Soil management for high productivity in horticulture

K.A. Olsson and B. Cockroft

Department of Agriculture, Victoria, Irrigation Research Institute, Tatura and Research Institute, Kyabram respectively.

Summary

Horticultural productivity in Australia is well below the best possible largely because of limitations imposed by deficiencies in physical properties in the root environment. A general approach to soil management is described which aims to increase productivity by optimizing the soil environment with respect to the growth and functioning of plant roots. The approach is illustrated by examples of management systems which have been developed from these criteria.

Introduction

High yields and the efficient utilization of available resources are the bases of profitable production in horticulture. With few exceptions, for example Kinsella (1979), productivity in horticultural crops has not substantially increased over the past two decades despite considerable effort by agricultural scientists (Anon 1979). We consider this to be due largely to limits imposed by deficiencies in soil physical properties in the root environment and their effect on root activity. Most Australian soils that are used for horticultural production do not provide optimum conditions for the growth and functioning of roots. Few soils, even when irrigated and well managed, provide optimum levels of all root requirements for more than transient periods during the growing season. There is thus considerable scope for increasing productivity by improving soil conditions in the root environment (see also Collis-George 1979).

We outline a general approach to the management of horticultural soils which aims to develop stable, highly productive systems by overcoming soil problems and by providing conditions approaching the ideal for the growth and functioning of roots. Fundamental to the approach is 1) a knowledge of the particular soil and 2) an understanding of what roots require from their environment; essentially these requirements are optimum levels of water, aeration, mechanical resistance, temperature and nutrition. For the present purposes we establish working limits to these parameters from the literature; these are summarized in Table 1. Using this information we then aim to control levels of all parameters so that the soil environment approaches the ideal for maximum root activity. We illustrate the approach using two examples from irrigated horticulture - a perennial tree crop (peaches) and an annual vegetable crop (tomatoes). While the examples are drawn from experience with duplex soils in southeastern Australia, the principles have general application.

TABLE 1. Working limits of principal soil physical parameters influencing root elongation.

Parameter	For maximum root elongation rates	Root elongation ceases
Soil-water (matric) suction (bar)A	< 0.5	> 15
Air-filled porosity (% of soil volume air-filled at 0.1 bar suction)A	> 15	< 2
Mechanical (penetrometer)	< 6	> 30-40

resistance (bar)A		
Soil temperature (?C)B	18	30-35

A After Richards & Cockroft (1974) who cite reference sources.
B Nightingale (1935) for roots of peach and apple.

Orchard Soil Management

The first example concerns irrigated orchard trees in northern Victoria. The soil is a Shepparton fine sandy loam (red-brown earth) described by Skene and Poutsma (1962). The profile comprises a loam surface soil to 160 mm overlying a red-brown clay B horizon which extends to 600 mm. The surface soil is naturally low in organic matter and is prone to slaking when wetted rapidly by irrigation water. The B horizon has a low permeability to water (hydraulic conductivity at saturation = 3.5 x 10-5 cm s-1) and is poorly aerated (less than 5% of total soil volume is air-filled at 0.1 bar suction). Below the B horizon and extending to 1.5 m is a riverine layer of lighter texture and higher permeability (hydraulic conductivity at saturation = 1.1 x 10-4 cm s-1). Bulk densities are typically 1.5 g cm-3 in the surface soil and 1.6 g cm-3 (at 0.1 bar suction) in the subsoil. Tree roots grow mainly in the surface soil below cultivation depth (75 mm) where root concentrations are commonly 2-3 cm-2. Roots are sparse in the subsoil with root concentrations of <0.2 cm-2 below 800 mm (Cockroft and Wallbrink 1966). The growth of peach roots in district orchards is confined to short periods of the season, largely as the result of unfavourable soil conditions (Cockroft and Olsson 1972).

The upper 1.2 m of the natural profile stores 150 mm of "available" water. The orchardist usually irrigates after some 65-75 mm of water has been extracted from the upper 500-650 mm of the profile. The remaining storage is inaccessible to the trees for production purposes; this is attributable to the low root concentrations and low unsaturated hydraulic conductivities in the subsoil (Olsson and Rose 1978).

The commercial orchardist normally cultivates up to five times in a season to set up for irrigation, to control summer weeds and finally to set up for winter drainage.

In developing a soil management system for maximum production on this soil the aim is to optimize the five soil environmental parameters influencing root activity noted previously. We shall discuss each in turn.

Soil water

The surface soil develops a major problem when overcultivated and rapidly wetted at irrigation. The soil slakes and water penetrates only slowly through the surface soil and in extreme cases may reach only 70 mm depth. It is common practice to pond water on the soil surface for up to 24 hours in an attempt to obtain deeper penetration. Where this condition persists crop yields are markedly reduced.

The condition is overcome by eliminating cultivation and substituting weedicides to give weed control and by incorporating organic matter such as straw into the surface soil biologically, some 11 t ha-1 being required annually to maintain structural stability and to replace losses by soil respiration (Cockroft and Tisdall 1968). Straw, together with recommended amounts of fertilizer, is applied each October as a surface mulch at the above rate. The straw encourages a rapid buildup of biological activity, notably earthworms, and these agents incorporate the organic matter and fertilizer throughout the surface soil and produce the open, stable structure the roots require (Tisdall 1978). The mulch also conserves water which would otherwise be lost by evaporation from the soil surface beneath the orchard canopy, protects the soil surface from droplet impact from rain and sprinklers and acts as a thermal insulation, protecting roots at shallow depth from lethal summer temperatures. With the above management high infiltration rates (of the order of 200 mm h-1) have been maintained over the growing season and the profile has been wetted to 800 mm and deeper.

Once the problem of low infiltration rates has been overcome we aim for maximum root activity by maintaining the soil-water suction at c. 0.3 bar or lower (Cockroft and Olsson 1972) over the entire depth. Irrigations are given on average every 5 to 7 days by reference to tensiometers installed at several profile depths. Water is applied by fine sprays from fixed heads at 2m spacings along the tree line. This system applies water at the rate of 25 mm h-1 with a coefficient of uniformity of 80% giving close control of levels of soil water and keeping the traffic lanes between the banks dry. The amount of water applied at each irrigation is calculated from crop and weather data as described by Olssori (1977). The fine sprays and protective surface mulch allow a slow wetting of the soil surface further reducing any tendency for the surface soil to slake. Test wells installed on the clay layer in the deep subsoil (at 2 m depth) warn of any tendency to over-irrigate.

Soil drainage and aeration

Flat grades and slowly permeable subsoils cause the serious problem of waterlogging and attendant problems in the upper part of the profile after prolonged rain particularly in Autumn and Winter. Peach trees are particularly sensitive to these conditions and on average one third of trees in the region die every eight years (Cockroft and Bakker 1966). This problem is overcome by 1) encouraging runoff from the soil surface during Winter and by adding only sufficient straw in early Spring to ensure a bare soil surface by the Autumn, and 2) by increasing the permeability of the B horizon by shattering the clay to 600 mm depth and stabilizing with gypsum (Bakker and Emerson 1973). This treatment has been shown to raise the saturated hydraulic conductivity of the B horizon tenfold (Bakker, unpublished data). Experience with this technique is currently limited but there is evidence that beneficial effects on profile drainage have persisted for at least ten years under non-traffic conditions beneath the tree-line banks.

To ensure adequate aeration for root growth in the banks we aim to develop a stable structure that will provide 20% air space at 0.1 bar suction (Richards and Cockroft 1974). We can achieve this by cultivating the entire depth of surface soil to form aggregates, ideally between the sizes of four to six mm in diameter, and stabilizing as described earlier. For an average soil respiration rate (seasonal) of 0.75 x 10-9 g s-1 CO2 per cm3 of soil. oxygen will diffuse to the centre of saturated aggregates up to 6 mm in diameter where the inter-aggregate pore space contains 21% oxygen (Willoughby 1979).

In addition, the resulting well-drained profile, when carefully watered is less likely to favour the spread of infection by soil-borne pathogens such as Phytophthora spp.

Mechanical resistance

The soil can set hard after irrigation and restrict root growth by high mechanical resistance. The problem is compounded by the massive clay subsoil and by traffic compaction during orchard operations. Compaction by traffic is controlled by defining separate traffic and root zones. Surface soil is moved from the traffic lanes to form raised tree-line beds 320 mm high and 3-4 m wide leaving traffic to travel on the exposed subsoil which provides a firm, all-weather surface. The surface and subsoil treatments previously described are applied to the soil in the banks prior to planting. By careful control over irrigation the soil is kept moist and mechanical resistance remains low. For example, where the treated soil is kept wetter than 0.3 bar, we find penetrometer resistance remains below 10 bar, sufficiently low for continued root growth (Taylor et al. 1966; Richards and Cockroft 1974).

The present system of soil management with hilling and no cultivation achieves a fourfold increase in available water storage in the surface soil compared to a normal cultivated orchard where roots are confined to about half the depth of the surface soil. While the subsoil treatment has not increased the available water storage per se (Olsson and Willatt 1978) it has influenced the distribution of tree roots; root concentrations of 1.0 cm-2 have been measured at 1.2 m depth in 5 year old trees. At such root concentrations theory predicts that an additional 75-85 mm of water would be made available for transpiration after each irrigation (Olsson 1977).

Soil temperature

Temperatures rise above the lethal 35?C (Nightingale 1935) in the top 70 mm of soil wherever the surface receives direct radiation during Summer; tree roots do not grow there (Cockroft and Hughan 1964). These authors showed that it is possible to maintain soil temperatures close to the ideal of 18?C (Nightingale 1935). A large tree canopy will shade the entire surface during summer months and keep the maximum temperature below 25?C. A mulch of straw further reduces the maximum temperature to 22?C; it also raises the minimum temperature of a bare soil from 2?C to 6?C during Winter.

Nutrition

Fertilizers are applied at rates to give non-limiting leaf levels of nutrients as described, for example, by Leece et al. (1971).

System Performance and Profitability

Using the present system of soil management on this soil we have grown peach trees to 3.2 m high in three years compared to 1.8 m in commercial trees of the same age. A block of 60 trees (0.2 ha) has accumulated a canning yield of 135 t ha-1 in its first three cropping years (i.e. in its fourth, fifth and sixth years of growth). Cockroft and Tisdall (1978) have reported annual yields of 75 t ha-1 in mature trees under this system. These yields may be compared to the average of 18 t ha- commercial peach orchards in northern Victoria and 37 t ha-1 by the best local growers.

The profitability of the Tatura system is compared with that of a conventional cultivated orchard in Table 2.

TABLE 2. Cumulative net outlay/return ($ per ha) of Tatura system compared with conventional soil management over years 1-6 from planting[A].

Year	Conventional system	Tatura system	Difference
1	- 2001	- 2729	-729
2	- 2606	- 3806	-1200
3	- 3238	- 4960	-1722
4	- 3935	- 1119[B]	2816
5	- 2196[B]	2356	4552
6	- 615	5508	6123

[A] Based on operating costs only, other components of cost being assumed the same for both systems. The calculations allow 10% for cost of capital. Source: Dept. Agric. Vic. Agriculture Note Series No. 24 (1979) p. 65.
[B] First cropping year.

To allow comparison the calculations are based on operating costs only and no attempt is made to give a complete cost/return analysis, only differences being relevant in the present context. Other cost components. e.g. irrigation system, plant and a number of fixed costs have not been included since they were assumed to be the same for both systems.

Accepting these limitations we see that despite higher initial costs the Tatura system is highly profitable. This is due to earlier cropping and high, sustained yields - 135 t ha-1 accumulated at the end of the sixth year cf. 49 to ha-1 under conventional management in the above example. The Tatura system thus achieves a high level of efficiency in the use of resources particularly those of land, water and fuel energy. Further increases in productivity are promised using management techniques such as the Tatura Trellis (Chalmers et al.1978) which aims to maximize the efficiency of utilization of solar radiation.

Soil Management in Annual Crops

Vegetable growers use soils having similar properties to the orchard example to produce a range of annual crops. most commonly tomatoes. As a result of cultivation, grading, bed forming and other forms of soil disturbance, the surface soil sets hard after each irrigation or rain. The dense claypan subsoil prevents deep penetration of irrigation water and restricts drainage and root development. While the work has not advanced as far in annual crops the same principles are applied to developing suitable management systems.

Restricted soil-water supply to the plant roots is the major cause of low yields in these soils. Water often fails to penetrate into the formed-up beds and it cannot penetrate readily into the clay subsoil. The grower must fill up his furrows with water to gain a sufficiently long time for infiltration but in so doing he exacerbates the slaking problem in the surface soil. He can overcome this problem by first forming the surface soil into aggregates as described earlier; this ensures an ideal surface soil structure initially and avoids the need to sow or plant into powder which always sets hard. He then irrigates slowly by running the water along the bottom of the furrow, never filling it, so that most of the soil wets up slowly by capillarity. In this way the surface soil does not slake and water penetrates the beds readily. By encouraging a surface mulch the soil is protected when rain intervenes. Water requirements for root growth and transpiration are met by keeping the soil-water suction as close as practicable to 0.3 bar.

Soil drainage and aeration are controlled by having the surface soil aggregated in this way: attention to surface grades is also important. Internal drainage of the profile can be improved by the subsoil treatment described for the orchard example. Again we aim for an air-filled pore space of 20% at 0.1 bar suction throughout the root zone.

Mechanical resistance in these soils is usually high under commercial cropping because of the hard-setting surface soil and the dense subsoil, restricting root growth and leading to seedling emergence problems. The aggregated surface soil and the shattered subsoil treatments together with control over levels of soil water help to overcome these problems. Traffic compaction can be minimized by using equipment as little as possible. Engineers must develop some form of wheel design that eases the amount of soil compaction and in particular the shearing compression of driving tractor wheels. Again the aim must be to keep penetrometer resistance below 10 bar.

Soil temperatures must be kept as close as possible to the optimum for the particular crop. In Summer the grower needs to develop the crop canopy before the weather becomes hot to ensure maximum shading of the soil surface. An open, aggregated soil high in organic matter helps to reduce thermal diffusivity.

Soil nutrients can be maintained at optimum levels if the grower applies fertilizer at amounts based on field experience or leaf analysis.

We can thus develop a soil management system for an annual crop, even on these difficult soils, by following the above principles. The number of cultivations is kept to the minimum, for example, by using weedicides; minimum tillage reduces both shattering of aggregates and breakdown of organic matter as does direct seeding. We encourage the buildup of soil organic matter and the activities of soil organisms in order to maintain stability. Minimum tillage and slow wetting assist here so that roots are left in situ and organic matter within fine pores is not exposed to breakdown. The formation of organic mulches on the soil surface is important for reasons discussed earlier. These may comprise leaf litter, plant material left over after harvesting and possibly organic materials brought in from outside.

Using the above management commercial canning varieties have produced yields of 80-100 t ha-1 on this soil (S. Gurban, personal communication) compared with average commercial production of 30 t ha-1 and 40-48 t ha-1 by the best growers.

Conclusions

These examples demonstrate that there is considerable scope for increasing the productivity of horticultural crops by soil management where we control the root environment closely. In order to develop stable, highly productive systems the agricultural scientist must firstly have an understanding of his soil; for example infiltration behaviour, slaking, drainage, gaseous diffusion. compaction, organic matter equilibria and factors affecting the activity of soil fauna. By adopting a scientific approach to gain a detailed understanding of the soil environment in relation to the requirements of the root system he can always develop a soil management system that does have a significant effect on productivity. Further research is clearly needed to achieve a quantitative specification of the required soil structure and physical conditions which make up the root environment.

This knowledge should also lead to more precise land use recommendations than those currently in use. Once suitable sites have been selected the soil environment becomes a vital area for the manipulation of crop performance. The examples have shown that even major deficiencies in soil physical properties can be overcome. This is especially true in horticulture where high returns from intensive systems allow such soil modification to be economically feasible.

References

1. ANON (1979). Fruit Statistics. Australia. Aust. Bureau of Statistics, Canberra.

2. BAKKER, A.C., and EMERSON, W.W. (1973). Aust. J. Soil Res. 11: 159.

3. CHALMERS, D.J., VAN DEN ENDE, B., and VAN HEEK, L. (1978). HortScience 13: 517.

4. COCKROFT, B., and BAKKER, A.C. (1966). *J.* Aust. Inst. Agric. Sci. 32: 292.

5. COCKROFT, B., and HUGHAN, D.A. (1964).. Vic. Dept. Agric. Hort. Res. Stn., Tatura. Stn. Rep. No. 2.

6. COCKROFT. B., and OLSSON, K.A. (1972). Aust. *J.* Agr. Res. 23: 1021.

7. COCKROFT, B., and TISDALL. J.M. (1978). In "Modification of Soil Structure". (W.W. Emerson, R.D. Bond and A.R. Dexter, eds.) p. 387. (Wiley, Chichester).

8. COCKROFT, B., and WALLBRINK, J.C. (1966). Aust. J. Agric. Res. 17: 49.

9. COLLIS-GEORGE, N. (1979). J. Aust. Inst. Agric. Sci. 45: 106. KINSELLA, M.N. (1979). Acta Hort. (in press).

10. LEECE, D.R., CRADOCK, F.W., and CARTER, 0.G. (1971). J. Hort. Sci. 46: 163.

11. NIGHTINGALE, G.T. (1935). Bot. Gaz. 26: 581.

12. OLSSON. K.A. (1977). Ph.D. Thesis, Macquarie University.

13. OLSSON, K.A. and ROSE. C.W. (1978). Aust. J. Soil Res. 16: 169.

14. OLSSON, K.A. and WILLATT, S.T. (1978). The Institution of Engineers, Australia, National Conference Publication No. 78/8 p. 35.

15. SKENE, J.K.M. and POUTSMA, T.J. (1962). Tech. Bull. Dept. Agric. Vic. No. 14.

16. RICHARDS, D., and COCKROFT. B. (1974). Aust. J. Exp. Agric. An. Husb. 14: 103.

17. TAYLOR, H.M., ROBERSON, G.M. and PARKER, J.J. (1966). Soil Sci. 102: 18.

18. TISDALL, J.M. (1978). In "Modification of Soil Structure" (W.W. Emerson, R.D. Bond and A.R. Dexter, eds.) p. 297 (Wiley, Chichester).

19. WILLOUGHBY. P. (1979). M. Agr. Sc. Thesis, La Trobe University.