Approaches to Modeling Light Interception in Orchards

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Simple computer models can help horticulturists by simulating interactions between variables that are easy to understand individually but difficult to integrate intuitively. The difficulty for horticulturists in creating models has often been one of insufficient time or computer expertise. Recently, computer simulation modeling has progressed to the point where simple, yet useful models can be developed without spending much time on programming. One example is the simulation software "Stella" (Richmond et al., 1987) that allows development of a model without knowledge of a computer language. Computer models of biological systems typically are still only research tools and generally have not been developed to the point where they can give orchard managers complete answers to the complex of management decisions they face. Instead, models need to be looked at as tools to help us ask the right questions.

REASONS FOR MODELING CANOPY LIGHT INTERCEPTION

Light interception (and distribution through the canopy) is the driving force for leaf photosynthesis and has a major effect on transpiration via energy effects on leaf and air temperatures and leaf-air humidity gradients. It is thus a very important factor that influences tree productivity and water use. To ask questions about water use and yield efficiency (e.g., Does one orchard design have higher yield efficiency than another?), we need to have good information on canopy light interception.

Traditionally, yield efficiency has been expressed in units of yield per unit trunk cross-sectional area, per unit total leaf area, or per unit fruiting volume (Ferree, 1980; Hutton et al., 1987; Westwood, 1978; Westwood and Roberts, 1970). These criteria may be roughly correlated to productivity, but each has major limitations. Total leaf area does not distinguish between productive leaves in the sun and less productive shaded leaves, nor between leaves supporting fruit growth and those supporting shoot growth. The proportions of leaves in these categories can vary substantially from one planting, pruning, or training system to another, or at different times of the season. Trunk cross-sectional area is generally correlated with tree size (Chalmers and Van den Ende, 1975; Moore, 1978; Westwood and Roberts, 1970) and total leaf area, but this relationship can be greatly altered by such factors as pruning, rootstock, and tree age (Palmer, 1987). Fruiting volume may have some relation to canopy light interception but is poorly defined since the amount of leaf area in the volume is not specified; therefore, it is limited in usefulness, especially when applied to geometrically restricted planar canopies.

Therefore, we believe that a more accurate expression of yield efficiency would be on the basis of yield per unit canopy light interception. Monteith (1977) has shown for several crops, including Palmer's data on apples (1976), that total dry matter yield is a function of light interception during the season. Basing yield efficiency on light interception then indirectly estimates the fruit : total dry matter partitioning. This criterion is comparable to the harvest index term used in agronomy where whole plants can be easily harvested. The yield/light interception has been used recently for comparing different planting densities (Palmer, 1988) and tree forms (Robinson and Lakso, 1991).

Models could then be very useful in helping us ask better questions about orchard design and yield efficiency or water use. Models of light penetration and use within canopies could also be useful in asking questions and in integrating current data about the effects of

orchard design and tree training systems on fruit quality since light affects fruit size, color, soluble solids content (Barritt et al., 1987; Patten and Proebsting, 1986; Robinson et al., 1983; Seeley et al., 1980), and flower bud formation (Cain, 1971; Lakso, 1980).

DEVELOPING A CANOPY LIGHT INTERCEPTION MODEL

The following information is needed to develop a light interception model: total leaf area, dimensions and orientation of the canopy, and distribution throughout the canopy of leaf area, leaf angles, and total solar radiation, including direct, diffuse, and scattered (Ross, 1981).

To develop the ideal, most accurate tree canopy model (based on experience from field crop models), canopy dimensions would be defined by the combined positions of all individual leaves placed separately in the model, and would not need to be described by some geometrical shape. Leaf area distribution would follow some pattern through the canopy and over the season and would be clumped around branches and shoots rather than uniformly distributed. Leaf angle distribution would also be a function of canopy position, time of season, and perhaps even time of day. Light distribution of both direct and diffuse solar radiation is generally accepted to follow Beer's Law of light attenuation, $I/I_0 = e^{-KL}$, where I is light intensity above the canopy, I_0 is light intensity below a leaf area index of L , and K is the light extinction coefficient (Fig 1). K is a function of foliage density, solar elevation, leaf angle, and perhaps other factors, such as leaf folding or rolling (Ross, 1981). Therefore, the value of K might change through the canopy and over the day. The model would also need to include the distribution of sunflecks (Norman et al., 1971) throughout the canopy. Finally, the model would need to include scattering of both direct and diffuse solar radiation by leaves, wood, fruit, and the ground beneath the canopy.

To build such a model would be extremely complicated and to our knowledge never has been attempted for fruit trees, although some attempts have been made to model single leaves in simple field crop systems (Oikawa and Saeki, 1977). Instead, tree models

Fig. 1. Beer's Law of light attenuation. Light intensity decreases as an exponential decay function through the canopy.

Fig. 2. Examples of two simulated orchards generated by a computer CAD program and viewed at two different angles and elevations.

that incorporate various simplified assumptions have been developed. Several examples will be presented here to illustrate different ways of simplifying the canopy. These models attempt to simulate light interception by 1) canopy sections, 2) horizontal layers, or 3) the canopy as a whole. The last category is naturally much simpler to model, but is also more limited in the types of questions that can be explored. The first category can be used to investigate questions regarding canopy location effects on fruit quality and flower bud formation.

CANOPY SECTION MODELS

Charles-Edwards and Thornley (1973) developed a light interception model for a single apple tree. It was later applied to a hedgerow apple orchard (Charles-Edwards and Thorpe, 1976) and used to predict photosynthesis and transpiration within different sections of an isolated apple tree (Thorpe et al., 1978). The tree canopy was assumed to be ellipsoid with leaf area distributed uniformly throughout and leaf angles randomly distributed. Light attenuation through the canopy of both direct and diffuse solar radiation was assumed to follow Beer's Law with a constant K value. Scattering of light through the canopy was ignored in the initial version of the model but included in a simplified way in the photosynthesis and transpiration model. Despite the simplified assumptions, the results of the model agreed quite well with measured values of light interception in an apple hedgerow (Charles-Edwards and Thorpe, 1976) and with diurnal rates of photosynthesis and transpiration in a small apple tree. The authors believed that the main limitations to the model were that leaf clumping was ignored and light scattering was treated in an incomplete way. When leaf clumping was included in a coniferous forest model, the results agreed better with measured values of light interception (Norman and Jarvis, 1975) than when clumping was ignored.

CANOPY LAYER MODELS

Another approach to modeling canopy light interception is to treat the canopy as horizontal layers of leaves and assume the same light level throughout each layer. This is generally assumed for field crop models. Goudriaan (1977) has used this approach to develop a generalized plant model. DeJong and Goudriaan (1989) developed a

peach tree model based on this assumption. Other assumptions in the model are similar to those of Charles-Edwards and Thornley (1973); leaf area is evenly distributed, leaf angles are randomly distributed, and light attenuation is based on Beer's Law with a constant K value. In this model, scattering of light is dealt with in considerable detail. The model seems to give realistic values of canopy photosynthesis, although it never has been validated in the field.

WHOLE CANOPY MODELS

The simplest approach is to model orchard light interception by the canopy as a whole without dividing it into different sections. This approach has been used to make extensive studies of apple hedgerows (Jackson, 1978, 1980a, 1980b; Jackson and Palmer, 1972, 1979, 1980; Palmer, 1977, 1980). It was assumed canopy dimensions follow a triangular or quadrangular shape down the length of the row. To calculate light interception by the canopy, the proportion of total available light transmitted to the orchard floor (T) was first estimated according to the formula $T = T_s + T_c$ (Jackson and Palmer, 1979). T_s is the proportion of light falling on the orchard floor without passing through a tree, as estimated from the shadow cast by solid models. T_c is the proportion of the remaining light passing through the tree to the orchard floor according to Beer's Law, $T_c = (1 - T_s) e^{-K \cdot L}$. For apple trees, the value of K has been measured between 0.55 and 0.60 (Cain, 1973; Jackson, 1978; Palmer, 1977), and is set at 0.60 in the model. Canopy light interception is the proportion of light not transmitted to the orchard floor $(1 - T)$. The only inputs needed for the model are canopy and tree spacing dimensions and total leaf area. Despite these simplifying assumptions, model predictions have agreed well with estimates of total light interception from more complicated models (Jackson and Palmer, 1979).

Jackson (1978) and Palmer (1986, 1988) have found a good correlation between measured light interception and yields in young apple orchards. Given this relationship, many useful questions can be explored regarding the effects of tree spacing, tree dimensions, row orientation, and latitude on yield. They also have used the model to estimate "irradiance contours" throughout the canopy (Jackson and Palmer, 1981). This approach allows for calculation

of the proportion of canopy receiving < 30% available light, which has traditionally been considered the lowest acceptable light level for good fruit quality and flower bud formation in apple (Westwood, 1978). With this additional information, various orchard designs can be compared to predict the design with the greatest light interception but the lowest shaded area within the canopy. When researchers are establishing field trials to test different orchard systems, it would be valuable to run each system through the model to obtain estimates of percent light interception. Tree and row spacing and tree dimensions could then be set for each system to obtain the same level of light interception at maturity. This would provide a good basis for comparison of yield efficiency of the different systems.

We have just begun to use the approach of Jackson and Palmer (1979) to develop a simple model of a peach orchard using the Stella computer simulation language. The model only took ≈ 1 day to assemble. The model will be used to explore questions regarding water use of trees. Using a weighing lysimeter, preliminary data have shown light interception predicted by the model to be a better predictor of tree water use than total leaf area.

The model may also be useful for exploring questions regarding yield efficiency of peach trees planted at various spacings. Since yield and fruit size are closely correlated and yield is strongly influenced by thinning (Johnson and Handley, 1989), the concept of yield efficiency must be expanded to include fruit size. The model should be very helpful in examining the relationship between canopy light interception, yield, and fruit size.

Another approach that could be very useful in helping horticulturists to model canopy light interception is the use of three-dimensional computer-aided design (CAD) software packages. These programs allow one to create a three-dimensional tree of virtually any shape. The tree can then be copied to create a row and the row copied to create a three-dimensional orchard of any given spacing. The most advanced CAD programs allow the created object to be viewed from any angle and orientation. Therefore, the simulated orchard could be viewed from the perspective of the sun over the course of the day (Fig. 2) and values of T_r (% light falling on soil) could be easily estimated by image analysis or a simple count of shaded vs. exposed points on an overlay grid. This tool would be especially useful for canopy shapes that are not easily described by simple geometric figures.

In summary, recent advances in computer technology have provided horticulturists with some powerful yet easy-to-use tools to assist in the modeling of canopy light interception. In addition, simple approaches to modeling light interception, such as those proposed by Jackson and Palmer (1979), can simulate reality with reasonable accuracy. Together, these tools should be very useful in helping us ask better questions about the effects of orchard design on yield efficiency, water use, and fruit quality.

Literature Cited

- Barritt, B.H., C.R. Rom, K.R. Guelich, S.R. Drake, and M.A. Dilley. 1987. Canopy position and light effects on spur, leaf, and fruit characteristics of 'Delicious' apple. *HortScience* 22:402-405.
- Cain, J.C. 1971. Effects of mechanical pruning of apple hedgerows with a slotting saw on light penetration and fruiting. *J. Amer. Soc. Hort. Sci.* 96:664-667.
- Cain, J.C. 1973. Foliage canopy development of 'McIntosh' apple hedgerows in relation to mechanical pruning, the interception of solar radiation and fruiting. *J. Amer. Soc. Hort. Sci.* 98:357-60.
- Chalmers, D.J. and B. Van Den Ende. 1975. Productivity of peach trees: Factors affecting dry-weight distribution during tree growth. *Ann. Bot.* 39:423-32.
- Charles-Edwards, D.A. and J.H.M. Thornley. 1973. Light interception by an isolated plant. A simple model. *Ann. Bot.* 37:919-928.
- Charles-Edwards, D.A. and M.R. Thorpe. 1976. Interception of diffuse and direct-beam radiation by a hedgerow apple orchard. *Ann. Bot.* 40:603-613.
- DeJong, T.M. and J. Goudriaan. 1989. Modeling the carbohydrate economy of peach fruit growth and crop production. *Acta Hort.* 254:103-108.
- Ferree, D.C. 1980. Canopy development and yield efficiency of 'Golden Delicious' apple trees in four orchard management systems. *J. Amer. Soc. Hort. Sci.* 105:376-380.
- Goudriaan, J. 1977. Crop micrometeorology: a simulation study. Centre for Agricultural Publishing & Documentation, Wageningen, Netherlands.
- Hutton, R.J., L.M. McFadyen, and W.J. Lill. 1987. Relative productivity and yield efficiency of canning peach trees in three intensive growing systems. *HortScience* 22:552-560.
- Jackson, J.E. 1978. Utilization of light resources by HDP systems. Symposium on high density planting. *Acta Hort.* 65:61-70.
- Jackson, J.E. 1980a. Theory of light interception by orchards and a modeling approach to optimizing orchard design. *Acta Hort.* 114:69-79.
- Jackson, J.E. 1980b. Light interception and utilization by orchard systems. *Hort. Rev.* 2:208-267.
- Jackson, J.E. and J.W. Palmer. 1972. Interception of light by model hedgerow orchards in relation to latitude, time of year and hedgerow configuration and orientation. *J. Applied Ecol.* 9:341-358.
- Jackson, J.E. and J.W. Palmer. 1979. A simple model of light transmission and interception by discontinuous canopies. *Ann. Bot.* 44:381-383.
- Jackson, J.E. and J.W. Palmer. 1980. A computer model study of light interception by orchards in relation to mechanised harvesting and management. *Scientia Hort.* 13:1-7.
- Jackson, J.E. and J.W. Palmer. 1981. Light distribution in discontinuous canopies: Calculation of leaf areas and canopy volumes above defined 'Irradiance Contours' for use in productivity modeling. *Ann. Bot.* 47:561-565.
- Johnson, R.S. and D.F. Handley. 1989. Thinning response of early, mid, and late-season peaches. *J. Amer. Soc. Hort. Sci.* 114:852-855.
- Lakso, A.N. 1980. Correlations of fisheye photography to canopy structure, light climate, and biological responses to light in apple trees. *J. Amer. Soc. Hort. Sci.* 105:43-46.
- Monteith, J.L. 1977. Climate and the efficiency of crop production in Britain. *Phil. Trans. Roy. Soc. B.* 281:277-294.
- Moore, C.S. 1978. Biometrical relationships in apple trees. *J. Hort. Sci.* 53:45-51.
- Norman, J.M. and P.G. Jarvis. 1975. Photosynthesis in sitka spruce (*Picea sitchensis* [Bong.] Carr.) *J. Applied Ecol.* 12:839-878.
- Norman, J.M., E.E. Miller, and C.B. Tanner. 1971. Light intensity and sunfleck-size distribution in plant canopies. *Agron. J.* 63:743-748.
- Oikawa, T. and T. Saeki. 1977. Light regime in relation to plant population geometry. I. A Monte Carlo simulation of light microclimates within a random distribution foliage. *Bot. Mag. Tokyo* 90:1-10.
- Palmer, J.W. 1976. Interception and utilisation of light by apple orchards. PhD Diss., Univ. of Nottingham, U.K.
- Palmer, J.W. 1977. Diurnal light interception and a computer model of light interception by hedgerow apple orchards. *J. Applied Ecol.* 14:601-614.
- Palmer, J.W. 1980. Computer effects of spacing on light interception and distribution within hedgerow trees in relation to productivity. *Acta Hort.* 114:80-88.
- Palmer, J.W. 1986. Light interception and dry matter production by apple orchards, p. 24-27. In: A.N. Lakso and F. Lenz (eds.). The regulation of photosynthesis in fruit trees. Symposium Proc., N.Y. State Agr. Expt. Sta. Geneva, N.Y.
- Palmer, J.W. 1987. The measurement of leaf area in apple trees. *J. Hort. Sci.* 62(1):5-10.
- Palmer, J.W. 1988. Annual dry matter production and partitioning over the first five years of a bed system of Crispin/M.27 apple trees at four spacings. *J. Applied Ecol.* 25:569-578.
- Patten, K.D. and E.L. Proebsting. 1986. Effect of different artificial shading times and natural light intensities on the fruit quality of 'Bing' sweet cherry. *J. Amer. Soc. Hort. Sci.* 111:360-363.
- Richmond, B., S. Peterson, and P. Vescuso. 1987. STELLA, An academic user's guide to. Nancy Maville (ed.). High Performance Systems, Hanover, N.H.
- Robinson, T.L. and A.N. Lakso. 1991. Bases of yield and production efficiency in apple orchard systems. *J. Amer. Soc. Hort. Sci.* 116(2):188-194.
- Robinson, T.L., E.J. Seeley, and B.H. Barritt. 1983. Effect of light environment and spur age on 'Delicious' apple fruit size and quality. *J. Amer. Soc. Hort. Sci.* 108:855-861.
- Ross, J. 1981. The radiation regime and architecture of plant stands. Junk Publishers, The Hague, Netherlands.
- Seeley, E.J., W.C. Micke, and R. Kammereck. 1980. 'Delicious' apple fruit size and quality as influenced by radiant flux density in the immediate growing environment. *J. Amer. Soc. Hort. Sci.* 105:645-657.
- Thorpe, M.R., B. Saugier, S. Auger, A. Berger, and M. Methy. 1978. Photosynthesis and transpiration of an isolated tree: model and validation. *Plant Cell & Env.* 1:269-277.
- Westwood, M.N. 1978. Temperate-zone pomology. W.H. Freeman, San Francisco.
- Westwood, M.N. and A.N. Roberts. 1970. The relationship between trunk cross-sectional area and weight of apple trees. *J. Amer. Soc. Hort. Sci.* 95:28-30.