rootzone depth) after sowing in relation to each rootzone type**



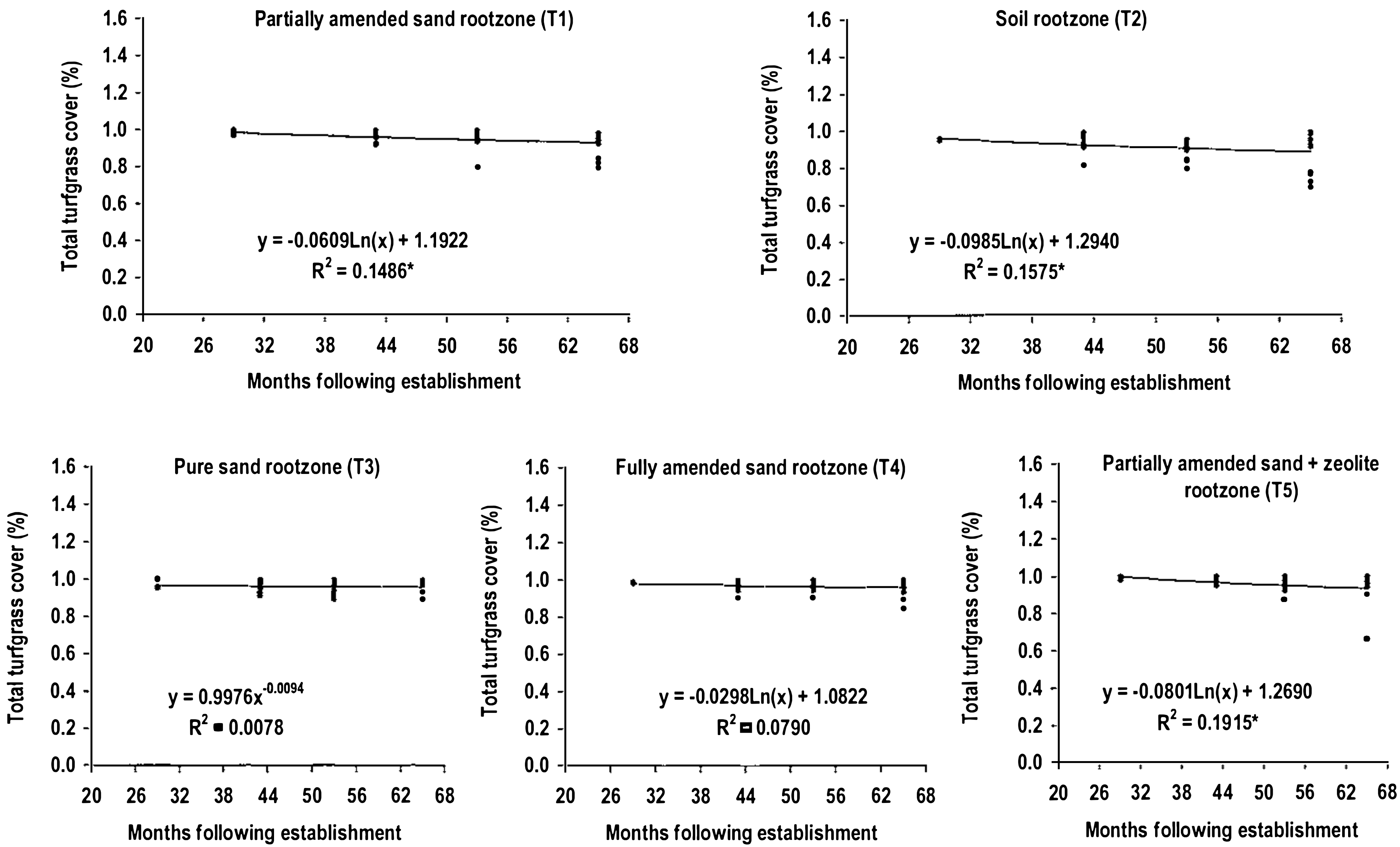

**Appendix Fig. 7-6b Natural diminishing equations for water-filled porosity (measured at -3 kPa in 35-70 mm rootzone depth) after sowing in relation to each cultivation/aeration treatment**



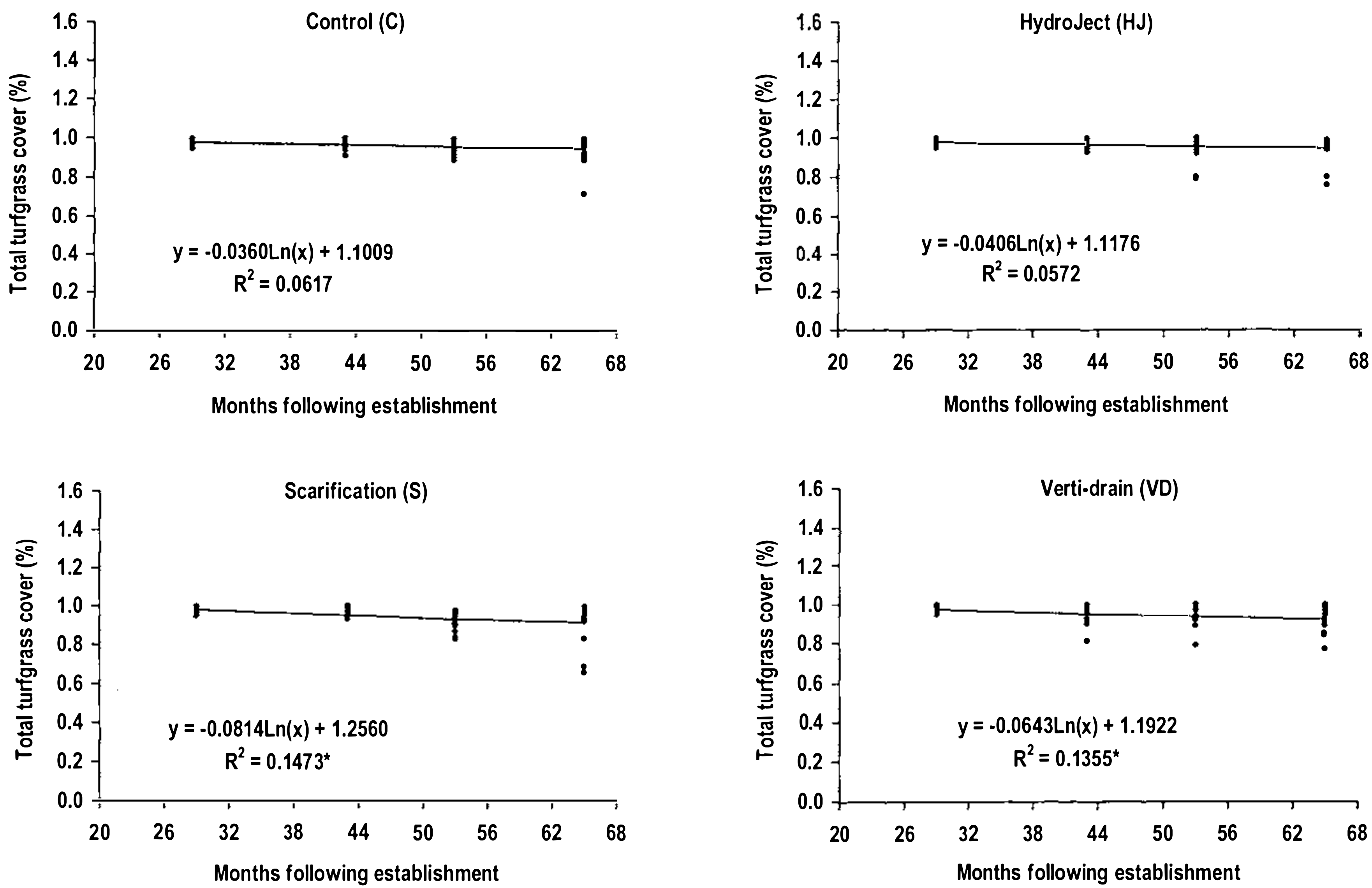

**Appendix Fig. 7-7a Natural diminishing equations for root mass distribution (percentage of root mass at 50-250 mm rootzone depth in the total) after sowing in relation to each rootzone type**



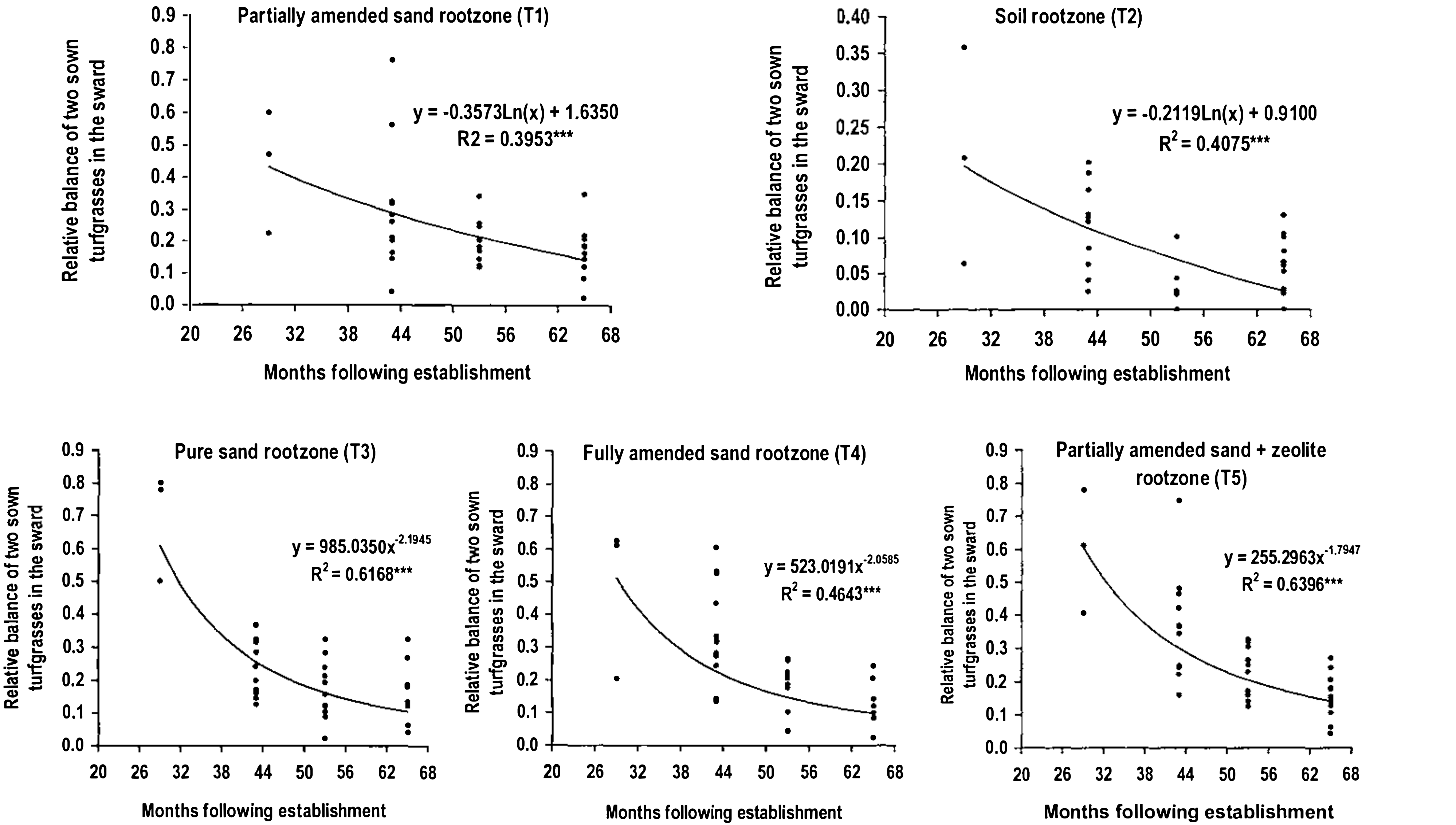

**Appendix Fig. 7-7b Natural diminishing equations for root mass distribution (percentage of root mass at 50-250 mm rootzone depth in the total) after sowing in relation to each cultivation/aeration treatment**



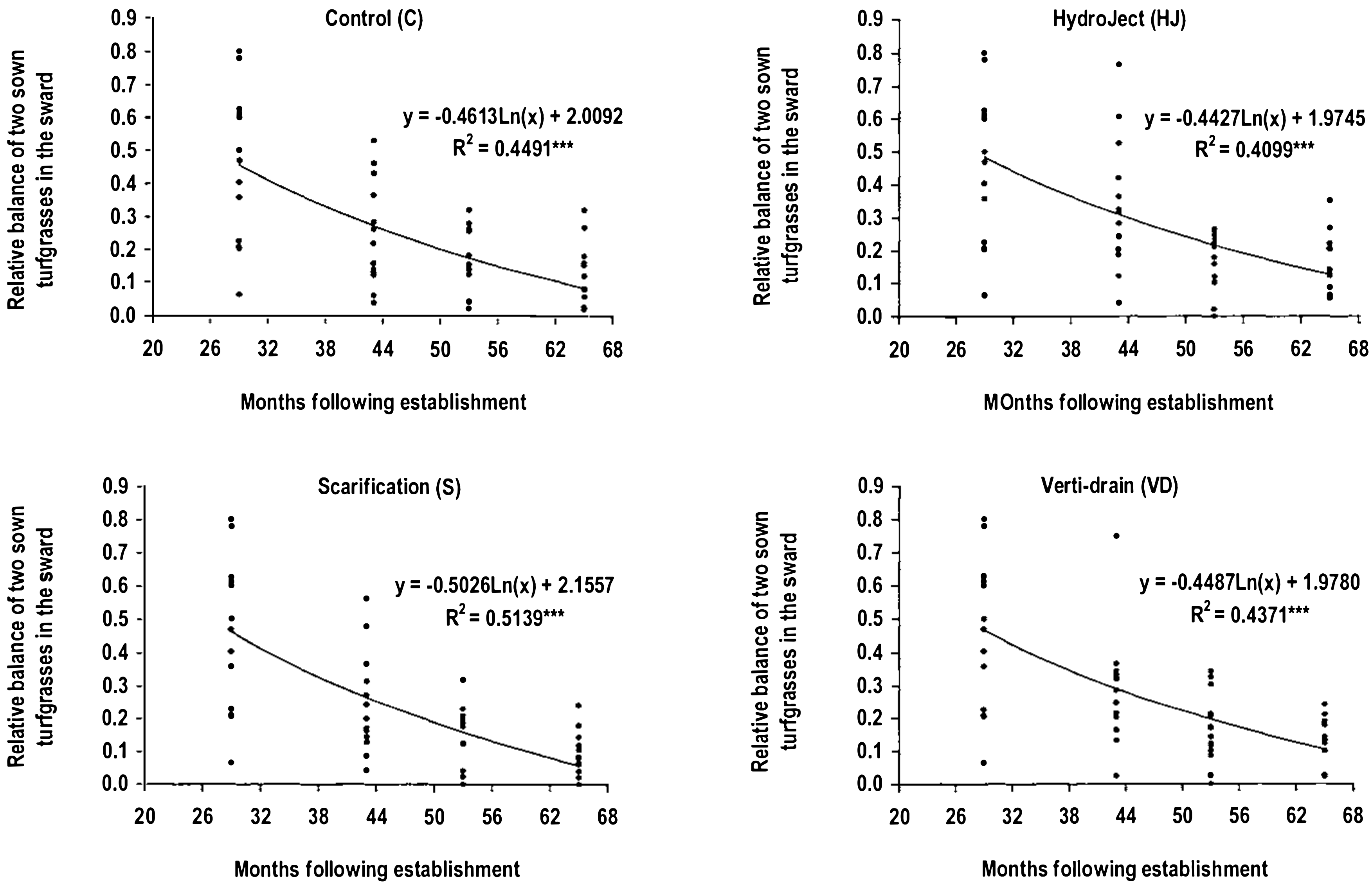

**Appendix Fig. 7-8a Natural diminishing equations for total turfgrass cover after sowing in relation to each rootzone type**



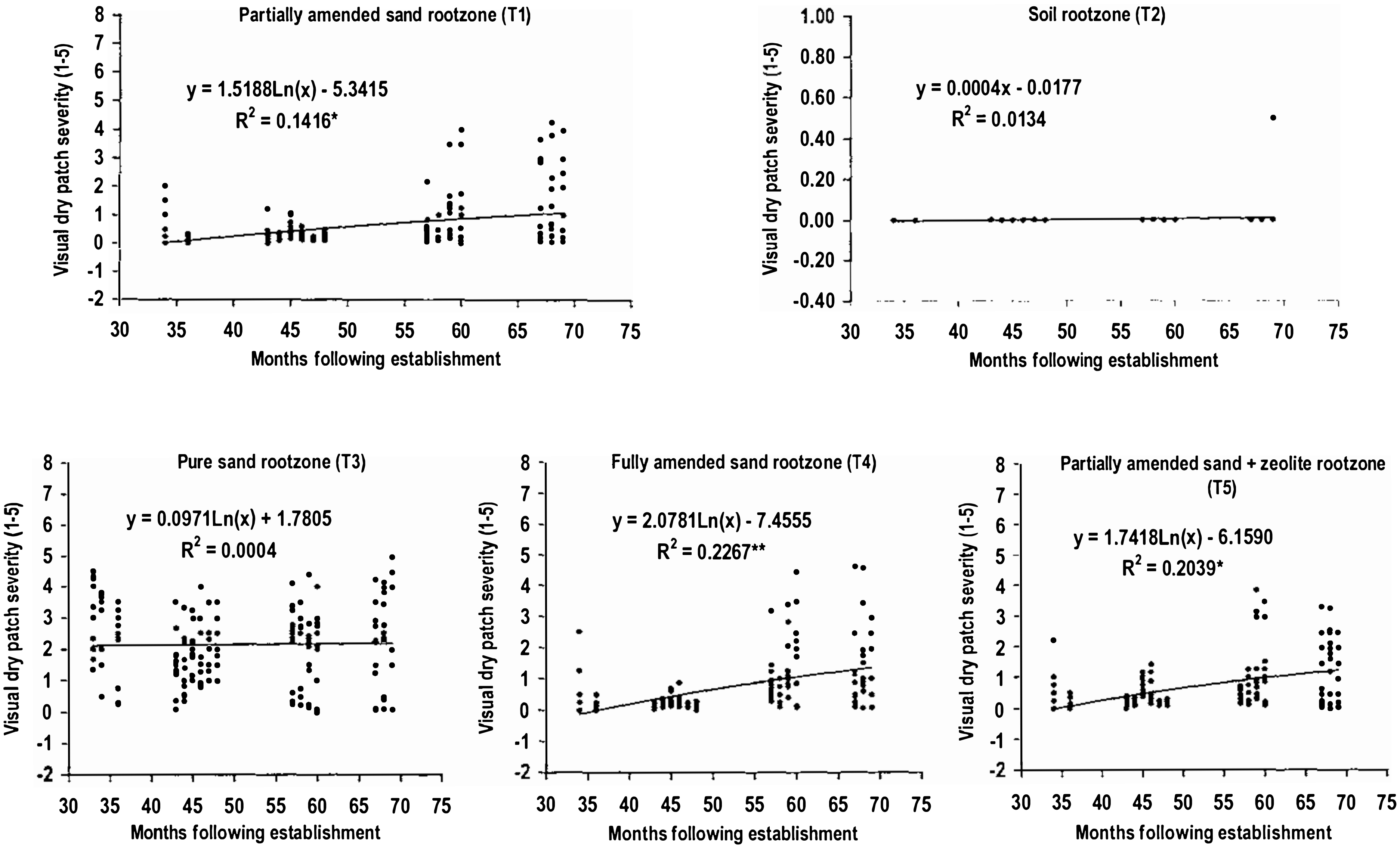

**Appendix Fig. 7-8b Natural diminishing equations for total turfgrass cover and after sowing in relation to each cultivation/aeration treatment**



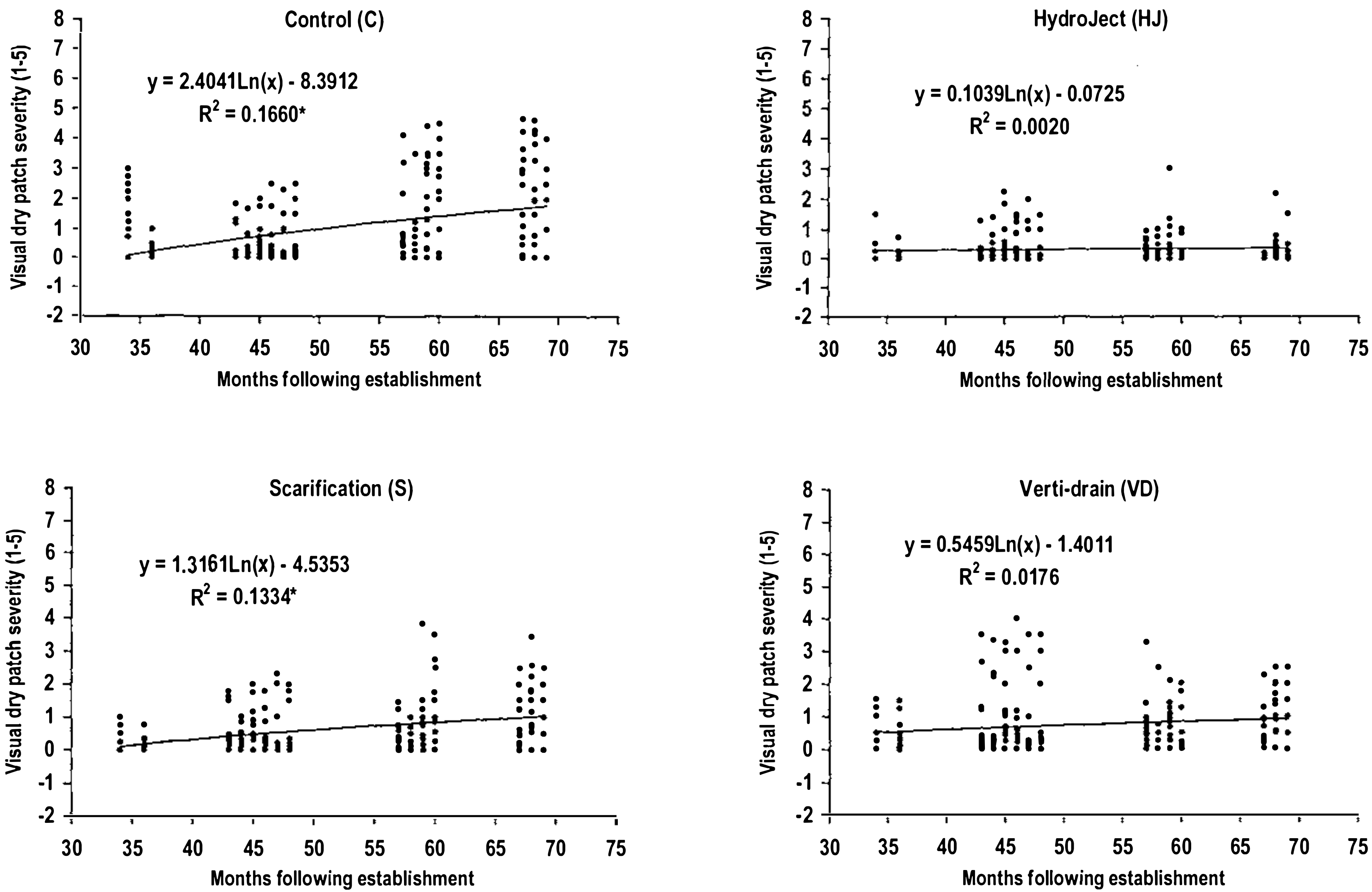

**Appendix Fig. 7-8c Natural diminishing equations for relative balance of two sown turfgrasses in the sward after sowing in relation to each rootzone type**



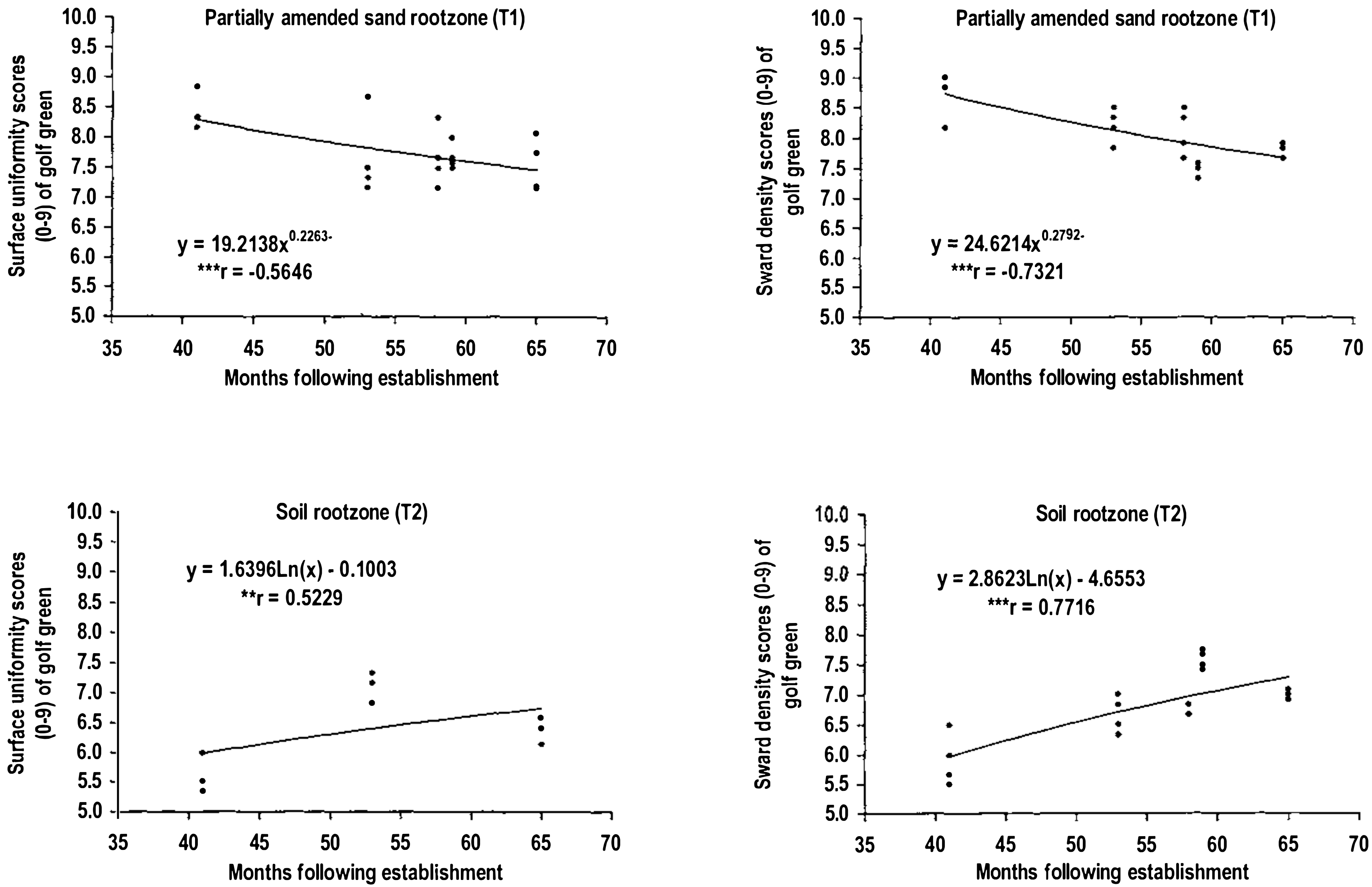

**Appendix Fig. 7-8d Natural diminishing equations for relative balance of two sown turfgrasses in the sward after sowing in relation to each cultivation/aeration treatment**



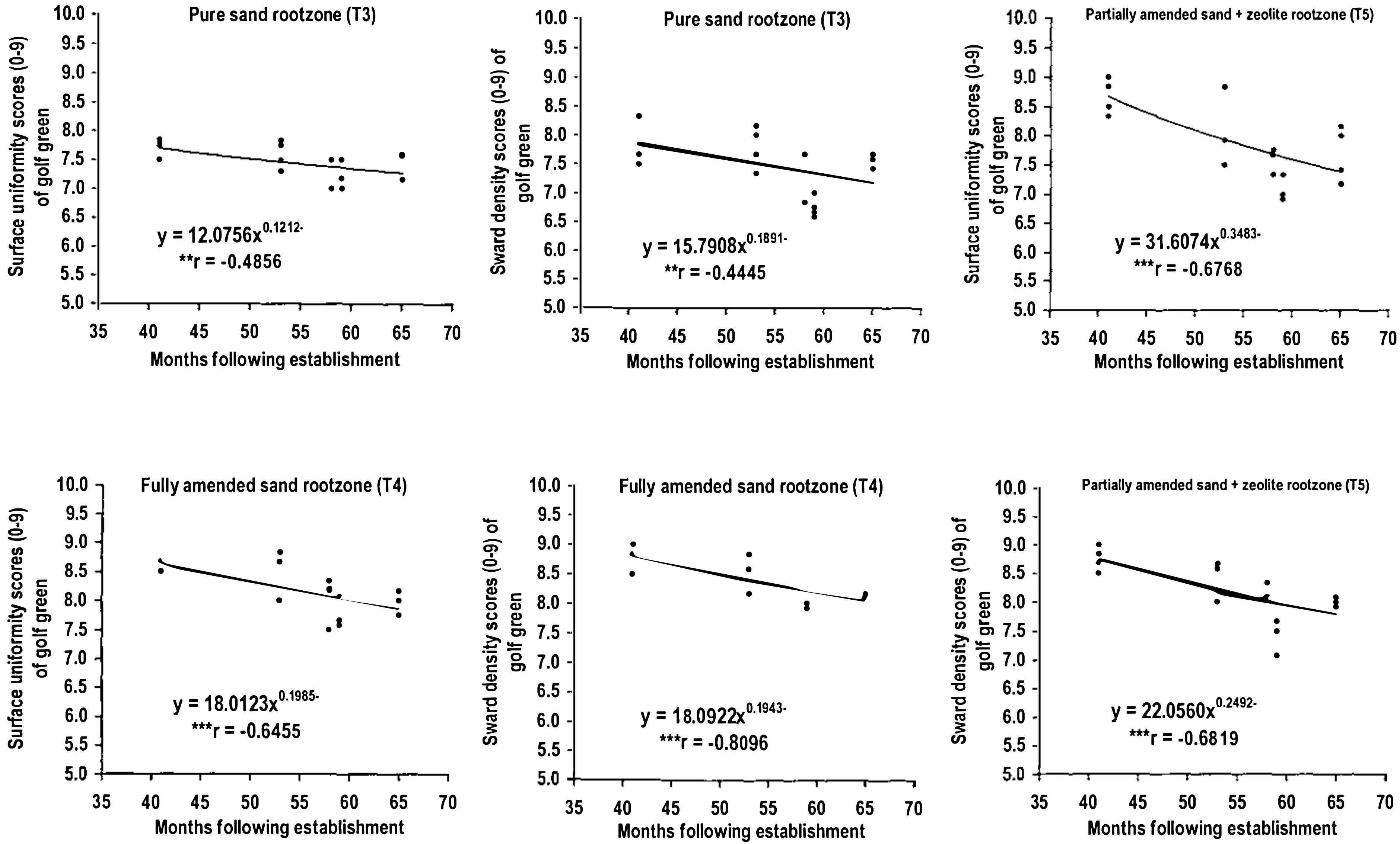

**Appendix Fig. 7-9a Natural diminishing equations for dry patch severity after sowing in relation to each rootzone type**



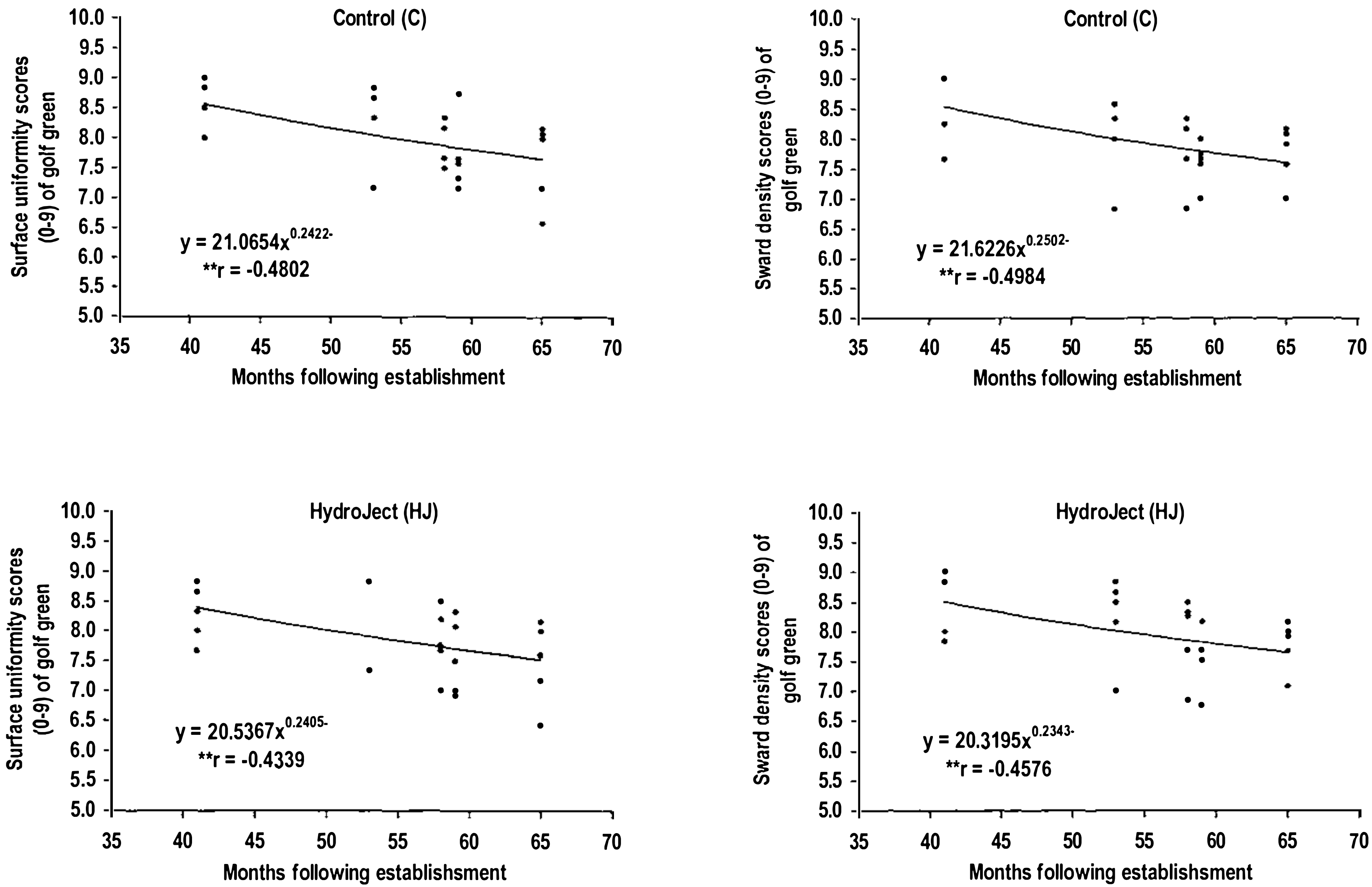

**Appendix Fig. 7-9b Natural diminishing equations for dry patch severity after sowing in relation to each cultivation/aeration treatment**



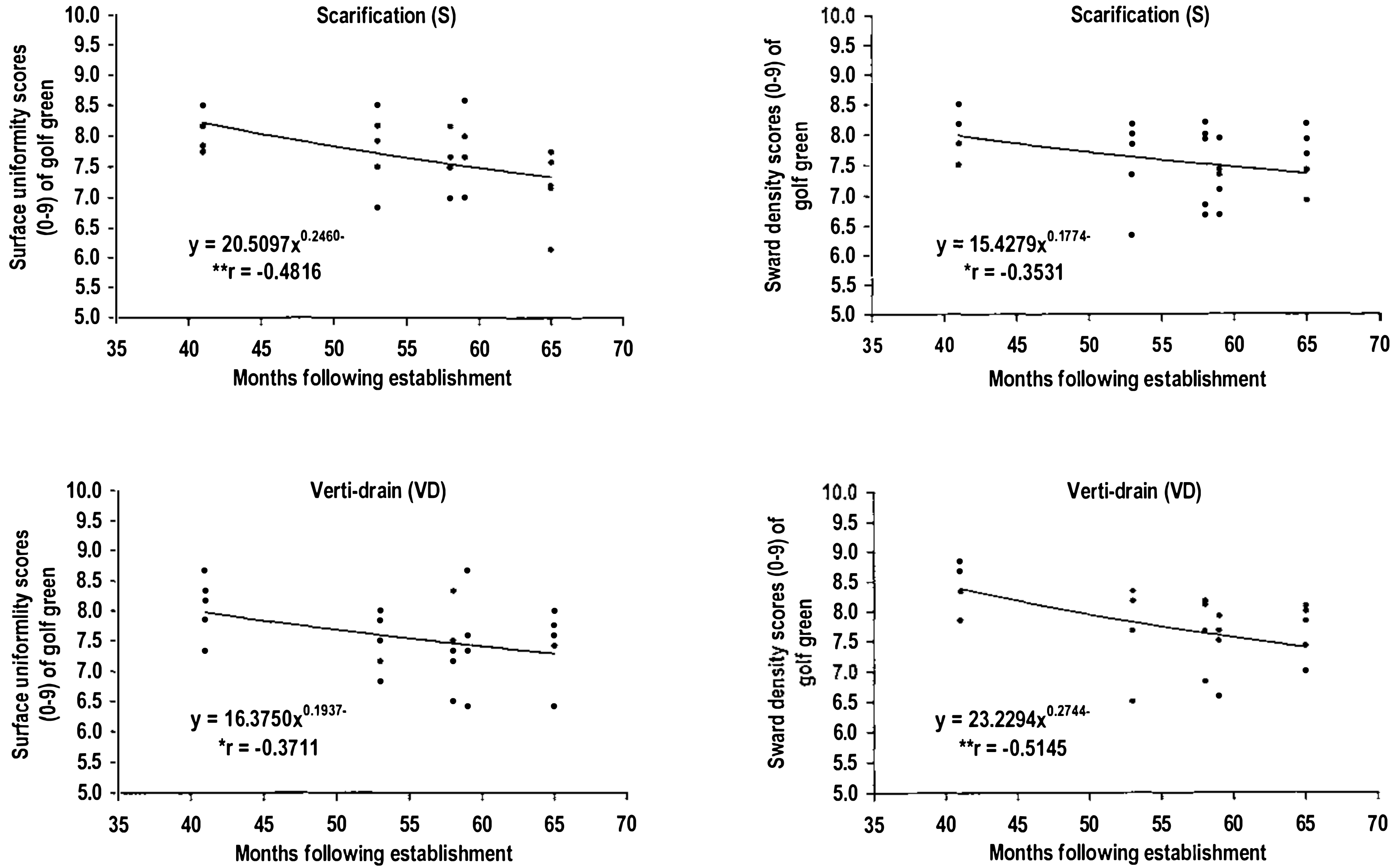

**Appendix Fig. 7-10a Natural diminishing equations for visual turf quality (uniformity and density) after sowing in relation to each rootzone type**



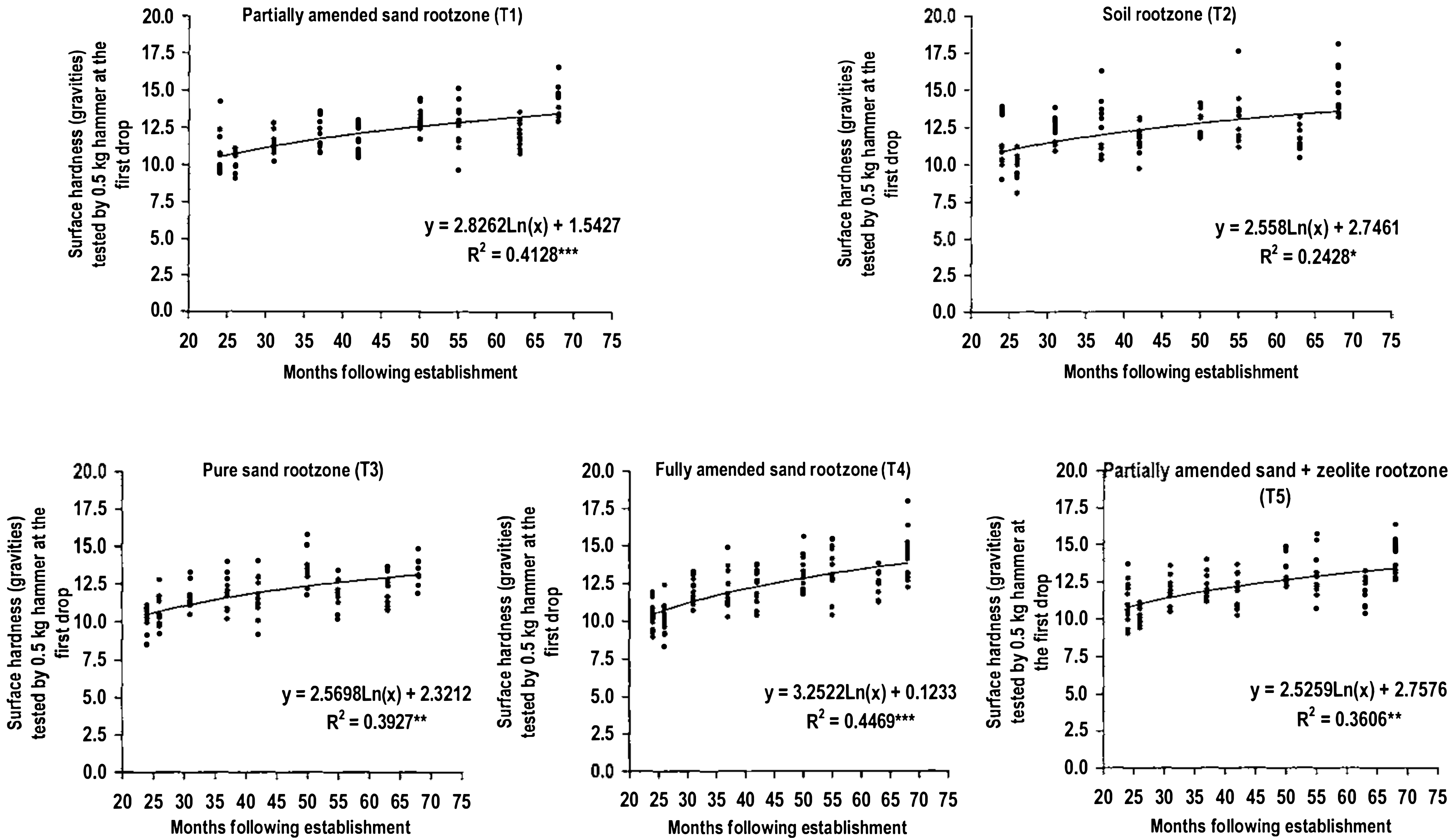

**Appendix Fig. 7-10b Natural diminishing equations for visual turf quality (uniformity and density) after sowing in relation to each rootzone type**



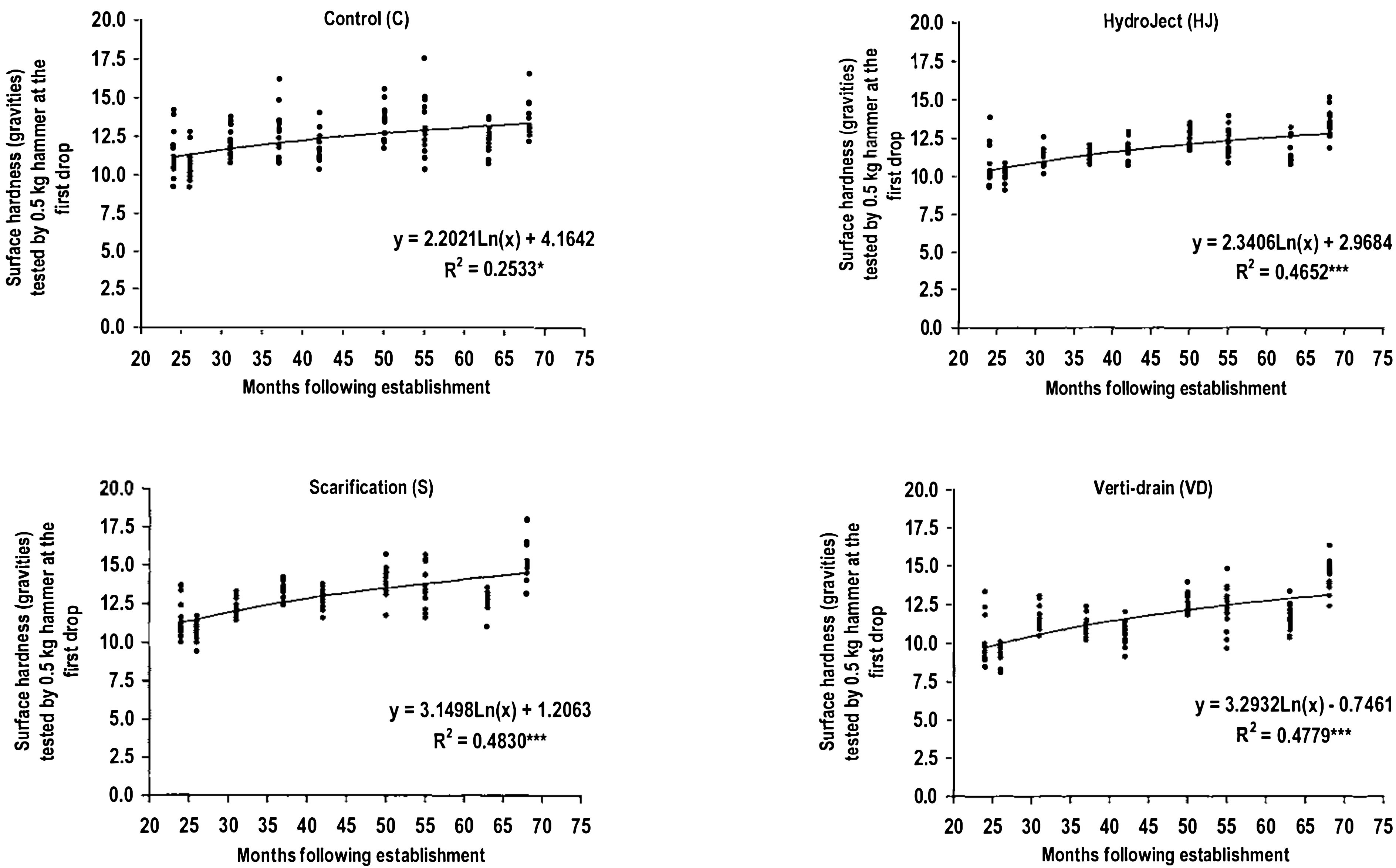

**Appendix Fig. 7-10c Natural diminishing equations for visual turf quality (uniformity and density) after sowing in relation to each cultivation/aeration treatment**



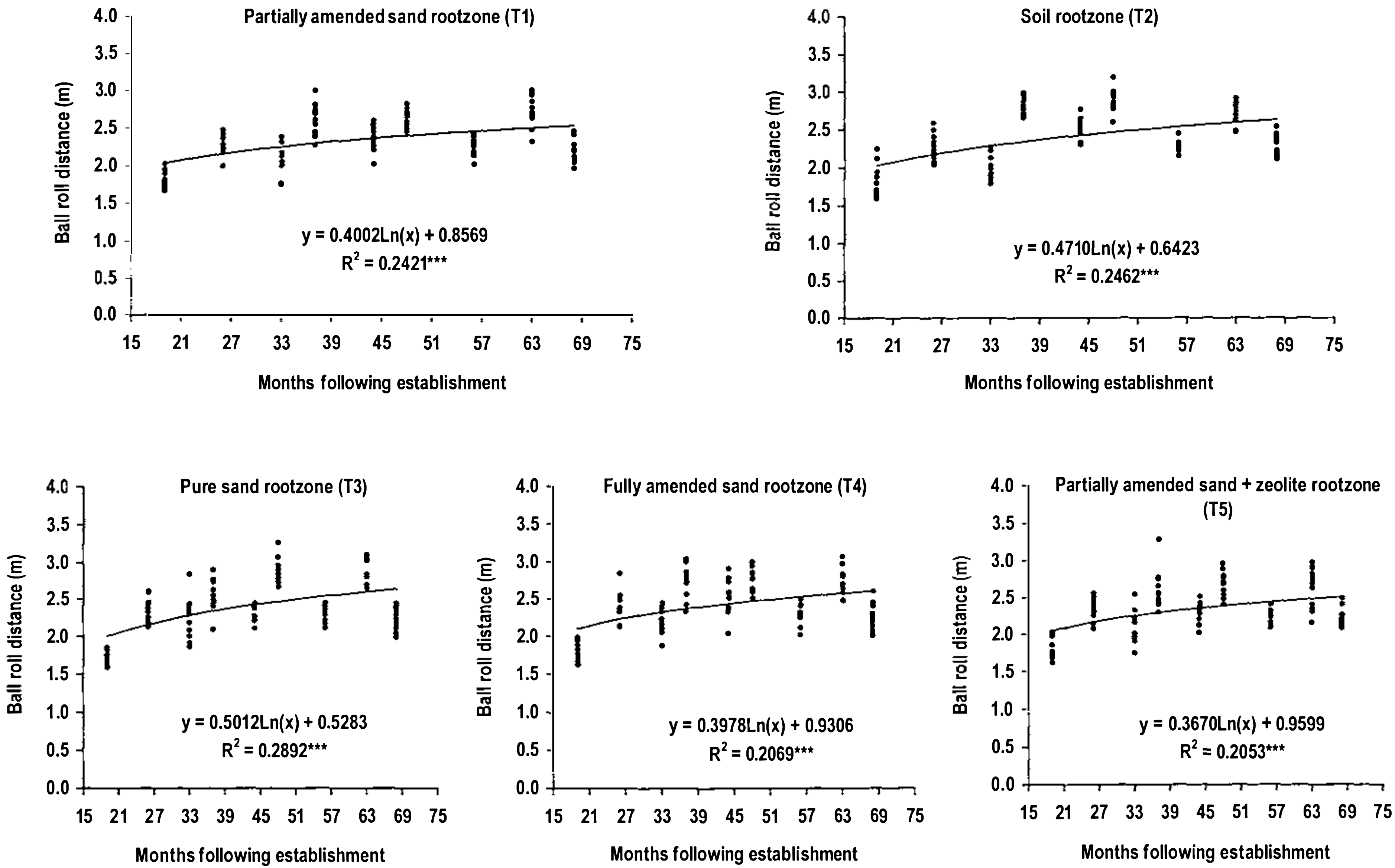

**Appendix Fig. 7-10d Natural diminishing equations for visual turf quality (uniformity and density) after sowing in relation to each rootzone type and cultivation/aeration treatment**



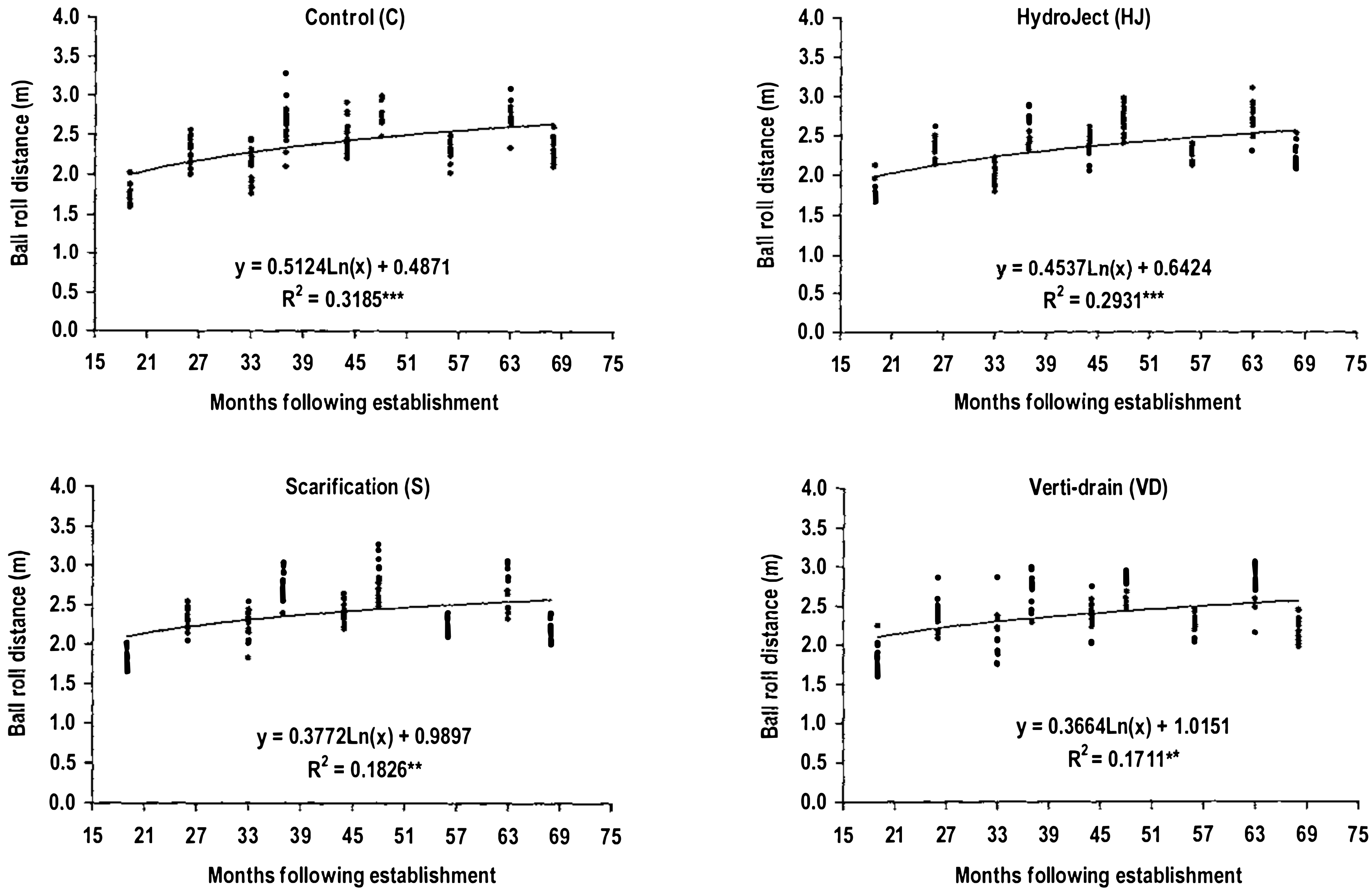

**Appendix Fig. 7-11a Natural diminishing equations for green surface hardness after sowing in relation to each rootzone type**




**Appendix Fig. 7-11b Natural diminishing equations for green surface hardness after sowing in relation to each cultivation/aeration treatment**




**Appendix Fig. 7-12a Natural diminishing equations for green speed after sowing in relation to each rootzone type**




**Appendix Fig. 7-12b Natural diminishing equations for green speed after sowing in relation to each cultivation/aeration treatment**