NATIONAL PROGRAM FOR
Sustainable Irrigation

A Review of Dr Bruce Cockroft's Work for Australian Irrigated Horticulture

Milestone Report 2

R.S. Murray

School of Earth & Environmental Sciences

The University of Adelaide

Published by: Land & Water Australia on behalf of the National Program for Sustainable Irrigation

Postal address: GPO Box 2182
Canberra ACT 2601
Office: L1, The Phoenix Building
86 Northbourne Ave
Braddon ACT
Telephone: 02 6263 6000
Facsimile: 02 6263 6099
Email: Land&WaterAustralia@lwa.gov.au
Internet: www.lwa.gov.au

Acknowledgment

The National Program for Sustainable Irrigation focuses research on the development and adoption of sustainable irrigation practices in Australian agriculture. The aim is to address critical emerging environmental management issues, while generating long-term economic and social benefits that ensure irrigation has a viable future. The Program has fourteen funding partners who are: Land & Water Australia (Managing Partner); Department of Agriculture, Fisheries and Forestry; Department of Natural Resources and Mines and Water, Queensland; Department of Primary Industries & Resources, South Australia; Department of Environment Water & Catchment, Western Australia; Department of Agriculture, Western Australia; Cotton Research & Development Corporation; Horticulture Australia; Goulburn-Murray Water,Victoria; Harvey Water, Western Australia; Lower Murray Water Authority, Victoria; Sunwater, Queensland; Grampians Wimmera Mallee Water, Victoria and the Ord Irrigation Cooperative, Western Australia.

Publication information

Title: A Review of Dr Bruce Cockroft's Work for Australian Irrigated Horticulture, Milestone Report 2 by R.S. Murray.

Product Code: ER071300

ISBN: 1921253525

Table of Contents

A REVIEW OF DR BRUCE COCKROFT'S WORK FOR AUSTRALIAN IRRIGATED HORTICULTURE

SUMMARY

The work of Dr Bruce Cockroft has established the importance of managing soil structure in irrigated horticulture in Australia. In particular, he has researched and promoted management strategies designed to maximize the rooting volume of irrigated crops with consequent substantial improvements in yield. These strategies have focussed on the creation and maintenance of good soil structure and structural stability and of low resistance to penetration, particularly in soils that are of poor structural quality.

INTRODUCTION

Over a period of more than 50 years Dr Bruce Cockroft has conducted research aimed at increasing the productivity of irrigated Australian horticulture through improved soil and irrigation management. Much of this work has been field-based research on red-brown earths with structurally fragile, shallow A horizons and impermeable clay B horizons in the Goulburn Valley, Victoria. These soils account for most irrigated production of peaches and pears and of tomatoes and vegetables for canning in the Goulburn Valley and also for a large amount of tree fruit, vines and vegetable production elsewhere in Southern Australia (Murrumbidgee Irrigation Area, Barossa Valley). An enduring theme of this research has been the growth of plant roots and the identification and removal of soil constraints to the development of extensive root systems. Such extensive root systems have improved productivity and secured unrealized yield potential. In the past 15 years Bruce's work has largely focussed on the creation and maintenance of soil structural quality in keeping with the concept of a "super soil", a soil which regularly produces 2-3 times Australia's best productivity.

He urges a system of soil management which begins with ripping and hilling/bed-forming in conjunction with the adoption of 11 measures (see below); these can really only be established *in toto* for new plantings and soil preparation may take some time. He maintains that virtually all 11 of these measures are required for the perpetuation of a very good soil but points out that few growers have implemented more than half of them. His findings are supported by experiments in pots and plots but do not appear to have benefited from extensive, rigorous field trials published in refereed journals which detail sustained and replicated yield gains.

His research and management recommendations have been communicated via refereed papers in reputable journals, in books, at conferences and in the "grey literature". In particular he has communicated directly to producers via quarterly growers reports.

EARLY WORK (1955-1990)

Grey literature (1955-1965)
An early publication with Hughan in 1955[1] reported on soil management trials established at Tatura in 1948 and noted that the highest peach yields occurred on soil under straw mulch where it was suggested root growth benefited from good soil structure, a steady supply of water and nutrients, no early competition from the roots of cover crops, absence of cultivation and moderate soil temperature. Other soil treatments, involving cultivation, root competition, a bare soil surface or alternate bay irrigation were considered to lack at least one of these factors which promote good root proliferation. It was also noted that, under the conditions of this trial, the cost of straw mulching could easily be met by the yield benefit. A new trial (established after the destruction of the old one by an excessively wet winter in 1956) was examined[3] after 4 years and considered soil management, tree spacing and replant site problems. Again straw mulching produced the highest early vigour (as gauged from butt circumference), especially on a site previously planted with clover. Tree spacing and replanting did not appear to be major factors in early vigour. Further publications during this period dealt with the scheduling of irrigation in orchards using tensiometers at depth, fruit growth measurement, soil consistency evaluation by hand, and evaporation measurements for guidance[2]; an examination of the physical properties of 10 representative Victorian soils in relation to their fertility[4] and a pedological survey of the soils of the Goulburn Valley area in relation to their potential for irrigated horticulture[5]. These early publications in the grey literature set the scene for the main thrust of Bruce's research in the future and lead to a new system of soil management which was rapidly adopted by fruit growers[40] ("system 2", Table 2).

Refereed and other publications (1966-1990)

Refereed publication began in 1966 with the examination[6] of 150 paired sites to explain the wholesale loss of many, but not all peach trees in the Goulburn Valley a decade earlier. This work concluded that depth to a restricting soil layer, thought to affect the rate at which the water table begins to encroach into the root zone was the main cause; no dead trees occurred where this was deeper than 3m. Further work with peach and pear trees followed[7-9]. The roots of orchard trees (peaches, pears) growing in Red Brown Earth soils were observed[7] to be as shallow as the conditions imposed by surface soil management (cultivation depth, competition with cover crops, soil temperature) would allow. These roots were also confined to the top 0.9m of soil by the impenetrable clay B horizons below, creating a rather limited root volume. This contrasted with the much deeper root systems (several metres) found for these trees elsewhere in the world. Further work[8] showed fruit yields were similarly affected and that surface soil management (mulching, reduced cultivation, herbicide) could improve matters by effectively enhancing the volume of soil available for root growth. The vigour (butt circumference) of these trees was also found[9] to be correlated with the available soil depth. This early work was underpinned by studies[10-11] of the mechanics of root growth which suggested that the process of root growth is quite different from the usual process of measuring soil penetration resistance in that root growth involves cylindrical expansion of the root and much less friction with the soil. Publication in the grey literature continued in relation to the trial discussed above. Cockroft and Morris[13], noting that peach trees are relatively short-lived and that there must be a replanting program in any peach orchard, examined possible causes of poor establishment. The trial established in 1958 (see Cockroft & Morris, 1963) was used as the basis for this. Factors examined included previous soil management (an earlier trial), soil management since the new planting, effect of replanting where peach trees were previously grown and the effect of supporting young trees with stakes. Early vigour was seen to be depressed by continued cultivation and bare soil but improved by 15cm thick straw mulching (especially on soil previously mulched or sown to clover) ripping + gypsum and on soil previously sown to clover/lucerne (these last two were both attributed to better subsoil drainage). No effects of replanting in former peach tree sites or of staking young trees were observed.

During the 1970's the research was largely focussed upon either root growth in relation to the soil water regime or upon root proliferation in relation to the management of soil structure and its stability. It was observed[14] that very little root growth in peach trees occurred in Summer, compared with Spring and Autumn, even in the absence of obvious water stress and it was suggested that root growth may be suppressed by relatively fast soil drying rates caused by rapid transpiration, low soil water storage and confined root volumes. Further work[17] confirmed that there is indeed no inherent root dormancy in summer and that root growth declined with the increased drying rates caused by high root concentrations, increased transpiration and infrequent irrigation. It was concluded that while "normal" irrigation practice met transpiration needs, root growth was suppressed but that with more frequent irrigation (to –40kPa), it continued all season. However, there appeared to be no productivity benefit (pruning weight, fruit dry weight) of this enhanced root growth in the first season.

The importance of soil management was also established during the 1970's. A study of peach tree roots[15] showed that roots largely avoided the traffic zone between tree lines because of its high penetration resistance resulting from cultivation, traffic compaction and flooding. The surface soil in this traffic zone was regarded as effectively wasted and it was recommended that it either be used to create larger raised banks for root exploration or, better, to be managed in ways which produced and preserved better structure and encouraged root growth (biological activity, capillary wetting, more frequent irrigation). The problem of replanting was also examined[16]. Peach trees are relatively short-lived so early establishment is important but this was seen to be compromised by the poor rooting volumes imposed by cultivation, traffic compaction, weeds, high temperatures, shallow topsoils and hostile subsoil. Based on a trial involving 2 years of establishment on an old site, straw mulch was again clearly found to promote the best growth (butt, circumference, pruning weights) with some carryover effects of previous practice (cover crops, cultivation). Roots were found growing in the mulch confirming that the depth of soil and the quality of that soil are important issues.

The research by this stage was increasingly concerned with rooting volume as a major limitation to the realization of potential yields and the management of soil structure was firmly on the agenda. A chapter[18] in the book *Modification of Soil Structure* reported that good management of soil structure had quadrupled yields of irrigated peach trees on a difficult duplex soil. Increases in soil volume and improvements in physical properties could be created and then sustained by:

- Deep ripping to 600mm with gypsum addition and cultivating in straw before planting.
- Mounding up soil as a bank in the tree line, where it could support root growth, leaving traffic to move on subsoil.
- Zero cultivation, reduced traffic, organic matter addition, spray irrigation for slow wetting and frequent irrigation (to –30kPa or wetter) to sustain root growth so that the structure and structural stability of the soil improves.
- Weed control with herbicides.
- Use of the tree canopy and mulching to moderate soil temperatures.
- Test wells to monitor the B horizon for water-logging.

These recommendations for the creation and maintenance of enhanced rooting volumes were underpinned by a study[19] of the impacts of organic materials, microbial activity and physical disruption on the structural stability of soil. This study concluded that:

- While readily decomposable organic matter (e.g. oaten hay, sheep faeces) stabilized soil aggregates, slowly decomposable organic matter (e.g. pre-rotted organic matter) did not.
- Any restriction of microbial activity in soil increases the impact of aggregate disruption on aggregate stability and this is not countered by the addition of organic matter. This means that soil disruption (cultivation) and field conditions which curtail microbial activity such as rapid drying and high temperatures should be avoided by maintaining moisture and screening the soil from radiation.

In 1980 Olsson and Cockroft[20] re-iterated that they considered unrealized potential in horticultural production to be due to soil physical constraints to root proliferation and activity. They approached this by considering what roots require in terms of matric suction (<0.5 bar), air-filled porosity at field capacity (>15%), penetration resistance (<0.6MPa) and soil temperature (18˚C). Management strategies were suggested to optimize water availability (no till, organic matter, mulching, soil water monitoring, spray irrigation), aeration (winter runoff, deep ripping + gypsum), penetration resistance (raised banks, controlled traffic, moisture maintenance) and soil temperature (canopy shading, mulching). They pointed to outstanding peach yields as evidence of the success of these strategies and to the attainment of superior profitability 3 years after planting. Furrow-irrigated tomatoes were discussed as an example of annual crops which benefit from similar measures. Here they suggested that the soil forming the hills should not be pulverized but formed into aggregates so that there is less slaking and that the hills should be wet up by capillarity from furrows which are never filled by irrigation; this also alleviates aeration problems. While they acknowledged that soil penetration resistance may be more pronounced under the more intense cropping conditions associated with tomato production, the promotion of aggregated topsoil, subsoil treatments and traffic minimization provided opportunities to reduce the problem while canopy shading can reduce soil temperature.

In discussing irrigation in general[21,23] Bruce Cockroft and co-authors have pointed out that while Red Brown Earths are Australia's most important irrigated soil group, their generally hostile B horizon and fragile A horizon underlies a history of structural collapse under irrigation. The clay B horizon is usually poorly drained so that the soil remains wet longer accelerating structural collapse and leading to disease and loss of nitrogen. The A horizon is usually high in sand and silt, has low organic matter and biological activity so that it slakes easily leading to crusts and high strengths. Cultivation to break up this poor structure just makes the soil more unstable towards subsequent wetting events. These poor properties have in the past fuelled a swing away from crops towards pastures.

The best soils have properties that contrast with those of Red Brown Earths and produce greatly superior yields under similar conditions. Indeed, at the time of publication, the authors pointed out that average commercial yields of irrigated horticultural products in Victoria were only about 30% of the best experimental yields. However, they also held that these soils have the most potential for improvement using appropriate management[18]. They regarded continuous moist (not wet) conditions as the key to the continuous activity of roots and microbes which is essential to the creation and maintenance of good soil structure. In this regard the authors held that rapid drying is to be avoided but also acknowledged that this is difficult to do. Nevertheless, early indications from field trials showed substantial increases in production (over district averages) on “modified” Red Brown Earth soils (pastures x2, peaches x4).

In 1985 Cockroft, Mason and Martin[22] reviewed the previous 50 years of agricultural science achievements, irrigated farming problems and how they had been, and were being solved, using irrigated pastures, field crops, row crops and horticulture as examples. They pointed to management innovations such as laser land-forming, soil amelioration, minimum tillage, wheat varieties, biological control and grazing management. They also discussed changes in whole farm systems using as examples the dramatic changes that have occurred in the production of tomatoes, prime lambs, dried vine fruit and tree fruit. They concluded by lamenting the relatively inefficient conversion of irrigation water into farm product in Australia and argued against the urbanisation of agricultural science and in favour of well-funded scientific research programs based in the main production areas where easy communication with producers can occur.

INTENSIVE SOIL PREPARATION AND MANAGEMENT (1990-)

In 1993 Cass, Cockroft and Tisdall[25] noted that the expansion of deciduous fruit and viticulture was likely to occur on inferior soils leading to poor yields and sustainability. In particular they observed that in climatic zones suitable for Australian grape production, “good” soils are limited and new enterprises are likely to encounter shallow topsoils overlying hostile subsoils. They stated that most growers are so accustomed to poor soil structure that they do not recognize it as a major limitation to productivity and pointed out serious shortcomings in soil preparation and management.

- Deep ripping is often ineffective and needs to be carried out slowly, possibly with several passes at increasing depth, with appropriate implements at suitable water contents (below the plastic limit) then stabilized with added calcium. The object is to fragment the subsoil to less than 20mm, not to powder (too dry) or remould it (too wet), and to create continuous pores to depth.

- The added calcium requirement (lime or gypsum) should be properly assessed depending on soil pH, sodicity and free lime. If the subsoil is sodic, gypsum must be applied in advance of deep ripping to ensure that the ripping is effective.
- Although commonplace in new orchards, few grape growers hill the topsoil in the vine row where the structure of this deeper, untrafficked topsoil can be well-managed and where roots can proliferate.
- Drip irrigation which is particularly deleterious to soil structure is widely used instead of sprays and is counter-productive in that it limits root exploration and promotes the congregation of roots in small volumes. Minispray irrigation was recommended over drippers as it produces slower wetting and extended root growth over a greater soil volume. Application rates <5mm/hr are recommended. Soil wetness encourages structural collapse and requires close management.
- Adjacent soil is subjected to heavy traffic compaction which is cumulative and difficult to reverse. The no-till technology developed in the fruit industry needs appropriate application to viticulture.
- Use of fibrous roots such as ryegrass seems unknown. Fibrous root systems stabilize pores and create new pores in the winter. This can be sprayed off in spring (with a herbicide which leaves seeds intact for regeneration) to create a population of living or dead roots in the soil at all times.
- Soil is left exposed to rain and forms surface crusts. The dead rye grass can be supplemented with straw in Spring as a mulch to protect the soil surface and to encourage earthworms.

The authors pointed out that a large range of pore sizes is needed in soil to fulfil various functions such as adequate water storage and aeration, good infiltration and low resistance to penetration and that management should aim to preserve the appropriate minimum proportions of these various pore classes. Macropores in particular are vulnerable to disruption from traffic and irrigation, particularly drip irrigation. In reviewing the work of others, the authors noted that grapevine roots penetrated soil by 2-3 metres when structure was non-limiting and also populated surface soil under good conditions (temperature, moisture, absence of cultivation). They held that there is no doubt that better and more uniform conditions in the vineyard will improve grower control of production and quality.

Despite the lack of good soil resources to underpin expansion of irrigated vineyards and orchards, the authors recommended a heightened recognition of poor soil as a limit to production and good site selection supported by soil tests. They expressed optimism about the potential to establish and maintain good soil structure with careful and rigorous preparation and management[18]. They noted that each of these management components had been field-tested in the Goulburn Valley and that good yields had been obtained by establishing near perfect soil conditions prior to planting. However, they also noted that the narrower row spacing in vineyards than in orchards (3-4 versus 6 metres) demanded some development of this management approach for application to vineyards.

Olsson, Cockroft and Rengasamy contributed to the book *Subsoil management techniques* in 1995[27]. They began with the premise that plant production approaching the potential yields based on sunlight and water can only be obtained from soils which support the largest root systems. They noted that research on soil amelioration had largely been focussed on top-soil and that current attempts at sub-soil amelioration were generally short-lived. They proposed to establish guidelines for field management for different crops. It was pointed out that sub-soil constraints lead to small root systems which are poorly buffered against excursions in water availability, aeration, temperature and nutrient concentrations and require frequent irrigation. They indicated that poorly permeable sub-soils lead to saturation during irrigation and rain but that poor water storage and movement means that roots cannot sustain substantial transpiration rates for very long after irrigation and need frequent irrigation compared to deep, extensive root systems. In reviewing the work of others, they showed that while deep tillage improves root concentrations in the subsoil, the roots congregate in the voids between peds rather than occupying the whole soil volume; indeed the authors point out that although soil may have macropores, the matrix itself may be quite hostile to roots. They proceeded to suggest subsoil improvement strategies based on:

(1) assessment and amelioration of soil chemical constraints (toxins, sodicity, nutrients),
(2) deep tillage based on sound soil engineering principles and with suitably designed tines, and
(3) stabilisation of tilled subsoils by the encouragement of roots, hyphae, micro-organisms and earthworms using slow irrigation to ensure wetting under tension.

They concluded with management suggestions for fruit trees, row and field crops; these emphasized the importance of traffic avoidance, maintenance of continuous root growth and slow (spray) irrigation.

In 1995 Cockroft and Cass[26] wrote a useful chapter for a book intended as a resource for those interested in Australian horticultural production. This work reviewed the 5 main soils used for horticulture in Australia and discussed soil requirements for good plant growth, principles of irrigation, drainage, fertilizer use and salt management as well as soil preparation and management based on the ideas developed in irrigated orchards. The book contains some information about specific crops such as citrus, vines, sub-tropical fruit and vegetables. In relation to vineyard management, the work recommended winter cover crops in the vine bank and spray irrigation. It acknowledged the difficulties in direct adoption of orchard approaches to soil structure management due to closer row spacings but urged serious efforts to reducing the mass and frequency of mid-row traffic or the adoption of machinery that straddles rows.

In 1997 Cockroft and Olsson K.A. wrote *Case study of soil quality in south-eastern Australia: Management of structure for roots in duplex soils*[31] based on their experience with irrigated tree and row crops. Table 1 below, adapted from their work, summarizes their recommendations.

Soil physical attributes needed for extensive root proliferation	Conditions required to create these soil attributes	Field operations
Large volume accessible to roots	• Soil loosened to 500mm • Maximum volume of surface soil • No compaction • Minimum root cutting by cultivation	• Deep tillage, subsoil stabilized. • Bed-forming/hilling • *Controlled traffic* • *Reduced tillage*
Penetration resistance low (<0.5MPa) over the agronomic range of water contents	• Loose, soft soil • Low strength aggregates • No large clods	• All of above • *Calcium and organic matter additions* • *Winter cover crops* • *Slow wetting and avoidance of saturation*
Continuous soil water supply	• Adequate macroporosity (>15%) for infiltration • Adequate water storage pores (>20%) • Adequate unsaturated hydraulic conductivity (>10^{-9} m/s @ -100kPa) • Reduced evaporation	• All of above • *Summer mulching* • *Moisture maintenance*
Aeration/drainage (>15% air-filled porosity[a] ; >10% oxygen in soil air)	• Adequate macroporosity (>15%) • Good drainage • Absence of shallow water table	• Deep tillage • Bed-forming/hilling • Graded soil surface • *Precise irrigation* • *Winter cover crops* • *Soil water monitoring*
Temperature (18-28C)	• Well aggregated soil • Shaded soil	• All italic items above (except soil water monitoring) • *Canopy shade*

[a] Aeration >10% 24 hours after irrigation is widely accepted as adequate but should be higher eventually especially if biological activity is high

Table 1: A summary of soil management recommendations for tree and row crops (adapted from Cockroft and Olsson, 1997)[31].

Having created suitable soil structure by disturbance (tillage, roots, biological activity), this structure then needs to be stabilized and maintained indefinitely by calcium, roots, fungal hyphae, organic matter and the exudates of soil organisms. The authors stated that this scheme could also guide the amelioration of subsoils.

This research lead to a further new system of soil management which was rapidly adopted by fruit growers and is the current normal practice amongst many growers over a large area[40] ("system 3", Table 2).

SOIL COALESCENCE (1996-)

The soil structure in raised soil beds in irrigated orchards, although good immediately after forming, was observed [28-30, 32] to decline over the longer term with the beds becoming stronger and less porous even though they were untrafficked and possessed a high proportion of water-stable aggregates. This phenomenon was termed *coalescence* and differed from soil crusting (due to rain/irrigation water impact) and hardsetting (due to slaking and structural collapse on rapid wetting) in that the latter two occur rapidly, usually during a single wetting and drying event. Neighbouring soil aggregates were observed to merge into one at contact points leading to high strength and poor aeration but the soil maintained adequate biopores and drainage.

This phenomenon was introduced in two papers presented at an international symposium *Advances in Soil Quality and Management.* The first of these[28] provided a brief, practical guide to growers in establishing, then maintaining an orchard soil but noted that coalescence is only partially overcome by the otherwise sound management strategies suggested. The second paper[29] reported observations of coalescence that suggested persistently high soil moisture as a causative factor but the presence of continuous root growth as an ameliorant.

Lanyon *et al.*[30] observed that coalescence was increased by excessive pulverization of the soil during bed formation, high irrigation rates, use of straw mulch and absence of roots. Cockroft and Olsson[32] found that the progress of coalescence could be followed by measuring penetration resistance which, however, continued to increase after coalescence was complete. Over 15 sites they observed that, on average, coalesced soils displayed 10 fold reductions in root length, a 45% reduction of macroporosity, a 75% increase in bulk density, a tripling of penetration resistance at field capacity and a 60% loss of soil organic carbon. They also noted that coalescence appeared wide-spread in zero-tilled soils but that there were rare examples where it had not occurred and that its absence appeared to be associated with concentrations of soil organic matter much higher than those needed to simply confer water-stability of aggregates. They concluded that while this suggested that it might be managed the mechanism of coalescence needs to be unravelled before it can be managed. This would seem to remain true at the time of writing this review.

FIELD PRACTICES AND THE "SUPER SOIL"

The creation and intensive management of soil structure has also been disseminated by Bruce as quarterly grower reports[33-39] in which recommendations for the "ideal soil" or "super soil" have evolved under discussion.

After a study of soils in Europe and the U.S. Bruce pointed out[34] that Australian horticulture produces only a fraction of potential yield and is well behind that in the best soils elsewhere, despite yield improvements over 50 years involving fertilizer, irrigation, drainage, ripping, hilling and other practices. This may be due to soil coalescence. The best overseas soils were noted to be recent alluvial/loess soils, largely sandy loams with high organic matter content (>10%), very good structure and structural stability and no coalescence. He urged technological progress to remain competitive and to improve soil greatly and convert plant vigour to fruit by changing "ordinary" soils to ones as good as the best overseas. He acknowledged that growers know about fertilizer, lime, gypsum, irrigation, drainage and diseases but attention to all these only produces moderate yields; structure is the key. He urges continued research into this particularly in relation to the role of soil biology[36].

Bruce considers a "super soil", a soil which regularly produces 2-3 times Australia's best productivity, to have eleven requirements all of which are achievable and which have been trialled individually and in combination [35].

Practices to avoid	Practices to use
Traffic compaction	Rye grass[e]
Clay contamination[a]	Capillary irrigation[f]
Powdering[b]	Organic matter[g]
Ex-cropping soil[c]	Reaggresizing[h]
Ex-pasture soil[c]	Lime[i]
Poor drainage[d]	

Notes

[a] Clay contamination from subsoil causes hardening of the soil and better methods of subsoil ripping, land forming and careful tree grubbing are needed to avoid contamination of the surface soil.
[b] caused by cultivation of soil that is too dry and excessive cultivation in general.
[c] these soils may have been degraded by constant cropping or by stock and machinery and require rejuvenation with rye grass for 6 months prior to planting.
[d] improved by bed slope and ripping.
[e] roots interrupt what may later go on to become a strong, impenetrable soil matrix. Roots throughout the year is the first key practice to prevent coalescence and promote macro-aggregation and microbial activity; no fallow periods should be permitted.
[f] capillary irrigation is recommended over spray, flood or furrow (buried capillary irrigation is almost standard in some tomato and vegetable production districts). This may produce coalescence of the subsoil where the pipe is but avoids it in the top soil[36]. Note: This seems to conflict with recommendations of spray irrigation elsewhere[25].
[g] organic matter is a key practice to establish stable micro-aggregates and to stabilize structure. The 6-7% needed to produce a super soil is a huge amount which is difficult to access and apply and hard to sustain unless constant inputs are made. Grasses are considered a good source because of organic matter placement by the roots and the encouragement of microbial activity[38].
[h] This for soils that are either initially "difficult" to prepare or else require careful cultivation to break up coalescence after the initial cultivation and 6 months of rye grass but it is not known when or how often this should be practiced.
[i] The best soils contain lime and organic matter and are of medium texture. It is suggested that for soils with lime 3% organic matter is adequate but for those without lime 6-7% organic matter is required[39].

The ultimate coalescence of soil in pot experiments was noted to be almost universal[37]. No single treatment avoided coalescence but combinations of the 11 factors above worked, especially those involving the 4 factors rye grass, capillary irrigation, organic matter and lime. One soil high in organic matter coalesced because of compaction. In the field coalescence was observed to begin at the bottom of the bed where soil is wettest and overburden is greatest[36].

This research has lead to a further new system of soil management currently being set up on the first orchards[40] ("system 4", Table 2).

System	Year Commercialised	Yield (t/h)	Description
1	Pre-1960	15	Cultivated, flood irrigated, winter cover crop.
2	1960	30	Zero till, flood irrigated, tree line weed spray, permanent surface drains.
3	1980	60	Zero till, spray irrigated, tree line bed, loosened subsoil, winter grass, summer mulch, drains.
4	2005	120	Pre planting build up of OM and soil structure, additional lime, no contamination with subsoil clay, drainage, tree-line bed, zero till, rye grass autumn/winter, summer mulch.

Table 2: The progressive development of the three new systems of orchard soil management by Bruce Cockroft[40]

CONCLUSION

The soil management recommendations described here and developed by Bruce Cockroft and his co-workers have been successfully adopted by growers in the Goulburn Valley and elsewhere and are largely based upon proven soil physical principles. There would seem to be obvious potential for research and extension of these soil management systems to other soils and irrigated enterprises in Australia. Root systems that are not constrained by poor soil structure will support the growth of productive plants that are buffered against adversity, promote soil and water conservation and allow growers a full "window" of management options.

REFERENCES

1. Hughan, D. and Cockroft, B. (**1955**) Soil management and peach yields. *J. Dep. Agric. Vict.* 53 : 162-164; 167

2. Cockroft, B. (**1963**) Timing of irrigation in Goulburn Valley orchards. *J. Agric. Vict.* 61 : 492-5; 521

3. Cockroft, B. and Morris, I. R. J. (**1963**) Peach soil management trial at Tatura. *Vict. Hort. Dig.* 7 (3): 14-18

4. Cockroft, B. (**1964**) Physical properties of some Victorian soils. *Tech. Bull. Dep. Agric. Vict.* (18): 3-10

5. Cockroft, B. (**1965**) Pedology of the Goulburn Valley area, Victoria. 1. Stratigraphy of layers. 2. Application in irrigated horticulture. *Tech. Bull. Dep. Agric. Vict.* 19: 1-27.

6. Cockroft, B. and Bakker, A. C. (**1966**) Peach tree waterlogging in the Goulburn Valley area. *J. Aust. Inst. Agric. Sci.* 32 : 292-3

7. Cockroft, B. and Wallbrink, J.C. (**1966**) Root Distribution of Orchard Trees. *Australian Journal of Agricultural Research* 17(1): 49-54.

8. Cockroft, B. (**1966**) Soil Management of peach trees in the Goulburn Valley, Victoria. *Australian Journal of Experimental Agriculture and Animal Husbandry* 6: 62-65

9. Cockroft, B., Wallbrink, J.C. (**1966**) Soil properties and tree vigour in the Goulburn Valley. *Australian Journal of Experimental Agriculture and Animal Husbandry* 6: 204-208.

10. Greacen, E.L., Farrell, D.A. and Cockroft, B. (**1968**) Soil resistance to metal probes and plant roots. *Transactions of the 9th Congress of the International Soil Science Society* 769–779.

11. Cockroft, B., Barley, K.P. and Greacen, E.L. (**1969**) The Penetration of Clays by Fine Probes and Root Tips. *Australian*

12. Cockroft, B. (**1970**) Estimation of Soil Permeability from Counts of Visible Pores. *Australian Journal of Experimental Agriculture and Animal Husbandry* 10(45): 460-461.

13. Cockroft, B. and Morris, I. R. (**1971**) Soil management of young peach trees in the Goulburn valley. *Victorian Horticulture Digest.* 15 (2): 9-14

14. Cockroft, B. and Olsson, K.A. (**1972**) Pattern of New Root Production in Peach Trees under Irrigation. *Australian Journal of Agricultural Research* 23(6): 1021-1025.

15. Richards, D. and Cockroft, B. (**1974**) Soil Physical Properties and Root Concentrations in an Irrigated Peach Orchard. *Australian Journal of Experimental Agriculture and Animal Husbandry* 14(66): 103-107.

16. Cockroft, B. and Tisdall, J.M. (**1974**) Soil Management of Irrigated Young Peach Trees in the Goulburn Valley, Victoria. *Australian Journal of Experimental Agriculture and Animal Husbandry* 14(67): 269-272.

17. Richards, D. and Cockroft, B. (**1975**). Effect of Soil-Water on Root Production of Peach Trees in Summer. *Australian Journal of Agricultural Research* 26(1): 173-180.

18. Cockroft, B. and Tisdall, J .M. (**1978**). Soil management, soil structure and root activity. **In:** *Modification of Soil Structure* (Eds:

W. W. Emerson, R. D. Bond and A. R. Dexter.) pp. 387-91. (Wiley: Chichester.)

19. Tisdall, J.M., Cockroft, B. and Uren, N.C. (**1978**). Stability of Soil Aggregates as Affected by Organic Materials, Microbial Activity and Physical Disruption. *Australian Journal of Soil Research* 16(1): 9-17.

20. Olsson, K.A. and Cockroft, B. (**1980**) Soil management for high productivity in horticulture. *Proceedings of the Australian Agronomy Conference "Pathways to Productivity"* Queensland Agricultural College (Gatton) April, 1980. pp30-39. AIAS.

21. Cockroft, B and Martin, F.M. (**1981**) Irrigation. **In:** *Red-Brown Earths of Australia* (Eds: J.M. Oades, D.G. Lewis and K. Norrish) pp133-147 (Waite Agricultural Research Institute and CSIRO Division of Soils, South Australia).

22. Cockroft, B., Mason, W.K. and Martin, F.M. (**1985**) Irrigation - 50 years of development and potential for the future. *J. Aust. Inst. Agr. Sci.* 51 (3): 206-213

23. Cockroft, B. and Mason W.K. (**1987**) Irrigated agriculture. **In:** *Agriculture in Victoria.* (Eds: D.J. Connor and D.F. Smith) pp. 159-177. (Australian Institute of Agricultural Science: Melbourne)

24. Cockroft, B. (**1991**) Soil management and soil structure. Advances in soil structure. Australian Society of Soil Science Conference, Shepparton, Victoria October 1991.

25. Cass, A., Cockroft, B. and Tisdall, J.M. (**1993**). New approaches to vineyard and orchard soil preparation and management. Vineyard Development and Redevelopment (ASVO Seminar), Mildura, Victoria, Australian Society Viticulture and Oenology.

26. Cockroft, B. and Cass, A. (**1995**) Horticulture. Soils and land management. **In:** *Horticulture Australia.* (Ed: B. Coombs) pp.79-90. (Morescope Publishing: Melbourne)

27. Olsson, K. A., Cockroft, B. and Rengasamy, P. (**1995**) Improving and managing subsoil structure for high productivity from temperate crops on beds. **In:** *Subsoil management techniques.* (Eds. N. Jayawardane and Stewart, B.A.) London, Lewis Publishers: pp35-65.

28. Cockroft, B., Olsson, K.A., Lanyon, D. and Cass, A. (**1996**). Soil quality for orchards on duplex soils. pp86-89. *Proceedings of the International Symposium: Advances in Soil Quality and Management: Science Practice and Management.* (Centre for Environmental Management) University of Ballarat, 17th-19th April. Eds: R.J. MacEwan and M.R. Carter.

29. Lanyon, D., Cass, A., Cockroft, B. and Olsson, K.A. (**1996**). Processes of soil structural quality decline induced by soil and irrigation management in permanent raised soil beds. p127. *Proceedings of the International Symposium: Advances in Soil Quality and Management: Science Practice and Management.* (Centre for Environmental Management) University of Ballarat, 17th-19th April. Eds: R.J. MacEwan and M.R. Carter.

30. Lanyon, D. M., Cass, A., Cockroft, B. and Olsson, K.A. (**1996**). Coalescence: a long term decrease of soil physical fertility in irrigated no-till raised soil beds. ASSSI and NZSSS National Soils Conference July 1996.

31. Cockroft, B. and Olsson, K.A. (**1997**). Case study of soil quality in south-eastern Australia: Management of structure for roots in duplex soils. *Soil quality for crop production and ecosystem health.* E. G. Gregorich, Carter, M.R. Amsterdam, Elsevier. 25. 339-350

32. Cockroft, B and Olsson, K.A. (**2000**) Degradation of soil structure due to coalescence of aggregates in no-till, no-traffic beds in irrigated crops. *Australian Journal of Soil Research* 38:61-70

33. Cockroft, B. Orchard Soil Management No. 16 September 1998 *A Future System of Soil Management.* (grower report).

34. Cockroft, B. Orchard Soil Management No. 22 March 2000 *A Study of the Best Soils of Europe and The United States.* (grower report).

35. Cockroft, B. Orchard Soil Management No. 43 June 2005 *The New System of Soil Management.* (grower report).

36. Cockroft, B. Orchard Soil Management No. 44 September 2005 *Next Experiments.* (grower report).

37. Cockroft, B. Orchard Soil Management No. 45 December 2005 *Pots and Combinations.* (grower report).

38. Cockroft, B. Orchard Soil Management No. 46 March 2006 *Soil Organic Matter: 7%.* (grower report).

39. Cockroft, B. Orchard Soil Management No. 47 June 2006 *Lime and organic matter.* (grower report).

40. Bruce Cockroft *pers. comm.*