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THE ARCHITECTURE AND RADIATION REGIME OF A KIWIFRUIT STAND

A thesis presented in partial fulfilment

of the requirements for the degree of

MASTER OF SCIENCE

in

PLANT SCIENCE

at

MASSEY UNIVERSITY

EDMOND ROBERT MORGAN

1988

Abstract

The theory of the interrelations between plant canopy structure and light penetration is reviewed using principles developed for point quadrat analysis. Estimates of leaf area index and leaf orientation can in principle be obtained from measurements of the average transmission of direct sunlight through vegetation using an indirect measurement procedure. The architecture of a kiwifruit (Actinidia deliciosa (A. Chev) C.F. Liang et A.R. Ferguson c.v. Hayward) canopy was measured using direct methods and the indirect measurement procedure. The methods gave good agreement for estimates of the mean leaf angle and the G-function. However the indirect procedure produced values for the leaf area index that were about 1.7 times greater than those obtained from direct methods. This was consistent over a range of leaf area indices (measured directly) from 1.7 to 3.5. The evidence provided suggests that this discrepancy is most likely due to the leaves in the canopy having a regular distribution rather than being randomly arranged.

The Poisson law and the positive and negative binomial models provided the basis for further analysis of light penetration into plant stands. The results were compared with observed values of light transmission through the canopy. It was suggested that the measured values of light transmission could be used in conjunction with expected values of light transmission calculated from the direct measurements of canopy architecture to estimate leaf distribution in the canopy. The distribution of leaves in a stand could be determined at two levels, one is a local level within each plant and the other level is associated with growth of the plants in the stand. At the level of the plant, light in the stand was attenuated about 1.7 times faster than expected for a random leaf distribution. At a higher level, which corresponded to the entire stand, light was attenuated about 1.4 times faster than expected for a random stand. The difference is attributed to the non-uniform (discontinuous) structure of the stand which results from localized variations in leaf area index.

The measurements of the distribution of leaf area in the stand are used in conjunction with the direct measurements of canopy architecture to construct a computer model that can be used to simulate the stand. The model is used to simulate the light environment in the canopy so that the daily integral of photosynthetically active radiation penetrating into the canopy can be determined as a function of the leaf area index. The available information on the effects of light intensity on kiwifruit growth was used to determine the leaf area index at which low light levels could begin to affect fruit growth and yields. For an orchard with a pergola trellis, the maximum leaf area index that could be allowed without affecting fruit growth was calculated to be about 1.6.

Acknowledgements

I would like to acknowledge and thank my supervisors, Dr. David Penny and Dr. Keith McNaughton (Plant Physiology Division, D.S.I.R.), for the time they have given me during the course of this study. Their advice and encouragement has been greatly appreciated.

Special thanks are due to Steven Green (P.P.D., D.S.I.R.). Steve built the system that I used for the indirect sensing measurements and wrote the computer programs needed to analyse the data obtained from measurements of light transmission.

I would also like to thank the Agricultural Physics Group of the Plant Physiology Division (D.S.I.R.) for their assistance. They provided all of the electronic equipment used in the experimental work and allowed me to work alongside them and to share their facilities in the orchard where the field work was carried out. They arranged for Dr. A.R.G. Lang to visit New Zealand and demonstrate his procedure for indirect sensing of canopy structure. I was grateful for the opportunity to meet Dr. Lang.

Mr. John Carson owns the orchard where the field work was carried out. I was very grateful to be allowed access to his orchard.

Staff and fellow students of the Botany and Zoology Department have provided a pleasant environment to work in. I have been grateful for advice and encouragement given me by various members of the staff and fellow post-graduate students with whom I have shared facilities in the department.

Family and friends have offered various degrees of support which I have appreciated.

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Introduction

In recent years the kiwifruit industry has expanded rapidly with the development of new markets. This has led to increased research into ways to improve the yield and quality of the crop. A factor which has been identified as influencing yield and quality is the radiation regime within the canopy (Grant and Ryugo, 1984; Morgan et al., 1985; Laing, 1985). These workers have shown that light intensity influences both the yield and the quality of kiwifruit through effects on flowering, leaf photosynthetic rates, fruit growth, and through influencing water use and temperature of plant organs.

Light intensity influences the number of flowers produced on the vine (Grant and Ryugo 1984; Morgan et al. 1985). Each year flowers are initiated for the following season's crop, probably about nine months before petal opening and pollination (Warrington, 1986). If the vines are shaded during the initiation period the number of flower buds is reduced and the following season's potential yield decreases. It is reported that replacement canes exposed to full sunlight were three times more fruitful than those trained in a shaded position (Grant and Ryugo, 1984). Studies in controlled environments confirm field results that low light levels (one third or less of full sunlight reaching the shoot) result in reduced bud break, fewer fruiting shoots, fewer flowering nodes per shoot and fewer good flowers per node (Morgan et al. 1985).

It is well known that photosynthesis decreases with decreasing irradiance, falling to negligible rates as light levels fall to below one-third of the intensity of full sunlight (Laing 1985). The shaded leaves produce less carbohydrate resulting in reduced potential for plant and fruit growth. A continuous leaf layer on a vine will absorb more than 90% of the incoming photosynthetic irradiance (Smart, 1984) so the effects of shading are major.

Shading of vines is also known to have an effect on fruit development and quality, but detailed information is sparse because it has been difficult to set up well controlled experiments. Shading reduces pollination through reduced bee activity at flowering. The size of a fruit depends on the number of fertilized ovules so reduced pollination leads to smaller fruit sizes. At this stage, however, it is not known whether the reduced bee activity is due to temperature or visible light levels at the flowers. A second problem associated with shading is that fruit are found to have a lower concentration of soluble solids than fruit from sunlit positions, resulting in later maturity and therefore later harvest (Grant and Ryugo, 1984).

The effects of shading listed here for kiwifruit have been reported for a wide range of crop species. For this reason the effect of stand architecture on the penetration of light into plant canopies has received considerable attention. The basis of the relationship between stand architecture and light penetration will be introduced here. This discussion will first examine penetration of light into a plant stand and will be followed by brief discussions on describing and measuring stand architecture. This will be followed by brief discussion on the problems of measuring the radiation regime within a plant stand.

Light penetration

A number of models have been developed which attempt to formalize the relationships between stand architecture and light penetration (e.g. de Wit, 1965; Duncan et al., 1967; Idso and de Wit, 1970; Lemeur and Blad, 1974; Allen, 1974; McPherson and Torssell, 1970, 1977; Mann et al., 1980). These models have been used to investigate factors affecting penetration of light into plant stands and provide a logical basis for planning crop management procedures and for planning further experimentation.

The model of McPherson and Torssell (1970) was used in the early stages of this work to develop an understanding of the various factors affecting radiation within the canopy. The radiation field within a plant stand is determined by the angular distribution and wavebands of the incident radiation, the architecture of the stand, and the spectral properties of the leaves, stems, flowers (or fruits) and the soil which comprise the stand. If attention is confined to the photosynthetically active radiation (PAR), then the importance of the architectural factors is greater than that of the spectral properties by an order of magnitude (e.g. Ross, 1971). For example, for PAR the scattering coefficient of the leaves and soil is about 10 or 20%, so that multiple scattering of radiation can be neglected in this case (Ross, 1971). To a first approximation, the distribution of radiation in crops is an architectural problem and not an optical one.

PAR in plant stands may be divided into three components according to it's immediate source. These are direct solar radiation, diffuse sky radiation and reflected radiation scattered from plant organs within the canopy and the soil beneath. Direct solar radiation is the most important of these components so a correct treatment of the sun-flecks in crops is a central problem in describe the radiation regime within a plant stand. Various analyses (Nilson, 1971; Ross, 1975; Mann, et al., 1977; Ross, 1981; Lang et al., 1985; Lang and Xiang, 1986) indicate that the treatment of sunflecks beneath a canopy is a purely geometrical problem albeit a difficult one to solve. If the geometrical arrangement of the foliage is known then penetration of direct sunlight into the canopy can be predicted. The penetration of diffuse radiation from the sky into the canopy can be described using the same procedures if the angular distribution of the sky light is known.

Describing stand architecture

Measuring and describing the architecture of a kiwifruit stand is an important first step in simulating the canopy radiation regime. Stand architecture can be thought of as a set of features delineating the shape, size, geometry and external structure of a plant or in the instance of a plant stand, a set of plants. A detailed description of stand architecture would include details of the size, shape, orientation, and positions of all the plant organs in the stand. It is usually impracticable to obtain such information for each organ so statistical characteristics of the plant stand are usually obtained instead.

The amount of material present in the canopy may be represented by the leaf area index, L. This is the ratio of the total leaf area (upper surface only) to the total ground area beneath. Similar indices can be constructed for the surface area of stems and fruit and flowers. A foliage area index can be constructed for the entire canopy by combining area indices for the leaves, branches and reproductive organs.

The orientation of leaves in a canopy is described by the distribution of leaf angles. Leaf angle distributions describe the fraction of the total leaf area in a canopy oriented at various angles to the vertical (leaf inclination angle, θ_L) and to the points of the compass (leaf azimuth angle, ϕ_L).

The simplest descriptions of stand architecture and light penetration treat canopies as a "horizontally homogeneous turbid layer" (e.g. Ross, 1981). These models usually assume that plant organs are randomly distributed in space. However, descriptions are available for regular and clumped distributions of organs (Acock, et al., 1970; Nilson, 1971; reviews by Ross, 1975, 1981). These treatments use empirical coefficients to correct for deviations from randomness found in discontinuous canopies.

Stand structure refers to the collective arrangement of the foliage of the individual plants that make up the stand. A stand is said to be discontinuous if there are large gaps between plants, e.g. a row crop before canopy closure (such a stand is treated as having a clumped canopy by the simple models listed above).

More sophisticated treatments have been developed to account for the effects of canopy structure on light penetration in discontinuous canopies (e.g., Allen, 1974; Mann et al., 1980; Lang and Xiang, 1986). Discontinuous canopies include large or irregular areas in which there is no foliage, e.g. in many crops before canopy closure, or breaks in forest canopies caused by the fall of large trees.

The treatments given by Allen (1974), Mann et al. (1980) and Lang and Xiang (1986) treat the canopy as being comprised of zones that contain different amounts of foliage (i.e. a non-uniform canopy). This seems to provide a more appropriate treatment for light penetration into plant stands than treating the canopy as a continuous layer. For example Lang and Xiang (1986) found for their remote sensing procedure that treating the canopy as being comprised of different zones gave more accurate estimates of leaf area index than regarding the canopy as a uniform layer of foliage. A uniform canopy has equal amounts of foliage in all of its zones.

Measuring stand architecture

The most obvious method for obtaining information on stand architecture is to measure the area, shape, angle and position of each plant organ by hand. Unfortunately these procedures tend to be very time consuming and therefore expensive. They also tend to disturb the canopy and, at least in the case of measurements of leaf angles, such disturbance can compromise the quality of the data. These limitations have led to interest in the development of indirect methods for measuring canopy architecture.

One group of indirect methods is based on the probability of probes, either mechanical or notional, penetrating the canopy. The technique of point quadrat analysis was introduced as a tool for measuring canopy architecture by Warren Wilson (1959, 1965). One of the procedures he discussed involved recording only the first contact made with foliage by the probe. Repeated measurements give the mean number of first contacts per hundred quadrats (Warren Wilson, 1965). The proportion of the quadrats that make no contact with the foliage is equal to the proportion of the incoming sunlight that penetrates the canopy without interception. If some assumption is made about the distribution of the foliage then theoretical analyses of the effects of leaf area index and leaf orientation on light interception are possible.

Lang (Lang et al., 1985; Lang and Xiang, 1986; Lang, 1986; Lang, 1988) used the principles of point quadrat analysis developed by Warren Wilson (1959) to develop a technique for remote sensing of canopy architecture. He measured the penetration of direct sunlight through the canopy for a range of sun angles; this information was used (successfully) to infer details of canopy architecture in plant stands where the leaves are randomly distributed.

Measurement of the canopy radiation environment

The problem of obtaining accurate measurements of the solar radiation beneath plant stands is complicated by the highly irregular distribution of radiation in both space and time. Reifsnyder et al. (1971) analysed the problem of obtaining accurate measurements of the light environment beneath two forest canopies. Only one or a few sensors were needed to obtain a statistically adequate estimate of a daily average for radiation penetration, but many were required to obtain satisfactory instantaneous measurements. A further problem is that the sensors suitable for measuring short-wave radiation or PAR are expensive and may require elaborate recording systems. This has meant that a lot of measurements have been made with only one, or a few, radiometers.

The difficulties of measuring radiation within and beneath canopies encourage the use of models from which canopy light levels can be calculated. Much theory is available to describe the transmission of radiation through canopies. However the complexity of canopy architecture and the variability of the above crop radiation environment means that the mathematic methods are complex and the calculations can be tedious. Hence this theory is often used in simulation models which are solved using computers.

Scope of this thesis

At the outset of this work the primary objective was to evaluate a remote sensing procedure for measuring canopy architecture in a kiwifruit orchard. The architectural information obtained from these measurements was used to model the penetration of light into a kiwifruit canopy growing on a pergola type trellis.

This thesis has four further chapters which are largely self contained. Each chapter deals with a different aspect of this work. The second chapter deals with the direct measurement of the architecture of the stand used for this work. The third chapter is concerned with the remote sensing procedure to measure stand architecture and the results are compared with results from the second chapter. In the fourth chapter theoretical expressions used for describing the effects of leaf distribution on light penetration are analysed. The fifth chapter describes a model that was used to simulate the radiation regime within the stand.

Measurements were made of the leaf area index, L, the mean leaf angle, θ_L, and the projected leaf area, $G(\theta_L)$ using both direct and indirect procedures. There was a large disagreement between the two estimates of L, but agreement was good for other parameters of stand architecture inferred from measurements made using the remote sensing procedure.

The cause of this disparity is most likely due to the regular, rather than random arrangement of leaves in the kiwifruit canopy. This means that the leaves intercept more light than they would if the leaves were distributed at random in the canopy. The effects of non random leaf distributions were analysed theoretically to show the effects of leaf distribution on light interception.

The information on the architecture of the kiwifruit stand obtained from the direct and indirect measurements was incorporated into a simulation model to predict light penetration into the canopy. This model was used to calculate the radiation regime in the kiwifruit canopy used for this study. It is estimated that light is depleted about 40% faster than in a uniform stand that has similar architectural properties, e.g. leaf area, leaf angle distribution, but with randomly distributed leaves. If the stand is treated as a uniform canopy, then light is depleted 70% faster than in uniform stand with randomly distributed leaves.

The information on canopy architecture used in the model to describe the canopy was obtained from measurements described in chapters two, three and four. The results from the model suggest that modifying stand architecture through orchard management decisions such as choice of trellis design, or pruning practices have considerable effect on the canopy radiation regime. Such modifications to canopy architecture may help to increase yields of high quality fruit through changes to the canopy radiation regime.