Chapter 4

TILLAGE IN HORTICULTURE

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High potential returns from fruit and vegetable production have traditionally justified high inputs of fertiliser and pesticides, frequent tillage, and usually irrigation. Soil degradation through excessive tillage has occurred across many horticultural industries. In many soils, this has been characterised by soil compaction, declining structural stability, slow infiltration of water and high runoff. This problem has been serious on silty soils and loams where flood irrigation is used. In coastal areas, high rainfall intensity has caused severe erosion of light-textured soils.

Some market gardeners add organic matter to the soil and adopt desirable crop rotation and cover-cropping programmes. However, growers generally see the costly improvement of soils as a low priority behind pest, disease and weed control, crop establishment and post-harvest handling of crops. Similar problems exist among orchardists, and any trend to reduced tillage has been for convenience (i.e. a cheaper system, better drainage and trafficability, use of low-flow irrigation) rather than to improve soil structure or root growth. An exception has been the avocado where the highest priority has been placed on soil management because of its intimate relationship with *Phytophthora* root-rot control.

Research into soil management of temperate fruit trees in Australia has been restricted mainly to stone and pome fruit in the Goulburn Valley and the Melbourne district in Victoria, and to citrus in Griffith, New South Wales. Therefore this chapter reports mainly on work from these areas. The review of tropical tree fruits is restricted to the avocado. Although no research has been published on soil management for vegetable crops, the principles are well understood. The final section therefore discusses in general the soils used for vegetables, the production principles, and soil-management problems. Trends in minimum-tillage research for vegetables are also reviewed.

TEMPERATE TREE CROPS

DISTRIBUTION

Australia's production from fruit trees comprises 48% citrus, 40% pome, 12% stone and 0.5% tropical fruits (Table 4.1), and is used for both processing and for fresh fruit. The total value of production in 1983 was $488m. Citrus is grown mainly on well-drained sandy soils, with stone fruit, especially peaches, on the second-best soils. Pome fruit is grown on a wide range of soil types.

Table 4.1 Australia's production from fruit trees in 1982 (Anon., 1983)

Crop	Production ('000 tonnes)						
	NSW	Vic.	Qld	SA	WA	Tas.	Total
Citrus	196	59	44	169	12	–	480
Pome	62	154	40	24	56	69	396
Stone	28	48	6	28	10	·0.4	120
Tropical	1[a]	–[a]	4	0.1	–[a]		5[a]

[a] Incomplete.

TRADITIONAL TILLAGE PRACTICES

Clean tillage, mainly with a disc plough, for at least a few months of the year, has been the standard practice for many years in orchards in Australia, with up to 13 cultivations per year. Tillage controls some pests, reduces competition from weeds, and enables land to be prepared for irrigation and drainage each spring (Frith, 1952; Nott, 1955; Selimi and Keatley, 1969). In spring, the land has been graded to repair wheel ruts caused by tractors and spray pumps, and to set up check banks and channels. In autumn, some orchardists have ploughed and hilled the soil against the tree-line. Frequent tillage, however, has worsened the structure of silty surface soils and led to severe erosion on sloping land (Goudie, 1950; Slack and Duncan, 1981). By the late 1940s in Goulburn Valley orchards, water penetrated to a depth of only 7-10 cm after 24 to 48 hours of flood irrigation, and the soil set hard on drying. Aggregates at the surface were waterlogged for up to 48 hours during flood irrigation, which possibly worsened the structure further and prevented aeration of deeper layers during irrigation (Cannell, 1979).

With perennial crops such as fruit trees it was not difficult to devise new methods of soil-surface management. Tillage could be eliminated altogether once effective herbicides became available in the 1950s. Many trials with temperate fruit trees have compared the various forms of tillage and their effects on the physical properties of soil, penetration of water, root growth and crop yields (e.g. Greacen and Perkman, 1953; Black, 1963; Cockroft and Hughan, 1964; Mitchell and Black, 1968; Selimi and Keatley, 1969). Treatments were selected because they had been tested overseas, not because they were designed specifically for Australian soils. The work was descriptive, rather than mechanistic.

The aim of tillage research up to the 1970s was to produce a large tree with a large root system quickly, since yield was related to tree size or vigour (Table 4.2), and tree size was thought to be related to root vigour (Bouma and McIntyre, 1963; Cockroft, 1966; Culver and Till, 1967). Subsequent research has shown that vigorous trees are not necessarily desirable (especially when close-planted) because they can result in more vegetative growth and less fruit growth (Table 4.3).

Table 4.2 The relationship between vigour (as measured by pruning mass) and yield of conventional vase-shaped peach trees (Cockroft, 1966)

Treatment	Yield ($t\ ha^{-1}$)	Pruning mass ($kg\ tree^{-1}$)
Straw mulch	5.6	8.1
Tillage	4.8	6.7
Permanent sod	4.4	5.3
Bare surface	3.0	5.2

Table 4.3 The relationship between vigour (as measured by increase in trunk area) and yield of close-planted peach trees (Chalmers *et al.*, 1981)

Yield (kg tree^{-1})	Increase in trunk area (cm^2)
17.5	7.38
15.4	7.03
14.8	9.72

DEVELOPMENTS IN IRRIGATION PRACTICE

Until about the 1960s, trees were irrigated infrequently by flood, furrow or overhead sprinklers every 3 to 4 weeks, since it was wrongly believed that water was equally available from the soil at water contents anywhere between field capacity and permanent wilting point (Veihmeyer and Hendrickson, 1945; Greacen, 1977). On the shallow soils of the Goulburn Valley, with low levels (11%) of available water, trees were therefore underwatered and roots stopped growing during summer (Cockroft and Olsson, 1972).

The rapid wetting of the surface soil by flood irrigation caused the soils to slake, thereby restricting infiltration. This problem was severe on the loam soils of the Murrumbidgee Irrigation Area (MIA), New South Wales, and the Goulburn Valley, Victoria. Orchardists therefore ploughed the soil before every (or every alternate) irrigation, worsening the soil for the next irrigation. Even with the sandy soils used for citrus, the impact of water from overhead sprinklers tended to compact the surface of the soil and to reduce infiltration.

At first, irrigation and tillage treatments were applied to the entire floor of the orchard. This was wasteful because roots do not grow in compacted traffic-lines (Richards and Cockroft, 1974). Later, treatments were confined to a narrow strip along the tree-line, with the rest of the area under mown pasture. This was cheaper, trafficability was improved, and the risk of erosion was reduced (e.g. Baxter, 1970). Since the late 1960s, low-flow irrigation has gradually been replacing flood or overhead sprinklers, mainly for convenience and for better trafficability, although it has also resulted in water being used more efficiently (e.g. Black *et al.*, 1977). Low-flow irrigation is used to avoid the scalding of leaves of citrus in areas with salty water (e.g. Sunraysia and further down the Murray River).

DEVELOPMENT OF IMPROVED SURFACE MANAGEMENT

Attempts were made to eliminate tillage when it became apparent that excessive cultivation was responsible for serious soil degradation. A range of new surface-management techniques was tried, including 'bare surface', 'permanent sod' and 'mulch'.

In bare surface management, herbicides controlled weeds so that little organic matter was added to the soil. Initially oil was used as the herbicide, but this tended to make soils water-repellent. Later, more selective and less persistent herbicides (with improved specificity or ones that were non-persistent) were used (Campbell, 1971; Cary and Weerts, 1977).

With the permanent-sod technique, volunteer or sown pasture was mown six to seven times per year, with clippings retained on the surface. Where tillage continued to be used it was common to grow cover crops in winter and cultivate frequently in spring and summer.

With mulching, straw or black polythene sheeting was laid on the soil to control weeds and reduce wasteful evaporation from the soil surface.

Two or more techniques might be combined, for example with bare surface on the tree-line and sod (mown or suppressed with low levels of herbicides) or tillage between the rows. The orchard is thus permanently set up for irrigation by flood or sprinkler systems. In some areas laser-grading of the land has improved irrigation and drainage of the surface.

Few regions have been surveyed in detail to document the many and varied systems of reduced tillage now used in orchards. However, officers of the appropriate Departments of Agriculture have estimated the percentage of orchards under given systems in each region (Table 4.4). There is a clear trend away from tillage in orchards, except for stone fruit in the Murrumbidgee Irrigation Area (MIA).

Table 4.4 The percentage of orchards in each temperate region under a given system of soil management (State Departments of Agriculture, unpublished)

Region	System of soil management			
	Total bare surface[a] (%)	Bare surface strip[b]: Tillage[d] (%)	Bare surface strip[b]: Permanent sod[d] (%)	Tillage[c] (%)
Sunraysia:				
Citrus	10–15	30	50	2–5
Southern Victoria:				
Pome and stone fruit	1–2	0	85	10
Goulburn Valley, Vic:				
Pome and stone fruit	0	22	70	8
Riverland, SA:				
Citrus	75	0	25	0
Stone	0	0	55–60	40–45
Adelaide Hills:				
Pome	0	0	90	10
Stone	0	40	0	60
Murrumbidgee Irrigation Area:				
Citrus	98	0	1	1
Stone	0	0	0–45	55–100
Western Australia:				
Citrus, pome, stone	0	0	70	30
Tasmania:				
Pome	0	10–20	70–80	10

[a] Bare surface over entire floor of orchard.
[b] Bare surface on narrow strip on the treeline only.
[c] Orchard under some form of tillage for all or part of the year.
[d] Area between rows under tillage, or permanent sod mown or controlled by low rates of herbicide (called suppressants).

Where furrow irrigation is practised the soil must be tilled at least in spring to set up the orchard for irrigation, and again in autumn to set up for drainage. With stone fruit in the MIA and the Adelaide Hills, the whole orchard is tilled several times each year. With most citrus grown in the Riverland and the MIA, herbicides control weeds over the entire floor of the untilled orchard. In other regions, orchardists are gradually using bare surface on the tree-line, and controlling sown or volunteer grass, medic, clover or lucerne between the rows by mowing, with low rates of herbicides, or by tillage. At present few orchards are mulched, mainly because it is too costly to cart and spread conventional bales of straw. A few orchardists are finding it economical to spread large round bales on the tree-line using feeding-out machines, which are available commercially.

EFFECTS OF SURFACE MANAGEMENT ON YIELDS AND SOIL PROPERTIES

Yields

The response of fruit trees to different surface soil-management techniques has been variable, particularly in early experiments (Tables 4.2 and 4.5). Responses have varied with region, crop and even year. The yield responses to the various techniques are summarised below.

Permanent sod This practice has increased the yields of peaches, pears and apples (Table 4.5), but also reduced the yields of oranges at Griffith and of peaches near Melbourne (Bouma and McIntyre, 1963; Mitchell and Black, 1971). The lower yields were attributed to an insufficient supply of water or nutrients.

Table 4.5 Yield of fruit trees under various tillage practices

Crop	Yield (kg tree^{-1})				Reference
	Tillage	Bare surface	Permanent sod	Straw	
Orange:					
No N added	133	36	–	69	Bouma and
N added	146	182	–	141	McIntyre, 1963
Peach	82	79	96	76	Cockroft, 1966
Pear	73	–	84	70	Selimi and Keatley, 1969
Apple	39	64	76	–	Baxter, 1970

Mulch A mulch of straw has increased the growth and yield of peaches (Table 4.2). A mulch of black polythene sheeting also increased the yields of apples by 16%, of peaches by 10%, and of oranges by 36% (Bacon, 1974). Increased growth and yield due to mulching have been attributed to stable, permeable soil, less competition from weeds or sod for nutrients and water, greater volume of soil available for roots, and warmer soils in spring. Mulches have also decreased yields on occasions (Table 4.5), apparently because of greater waterlogging and denitrification in soil in spring.

Other tillage practices Hilling of the surface soil towards the tree-line has made more soil available to roots, especially where shallow surface soils limit the growth of the trees (Cockroft and Wallbrink, 1966b). Hilling also improves surface drainage and generally leads to larger trees and higher yields. Improved drainage of subsoils may also affect growth; for example, deep-ripping a hard clay pan in a red-brown earth almost doubled the vigour of peach trees in the Goulburn Valley (Bakker, 1977).

Soil management affects water supply to the crop, drainage and aeration, plant nutrition, soil strength and soil temperature. Therefore crop responses to altered management are complex. The variable responses to soil management highlight the need for the coordinated study of all components of the cropping system.

Soil properties

The following sections give details of the effects of various surface management treatments on the properties of soils in orchards.

Effects of cultivation

Immediately after cultivation, the soil is loose, and infiltration is high until the large pores are filled, then the deeper untilled layers control infiltration. Bouma and McIntyre (1963) reported that in a fine sandy clay loam at Griffith, the initial infiltration (0-30 seconds) in a citrus orchard was 1.9 cm and 1.0 cm in freshly tilled and permanent sod, respectively. However, the final infiltration (2-3 hours) was 2.7 cm and 11.5 cm respectively, indicating that destructive tillage of the surface layers had limited the redistribution of water to deeper layers. Crusts with low permeability may form at the surface after excessive tillage, leading to high runoff. A compacted layer, or tillage pan, may develop just below the tilled layer due to stresses applied by machinery, and this may restrict deeper penetration by roots and water.

Frequent cultivation oxidises organic carbon and limits the amount of residues added to soil. Levels of organic carbon and water-stable aggregation therefore decrease (Rovira and Greacen, 1957), leading to reduced infiltration. Haynes and Goh (1980) showed that organic carbon in the top 5 cm was 3.04% and 4.14% in orchards under tillage and reduced tillage respectively, while Bouma and McIntyre (1963) reported that water-stable aggregation (> 1 mm diameter) in a fine sandy loam in a citrus orchard at Griffith was 1.95% under tillage, 20.22% under permanent sod and 7.20% under bare surface.

Cultivation breaks organic bonds between aggregates so that after irrigation or heavy rain the weakly structured macro-aggregates slake to micro-aggregates. The slaked soil often sets to a hard compacted mass on drying, which subsequently restricts root growth in orchards and leads to severe erosion on sloping land (Richards and Cockroft, 1974; Slack and Duncan, 1981; Tisdall and Oades, 1982). Restriction of microbial activity by dryness between irrigations worsens the effect of tillage, but if the soil is kept moist by frequent irrigation, microorganisms may produce binding agents, which compensate partially for organic bonds broken physically (Tisdall *et al.*, 1978).

In summer, the upper layers of tilled soils are usually hotter than in covered soils and can reach temperatures that reduce the activity of the roots, so reducing the growth of shoots. Cockroft and Hughan (1964) and Chalker (1979) have shown that very high temperatures (see Table 4.6) in uncovered soils can damage and even kill roots in orchards.

Table 4.6 Soil temperature at 25 mm depth under various tillage practices (Cockroft and Hughan, 1964)

Treatment	Temperature (°C)		
	Highest recorded	Mean maximum	Mean minimum
Tillage	49	21	13
Bare surface	52	22	13
Permanent sod	24	15	12
Straw mulch	24	15	12

Roots are also cut by cultivation so that no roots grow in the tilled layer (Cockroft and Wallbrink, 1966a; 1966b; Mitchell and Black, 1968) (Table 4.7). Tillage reduces populations of earthworms (Figure 4.1) and shears the soil at some depth below the surface, sealing off shrinkage cracks and old channels formed by roots and earthworms. This results in few pores being continuous to the surface of the soil (Baeumer and Bakermans, 1973; Tisdall, 1978), thereby causing reduced infiltration in orchards. Deep tillage, however, loosens the subsoil and breaks any plough pans or compacted layers within range of a young crop and improves drainage, especially when the soil is stabilised with gypsum (Bakker, 1977).

Table 4.7 Concentrations of peach roots in silty soils in the Goulburn Valley under various tillage practices (Cockroft and Wallbrink, 1966a)

Depth Interval (cm)	Root concentration ($cm\ cm^{-3}$)			
	Tillage	Bare surface	Permanent sod	Straw mulch
8–0	0	0	0	1.5
0–8	0	2.0	0.3	2.0
8–18	1.7	2.4	1.5	1.4
18–30	0.5	0.6	0.8	0.7
30–45	0.5	0.4	0.7	0.7

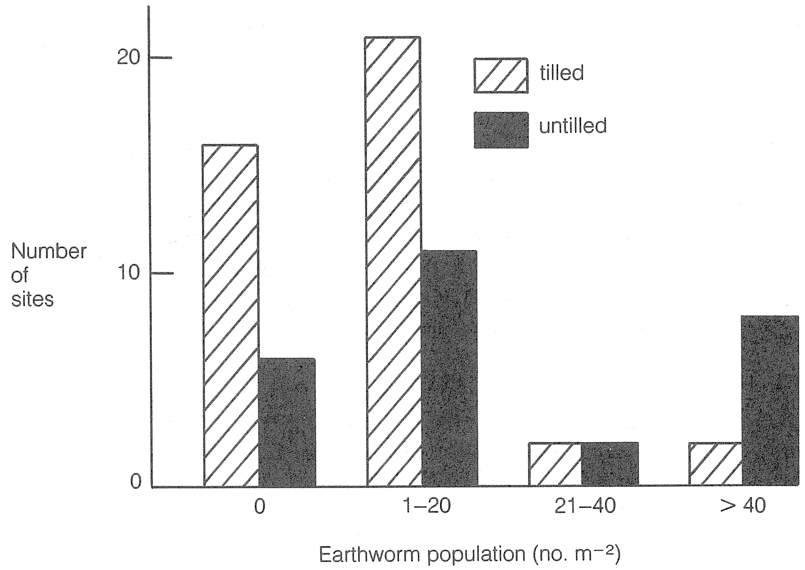

Figure 4.1 Distribution of earthworms in 69 tilled or untilled orchards (Tisdall, 1978)

Surface management without cultivation

Soils generally become compacted under reduced tillage, mainly at the expense of large pores (Bouma and McIntyre, 1963; Cockroft and Hughan, 1964). For example, in a fine sandy loam under peaches in the Goulburn Valley, the bulk density and macroporosity (% air-filled porosity at 4 kPa water suction) of soil (0-75 mm depth) were 1.4 g cm^{-3} and 9.0% respectively under conventional tillage, and 1.5 g cm^{-3} and 6.6% respectively when not cultivated (Cockroft and Hughan, 1964). However, roots are not cut, and some soils under reduced tillage contain pores that are continuous to the surface of stable soil. Roots and water follow these pores. This leads to high rates of infiltration, despite generally higher bulk densities. This increases the volume of soil and water available to roots (Bouma and McIntyne, 1963; Cockroft and Hughan, 1964; Tisdall, 1978; Ehlers *et al.*, 1983; Tisdall *et al.*, 1984).

Bare surface Under bare surface, with no added organic residues, levels of organic carbon gradually decrease, the soil becomes unstable with low macroporosity, and crusts form on the unprotected surface. Infiltration rates are low causing high runoff (especially where oil is used as a herbicide) and the risk of erosion is increased on sloping land. Soil may recover to some extent over winter (Cockroft and Hughan, 1964); the water-stable aggregation on a bare sandy loam left untilled for 6 months over winter increased by 48% (Adem and Tisdall, 1984). Soil temperatures (Table 4.6) and cycles of wetting and drying are more extreme and earthworm populations are lower than in covered soils in orchards (Haynes, 1980). Increased temperature in spring in a sandy soil under bare surface at Griffith may have lengthened the growing season for citrus, and led to larger trees when compared with other tillage practices (Williams and Gates, 1956). Bare surface has been used in low lying areas to limit frost damage in citrus and other fruit trees (Cary, 1968; Anon., 1979).

Replacing tillage with herbicides (i.e. bare surface) has not improved soil structure in orchards. However, systems where organic matter accumulates near the surface of the soil (i.e. permanent sod or straw mulch) do improve soil structure.

Permanent sod Intense faunal activity plus localised drying around roots under sod provide intimate contact between particles of clay and organic matter, forming and stabilising aggregates of soil (Allison, 1968; Oades, 1978). The network of fine roots and mycorrhizal hyphae can also bind soil micro-aggregates (20-250 μm diameter) into stable macro-aggregates (> 250 μm diameter), which remain intact even after being wetted rapidly (Tisdall and Oades, 1982). This stabilisation is usually rapid; the growth of ryegrass (*Lolium* sp.) for 6 months increased the water-stable aggregation of a red-brown earth by 35% when compared with an untilled control (Adem and Tisdall, 1984). Although infiltration and water-holding capacity are high in soil under permanent sod, the sod competes with the tree during the growing season. Therefore fewer crop roots grow in the surface layers of soil (Table 4.7). Trees and yields tend to be smaller than with other untilled treatments (Table 4.2), although frequent exceptions occur (Table 4.5).

Mulch Mulches cool the soil (Table 4.6) and slow down evaporation from the surface by shading and protecting it from wind (Baver *et al.*, 1972; Bacon, 1974; Richards and Cockroft, 1974). Therefore mulches encourage microbial production of stabilising compounds at the surface and keep the soil soft, since soils become harder as they dry (Barley and Greacen, 1967; Tisdall *et al.*, 1978). Roots grow up to the surface, and often into a straw mulch, thus increasing the volume of soil and water available for roots (Table 4.7).

Mulches also increase faunal activity and hence the macroporosity and supply of water to roots. In a mulched fine sandy loam in a peach orchard in the Goulburn Valley under frequent irrigation there were 2000 earthworms m^{-2} and macroporosity was 19%, compared with 150 earthworms m^{-2} and macroporosity of 5% where food and water were scarce; infiltration was 80 times higher in the mulched soil (Tisdall, 1978). Earthworms also benefit the crop by mixing organic residues, fertilisers and insecticides with the soil (Stockdill and Cossens, 1969; Tisdall, 1978).

On the other hand, waterlogging to the surface under mulches in wet seasons was found to reduce root growth of a sensitive species such as peaches in the Goulburn Valley and Melbourne districts, and even to kill the trees (Black, 1963; Cockroft and Hughan, 1964; Rowe and

Beardsell, 1973) especially in soils with compacted layers at depth. Mulches may also increase the risk of damage from frost with sensitive crops such as citrus and apricots.

DEVELOPMENT OF AN INTEGRATED APPROACH TO SOIL AND CROP MANAGEMENT

Soil management

In Australia until the 1970s, methods of soil management in orchards mainly followed those used overseas, with little thought given to the specific needs of the trees. However, since the yield of conventionally pruned and spaced fruit trees is related to tree growth, and tree growth to root growth, Cockroft and Tisdall (1978) developed a system of soil management for fruit trees in which they aimed to provide optimum physical properties in soil for unrestricted root growth. That is, soil conditions were consciously managed to meet the known requirements of the crop. From the results of 25 years of research on a shallow fine sandy loam overlying a heavy clay in the Goulburn Valley, they defined the physical properties of this soil that limited root growth. They then extracted from the scientific literature a set of standards for the physical properties of soil (i.e. water suction, macroporosity, penetrometer resistance, temperature) that would not limit the growth of roots. By integrating this information, they aimed to produce and maintain a large volume of stable, well-drained, mulched surface soil with:

* water suction maintained at less than 30 kPa;
* penetrometer resistance less than 1 MPa;
* soil temperatures close to 22°C;
* macroporosity 20% (air-filled porosity at 10 kPa water suction).

In order to meet these specifications an entirely new system of soil management was needed. This included soil modification to 60 cm depth, hilled surface soil with subsequent elimination of tillage, and use of a straw mulch and frequent irrigation. Shading by the crop canopy and mulch, and effective herbicides, controlled weeds. Peach trees grown under this system grew 3.2 m high in 3 years compared with 1.8 m for commercial trees, and produced 75 t ha^{-1} compared with the average commercial yield of 18 t ha^{-1}. After 9 years under this system, the surface soil remained soft and stable, with high rates of infiltration and rapid drainage. Root length to 60 cm depth was 60% higher than that of peach trees in an adjacent orchard where traditional tillage was practised. The deeper wetting and higher root concentrations through the profile made an extra 75 mm water available for transpiration. Each year, yields were at least three times the average in commercial orchards (Tisdall *et al.*, 1984).

With this type of integrated research, it is not possible to determine the direct effect each factor has on yield, but as stated by Greacen and Gardner (1982):

> Certainly there is enormous scope for further analytical work on the details of the physics of clay soils but more importantly, perhaps, a major part of research effort should now be of an integrative nature and directed more at the level of crop production.

Orchardists in Australia and overseas are using this system to some extent commercially (i.e. they hill up the surface soil, eliminate tillage, irrigate often) especially in modern orchards, which are close-planted (van den Ende, personal communication). But orchardists generally see the benefits in reduced costs and in convenience (i.e. better surface drainage, trafficability, easier irrigation), rather than in improved physical properties of soil or increased root length.

Cockroft and Tisdall's (1978) system for orchards also forms the basis for systems (described later) being developed at the Irrigation Research Institute, Tatura, for annual crops including vegetables.

Crop management

In modern orchards, close-planted trees start yielding fruit after 2 years compared with at least 4 years in conventional orchards (Olsson *et al.*, 1984). In the past, once the trees had filled their allotted space, pruning controlled vegetative growth and hence controlled internal shading and competition for assimilates. However, Mitchell *et al.* (1984) showed that controlled water deficits in the early stages of fruit growth may control shoot growth, but stimulate fruit growth later in the season. Therefore in close-planted trees, the aim is no longer to produce a large tree with a large, actively growing root system. Nevertheless, a well-structured, permeable soil is needed to:

* provide a large store of water at specific stages of fruit growth (e.g. during rapid growth of fruit in the 6-8 weeks before harvest) and not others;

* allow good drainage to protect the roots from waterlogging - but withholding water from soil for several months may worsen soil structure by reducing faunal activity and microbial production of stabilising compounds in soil.

SUB-TROPICAL TREE CROPS

Survival of the avocado industry has depended on the development of better soil-management practices in order to control *Phytophthora* root rot. This is the most important disease of avocado trees in New South Wales and Queensland. The causal fungus, *Phytophthora cinnamoni*, is widely distributed in Australian soils (Pratt *et al.*, 1971) and has been the major cause of avocado death.

A survey of avocado groves in north-eastern New South Wales and south-eastern Queensland indicated that the incidence of trees declining with *Phytophthora* root rot could be related to soil properties, despite the incidence of *Phytophthora* on all sites (Broadbent and Baker, 1974). Soil properties that suppressed root rot (in avocados caused by *Phytophthora*) were high levels of nitrogen, organic matter, exchangeable calcium and magnesium. These conditions were achieved by growing leguminous cover crops, maintaining pH of the acid krasnozem soil in excess of 6 with dolomite, and regular applications of organic matter and inorganic NPK fertilisers. Soils for avocado must be deep and well drained (Chalker, 1979), which can even rule out many krasnozem sites despite the favourable physical properties of these soils.

Several soil-management treatments designed to control *Phytophthora* were investigated by Trochoulias (1981) in a field trial that has been in progress for 9 years. Gypsum at 10 t ha^{-1} annually produced a significant yield response whereas dolomite treatments, which produced similar exchangeable soil calcium levels, were no better than controls. This trial involved a systems approach and the contribution by individual components could not be separated.

Any management system now used for avocados avoids tillage because of the damage it does to structure and possibly to roots, which predisposes trees to *Phytophthora* infection.

VEGETABLES

DISTRIBUTION

Australia has a wide diversity of climates and soils which allows most vegetables to be produced outdoors throughout the year. Most of the vegetables in Australia are produced during winter in the northern States and during summer in the southern States.

The value of vegetables produced during 1982 (Australian Bureau of Statistics) was $550m with Queensland contributing $181m, Victoria $152m and New South Wales $88m. Queensland had seen the biggest increase in production, with the value (CPI adjusted) increasing by $46m in the 5 year period to 1982. In contrast, the value has declined by $10m in New South Wales over the same period.

Production statistics (Table 4.8) reflect the relative importance of vegetables between States. These include both fresh market and processing crops, and some important differences occur. For example, Victoria produces the largest quantity of tomatoes in Australia but almost exclusively for the processing industry. All the tomatoes produced in Queensland are for fresh markets. Much of the increase in Queensland vegetable production has occurred at Bundaberg and Bowen through increased tomato production.

Table 4.8 State production of major vegetables for the years 1981/82

Crop	Production ('000 t)					
	Qld	NSW	Vic.	SA	WA	Tas.
Cabbages		12.4	29.9	7.7	6.6	
Carrots	27.0	19.7	30.6	11.1	13.0	12.9
Cauliflowers	6.2	15.4	37.5	10.0	17.0	3.2
Beans (green)	11.7	4.3				9.7
Lettuce	8.6	9.8	14.7	4.0	5.4	
Onions	36.9	19.5	14.4	37.5	11.7	19.2
Peas (green)		2.1			5.0	31.0
Potatoes	135.0	107.5	354.2	93.3	64.3	160.8
Pumpkins	27.6	8.9		6.0		
Tomatoes	59.6	42.3	126.7	9.3		

SOIL TYPES

Vegetable crops, because of their high value, are mostly irrigated. They are grown on a variety of soils from sands through to black earths (Table 4.9). Light textured, well structured soils are preferred because of good drainage characteristics. This minimises the occurrence of damping off and root-rot diseases and also allows ready access of machinery, which is important, particularly at harvest.

Table 4.9 Major soils used for horticultural production in Australia

Soil type	Description	Problems	Major crops
Sands	Deep, well drained, well aerated uniform texture. Very low fertility and water-holding capacity.	Very difficult to maintain water and nutrient supply to crops. Susceptible to wind erosion.	Suitable for those crops where water and nutrient supply can be maintained. Used for root crops such as potatoes.
Krasnozems	Deep, well drained, well structured clay-loams. Low-moderate fertility and water-holding capacity. For virgin state fertility high with 7% organic carbon, pH 5.5–6.5 tending to be more acid in higher rainfall areas with intensive cultivation.	Acidity of older cultivation sites requires amelioration with lime. High incidence of erosion in areas of high rainfall, particularly intensively cultivated areas where soil structure is degraded and levels of organic matter are low.	Suitable for most fruit and vegetable crops. Extensively used for potato production. Also used for avocado production in the sub-tropics.
Black earths	Weakly differentiated heavy clay soils with uniform texture. High fertility and water-holding capacity. Organic carbon 4%. Relatively free draining, pH 6.5–8.0.	The heavier black earths are prone to waterlogging, which makes management operations difficult after rain. Black earths highly resistant to erosion.	The lighter (alluvial) black earths (25%–40% clay) are widely used for vegetable production. The heavier black earths (45–60%) are less suited to root crops and are used for crops such as beetroot.
Red–brown earths	Weakly structured soils with light undifferentiated A horizons consisting of sandy loams, loams, clay loams and loamy sands. The depth varies from 20–40 cm with an abrupt change to a heavier clay B horizon. Low water-holding capacity and low–moderate fertility. Organic carbon 2%. pH 5.5–8.0.	Many red–brown earths have a silty texture, the structure of which deteriorates rapidly under intensive cultivation. After drying, the soil sets hard and this leads to poor water infiltration. Susceptible to erosion, and excessive tillage should be avoided.	The coarser textured soils are well suited to a range of fruit and vegetable crops. The silty soils are poorly structured and require modified tillage to prevent deterioration of structure and compaction. These soils are not suited to root crops such as potatoes.
Podzolics	Wide range of types. Shallow sandy-loam topsoil (25 cm) overlying a distinct clay horizon—low fertility, low water-holding capacity. pH 5.0–6.0.	Poor water penetration at depth, easily eroded. Excessive tillage should be avoided.	Not suited to deep rooted fruit and vegetable crops. Used for shallow rooted vegetable crops where irrigation is available.

TRADITIONAL TILLAGE PRACTICES

Cultivation is an integral part of vegetable production systems. A variety of implements are used including rotavators, tined and disced implements. The reasons for tilling the soil are similar for most field crops and Kuipers (1984) listed the main ones as burying crop residue and reducing soil bulk density. To horticulturists, an ideal seedbed is conceived of as soil that is finely worked to an adequate depth, free of crop residues and weed growth. This soil condition is often described as fine tilth and it was believed until recently that it improved water penetration, water-holding capacity, drainage and rate of root elongation.

The removal of crop residues and weed growth is helped by mechanical pulverisation. The rotavator is well suited to incorporating large quantities of plant material in the soil and has been widely adopted by intensive vegetable growers over the past 20 years. Unfortunately, the ease with which it can transform the soil into a finely worked condition has led to its exclusive use for soil preparation by some vegetable growers. Soil degradation and erosion have been associated with the continuous use of rotavators. The damage to soil fertility caused by over-cultivation is illustrated by data from a krasnozem soil (Wollongbar series) near Alstonville, New South Wales, in which the total nitrogen level of a virgin soil was 0.62% compared with 0.43% for cultivated soil (Colwell, 1958).

Chemical analyses of krasnozem soils used for tomato production near Tweed Heads on the far north coast of New South Wales are shown in Table 4.10. The Duranbah site (Table 4.10) had been used for continuous tomato production for the previous 10 years and a significant reduction in organic carbon and total nitrogen levels has occurred compared with the Alstonville site, which had intermittent cropping in rotation with pastures. The heavy use of NPK fertilisers has resulted in an increase in phosphorus and exchangeable potassium levels at Duranbah. Topography is undulating, annual rainfall exceeds 1500 mm with a high probability of heavy rain during most of the year. Soil erosion has been a major problem on these soils. Despite the uniformly deep profile of the krasnozem soils, continuous use of a rotavator produces an impermeable layer which compounds the erosion problem.

Table 4.10 Chemical analyses of a krasnozem soil from two sites on the Far North Coast of New South Wales

Sampling depth (cm)	pH[a]	Phosphorus Bray No. 1 (ppm)	Organic carbon (%)	Total nitrogen (%)	Exchangeable cations (mequiv %)			
					N	K	Ca	Mg
Alstonville:								
0–15	5.2	6	3.8	0.42	0.04	0.38	3.5	5.2
15–30	5.0	3	2.8	0.30	0.03	0.25	2.3	3.7
Duranbah:								
0–15	5.4	36	2.1	0.26	0.03	0.64	2.7	6.1
15–30	4.9	5	1.4	0.18	0.06	0.53	1.8	4.1

[a] in 0.01M $CaCl_2$

Excessive tillage is common in many other vegetable-producing areas of Australia. In the Goulburn Valley of Victoria both fresh market and processing tomatoes are grown on poorly structured soils where slow water infiltration and redistribution are problems. The fresh market crop has a high labour demand and is grown on small areas of leased dairy farms. Vegetation is removed by several disc harrowings followed by cultivation with tined implements to produce soil of fine tilth. At this stage, the soil consists of 25% aggregates 0.5 mm diameter, and water-stable aggregation is half that of the same soil under pasture (Adem *et al.*, 1984). Water infiltration and movement is a problem from irrigation that is applied in furrows. The grower cultivates the soil to remove the hard pan prior to each subsequent irrigation while the plants are small. During the later growth stages, daily irrigation may be required.

Processing tomatoes are grown on areas of up to 150 ha in the Goulburn Valley where the land must be graded to facilitate furrow irrigation. Initially, contractors laser-grade the land, and rip the soil to a depth of 0.3-0.4 m with two or three large tines, to even out compacted and filled areas. In January, the grower disc-cultivates the land, then in May-June he forms rough beds in long straight rows, with a bar, a rotary bed former or traditional hilling shoes. The soil is finally tilled to incorporate fertilisers and herbicides and a final bed shaping is carried out before direct sowing. The naturally poor infiltration and drainage characteristics of soils in the Goulburn Valley are further compounded by this excessive tillage. Daily irrigation is needed until seedlings emerge. Prolonged periods of waterlogging predispose the seedlings to disease. *Phytophthora* root rot is now a serious problem on these soils.

CROP ESTABLISHMENT AND PRODUCTION REQUIREMENTS

Seedbed preparation and crop establishment

Most vegetable crops are grown on raised beds to improve soil drainage either for multi-rows or single rows, depending on species. As there is very little scientific information relating soil physical conditions to seed germination and seedling establishment, it is not possible to define ideal seedbed conditions. Nevertheless, finely worked seedbeds, whether required or not, are used for the establishment of vegetable crops throughout Australia. Vegetables are established from seed sown into the field or from transplants.

Pre-germinated seed has been found to be superior to conventional drilling where the seed is sown with a fluid carrier gel (Salter, 1978). Soil conditioners, gypsum, mulches and transplanted seedlings have been used to reduce or avoid the effect of crusts (Oades, 1976; Adem *et al.*, 1982; G.H. Price and C.R. McMahon, unpublished data; J.F. Gage and C. Narhung, personal communication). Mulches (straw or polythene) in vegetable crops have been shown to:

* allow slow drying of the soil around the seed and roots;
* protect the surface from the impact of raindrops;
* reduce extremes in soil temperatures, with better germination, and earlier or higher fruit set;
* control weeds and so reduce the cost of herbicides;
* reduce soil splash, which may reduce some diseases, although others may increase;
* encourage biological activity in soil (Sumeghy, 1970; Quinn, 1975; McLean *et al.*, 1982; Sarooshi *et al.*, 1982; Burt and Muller, 1983; Cox, 1983; D.R. Phillips, personal communication).

There has been a significant trend towards the use of container-grown (cell) transplants for vegetable production in recent years. The advantages of transplanting over direct sowing (McKee, 1981) include:

* maximum use of available land by shortening the growing season;
* more precise plant densities and elimination of thinning costs;

* possibility of selecting transplants for vigour and uniformity;

* less critical soil preparation and weed control.

Transplanting is more labour intensive and costly than direct sowing and a check in growth at transplanting can be a problem. This check rarely occurs with cell-grown transplants because there are sufficient established and experienced commercial enterprises supplying high-quality transplants. The most important requirement for the transplants is to ensure that the crop is well irrigated during the establishment period. Higher yields and earlier maturity have been reported for cell-grown summer lettuce (Fisher and Burge, 1979).

Liming and nutrition

Many soils used for vegetable production along the east coast of Australia are acid, and treatment with lime is necessary; the lime must be thoroughly incorporated in the soil to be effective. This requires some form of relatively deep tillage. Following initial treatment, the krasnozem soils on the Far North Coast of New South Wales require annual maintenance applications of about 2 t ha^{-1}.

Pre-plant fertiliser containing the major nutrients is needed to promote establishment and early growth and this is most efficiently applied in a band beneath the seed or transplant. Banding of superphosphate in preference to broadcast application is important on soils with a high phosphate-fixation capacity such as the krasnozems (Aitken and Hughes, 1980).

NEW APPROACHES TO SOIL AND CROP MANAGEMENT FOR VEGETABLES

The importance of organic matter is appreciated by few vegetable growers and therefore attempts to maintain or replace it are not widely made. Some market gardeners do add organic matter, especially to sandy soils, usually as fowl manure where a poultry industry is located nearby.

Levels of soil organic matter can be increased by a reduction in tillage and by ley-farming and the use of green manure crops. The importance of crop rotation and soil management is well illustrated by the following case studies.

The benefits of ley-farming can be seen by comparing management strategies used in two areas of krasnozem soil in north-eastern Australia. The intensive tillage practices used by vegetable growers on the coast near Tweed Heads were discussed earlier in this section (see Table 4.10). Tomato yields are from half to two-thirds that of their counterparts at Bundaberg where careful attention is paid to crop rotation.

The benefits of conservative crop rotations are displayed at Acacia Plateau, a small area of krasnozem soil about 100 km west of Tweed Heads, where an extensive pasture rotation is used for potatoes. Pasture (predominantly *Pennisetum clandestinum* (kikuyu)) is cultivated and sown to potatoes, returned to oats, sown again to potatoes then returned to pasture for about 3 years. After about 12 months, kikuyu re-establishes as the dominant pasture. This practice maintains organic carbon levels in excess of 5%. Infrequent supplementary irrigation is required with the well structured soils. Potato yields are twice the national average with significantly higher values for specific gravity of tubers and a premium paid for the fresh market crop. Disease incidence is very low.

Poor management has played a role in the occurrence and spread of Race 3 *Fusarium* wilt in tomatoes at Bowen. Located on the central coast of Queensland, Bowen has become the major winter-early spring tomato-producing area of Australia. The area under cultivation has expanded rapidly since the early 1970s. Continuous cropping has been widely practised and Race 3 *Fusarium* wilt, the first time it has been recorded in the world, appeared about 1980. The management practices used ensured the spread of this disease and it is now of major economic significance.

Minimum-tillage systems

The vegetable industry in Australia is geographically and politically fragmented. Unlike the larger primary industries such as wheat, wool and beef, it provides very little research funding. This means that matching government funds are not available, severely restricting the number and scope of vegetable research projects.

Some research funds have been made available for broad soil-conservation problems facing primary production generally. However, it remains to be seen whether any of these funds will be used to investigate the widespread soil degradation and erosion problems faced by the vegetable industry. In contrast, in 1985 there were 23 projects being conducted across the United States on production aspects of minimum tillage, no-tillage and conventional tillage systems.

The tillage requirements of the major vegetables produced throughout Australia need to be investigated. The availability of a comprehensive range of pre- and post-emergent herbicides has eliminated the need for tilling the soil for weed control. This approach must involve an assessment of the long term benefits for a particular system.

A system that is gaining wide acceptance for the production of high-value vegetable crops such as tomatoes and cucurbits is that of utilising a polythene mulch and trickle irrigation. The system was assessed by Sumeghy *et al.* (1983) and consisted of raised beds with the trickle irrigation line placed off-centre on top of the bed and polythene mulch covering the whole bed. In Bundaberg, Queensland, there has been the most widespread adoption of this system (J. Barnes, personal communication). Its main advantages are reduced water use by strategic placement of water during irrigation and the potential for optimising nutrition by frequent side-dressing of nitrogen and potassium fertilisers through the trickle irrigation. The main advantage of the polythene mulch is elimination of tillage to control weeds.

At the Irrigation Research Institute, Tatura, a system has been developed for double-cropping vegetables on permanent beds of shallow silty soils (Adem *et al.*, 1982; Adem and Tisdall, 1983, 1984; Adem *et al.*, 1984). The system is based on reduced tillage, mulching, and hilled surface soil with compaction confined to permanent furrows. In one or two passes, a spring-tined cultivator tills pre-irrigated permanent beds (at a water content just below the 'lower plastic limit') to produce a coarse tilth (Table 4.11) for good infiltration. Infiltration rate is

Table 4.11 Size distribution of aggregates of a silty soil prepared for annual row-crops in the Goulburn Valley (Tisdall and Adem, 1986)

Position	Aggregate-size distribution (g/100 g soil)				
	>20[a]	10–20	1–10	0.5–1	<0.5
Sowing line	5.7	32.3	47.8	7.0	7.3
Rest of bed	40.8	26.0	26.6	3.0	3.6

[a] Size-range of aggregates (mm).

inversely related to the percentage of aggregates less than 0.5 mm diameter. A small rotary hoe ahead of the seeder produces a fine tilth on the sowing line to enable good contact between seed and soil and a low risk of a crust forming, resulting in good germination and emergence of seedlings (Table 4.12). The roots of the disc-seeded cereal grown the previous winter help to stabilise the soil. Several operations are combined in one pass, and wheels travel along the permanent furrows, thereby reducing compaction of the beds. Beds are wetted by capillarity from water confined to 5 cm depth in the furrows to minimise slaking of soil in the furrows. This system has been used for several types of crops on the same land for several successive years, and the soil has remained stable, permeable and soft. Large increases in productivity have been reported. However, vegetable growers in the Goulburn Valley, as elsewhere in Australia, will be slow to adopt new tillage practices, which they consider a low priority behind other management practices.

Table 4.12 Emergence of maize seedlings in the Goulburn Valley in beds of a silty soil tilled with (R^+) or without (R^-) a small rotary hoe on the sowing-line (Tisdall and Adem, 1986)

Treatment	Days to 30% emergence	Final emergence (%)
R^+	5	84
R^-	7	69

Other specific benefits have been reported for minimum tillage. Rowse, Stone and Greenwood (1984) are developing a minimum-tillage system utilising a low-ground-pressure drilling system for wet soils, which allows planting schedules to be kept. Where irrigation is not used, minimum tillage conserves topsoil moisture and allows sowing to be carried out under moist soil conditions (Elliott, 1978) and higher yields have been reported for cabbage, cucumber, squash and tomato relative to crops sown by conventional tillage (Morse *et al.*, 1982). It would appear that specialised machinery needs to be developed before minimum tillage can be used (Morrison *et al.*, 1973).

Apart from the foregoing examples, most attempts to reduce cultivation for vegetable production have lacked an integrated approach and, in most cases, yields from minimum-tillage systems have been lower than from conventional tillage (D.E. Halseth, D.E. Knavel, H.J. Mack and H. Price, unpublished). McGuire (unpublished) indicated that weed control was a major problem without tillage. The costs of satisfactory weed control made the economics of no-tillage questionable (F.J. Benson, J.G. Elterich, unpublished). In these cases, comparisons are based on short-term experiments and the benefits of minimum tillage could become more obvious over the longer term.

In the coastal areas of eastern Australia, vegetable production is located in high-rainfall areas and soil erosion has been a major problem. Where conventional tillage is practised, even with better crop rotations, improved soil conservation together with improved drainage systems are required. Minimum-tillage systems must be investigated as a longer term solution to this degradation of soils. Conservation-farming practices utilising living mulches may also warrant investigation.

CONCLUSIONS

Degradation of soils through excessive tillage has been a common problem with horticultural production in Australia - loss of organic matter, soil compaction, declining soil structural stability, soil crusting, slow infiltration, high runoff and erosion and, in some cases, increased incidence of diseases.

The principles associated with improving levels of organic matter and soil structure are well established but the development of practicable farming systems requires much more work.

Methods of soil management aimed at reducing the amount of tillage have been developed for some tree crops and vegetables. These have been most successful where an integrated approach to soil and plant management has been adopted. They have led to improved soil structure and higher yields. Despite the successful development of soil-conserving management practices their adoption has been slow, and then mainly for convenience or to reduce costs. Horticulturists are often unaware of the benefits to the soil and the crop.

While there is awareness of the need to preserve good agricultural land in Australia, more extension is required so that commercial horticulturists are made aware of the benefits of proven management systems, and encouraged to experiment with novel systems of their own when successful alternatives to traditional practices are unavailable. Much more research on soil-conserving systems is needed, particularly for vegetables where the research effort is small and problems of high herbicide costs and the need for specialised machinery generally make minimum tillage systems uneconomic.

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