Applying ecological principles to the re-design of agricultural landscapes

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Abstract
It has been suggested that the only effective solution to land degradation in southern Australia's dryland cropping zone is to increase the proportion of perennial plants in the agricultural landscape. While this would involve radical change for Australian landholders, perennial farming systems themselves are not new. Studies of natural ecosystems and traditional mixed cropping systems suggest two advantages – more complete capture of resources and reduced risk of crop failure. But experience and ecological theory suggests this commonly comes at the cost of lower annual biomass production due to investment in roots and woody stems. Increased competition also places demands on design and management to ensure resources are directed into harvestable product. While exceptions to these generalizations provide some grounds for optimism and highlight the limits of ecological theory, there are significant obstacles to profitably perennialising southern Australia's dryland cropping zone. Chief among these are low and variable rainfall, ancient soils and the cost of the transition from annual plant-based land use systems.

Keywords
Persistence, productivity, trade-offs.

Introduction
In semi-arid climates, one way to reduce the risk of crop failure is to avoid the summer drought by matching short-lived annual crops to the length of the rainy season. The dryland monocultures that now typify modern agriculture originally evolved as a solution to this problem in the Middle East between eight and ten thousand years ago. This technological package of two grains (wheat and barley), three legumes (chickpeas, lentils and beans) and two grazing animals (sheep and goats) later spread to southern Europe (1). As agriculture spread to central and northern Europe over several thousand years, these plants and animals became adapted to the temperature constraints of higher latitudes. With the addition of several grains (oats and rye), two grazing animals (cattle and pigs), a few oilseed crops and the well adapted camp followers we refer to as weeds, this technology was exported around the globe.

Vast areas of forest, woodland and perennial grassland have been converted to synthetic annual grasslands of these crops. In few places however have the environmental consequences been as swift or dramatic as those in southern Australia. The question is can we develop commercially viable land use systems with a sufficiently high proportion of perennial plants to ensure their adaptation to this environment? In short, the question is can we have our cake and eat it?

Improving resource capture
Most land degradation problems can be traced back to a mis-match between sources and sinks of water and nutrients in time and space. An example of a mis-match in space is when shallow rooted crops and pastures cannot exploit otherwise scarce water and nutrients stored at depth. A classic mis-match in time occurs every summer in southern Australia when annual plants are not around to exploit two thirds of the available energy and up to one third of annual rainfall. Such imbalances are inherent in most high input annual plant-based systems and express themselves as erosion, eutrophication, soil acidity and soil and water pollution. The options are to change the management or change the structure of the farming system. Stirzaker (2) suggests that in irrigated horticulture where returns warrant large investment in environmental safeguards, the most sophisticated management in the world cannot overcome this fundamental problem. The rational choice is to over-water and over-fertilize as the optimal level of inputs is too difficult to call and the penalties for under doing them are higher than those for exceeding them.

Changing the structure means designing agricultural systems using plants that can capture water and nutrients when and where they are available. In principle this represents good commercial sense as well as environmental responsibility if the extra resources can be channeled into harvestable products. The experience of Ewel et al. (3) in testing this idea is instructive. They established structural mimics of a successional rainforest community in Costa Rica as a permanent alternative to slash and burn farming. In one treatment the natural process of succession was allowed to proceed. Another was a mimic made up strictly of exotic plants substituting for life forms found in the natural succession - tree for tree, vine for vine, shrub for shrub. A third was a mixture of the two. They then compared nutrient leaching in the three forest communities with that in maize and cassava culture. The mimics performed as well as natural succession in terms of nitrate leaching, soil erosion and primary productivity but they concluded that lower harvestable yields are likely in such mimic systems as they featured a high investment in structure.

Ong and Leakey (4) also took a successional perspective in reviewing the lack of adoption of agroforestry in Africa. Their starting point was the shift in attitude amongst researchers working in water-limited environments. The expectations of these researchers was that complementary use of resources by trees and crops would be the norm. Two decades later the view is that competition rules. While there is good evidence that the productivity of natural vegetation under savannah trees increases as rainfall decreases, experimental results indicate the opposite is true for agroforestry. Their explanation was that we are seeing successional processes at work. The agroforestry experiments they reviewed typically featured young fast growing trees, commonly legumes, which exhibited a high degree of competition. Ecological studies of savannah trees and understorey vegetation on the other hand suggested that mature savannah systems exhibit a higher degree of complementarity. They suggest competition is best avoided by selectively combining plants with complementary phenology (winter active/summer active), morphology (especially root architecture) and nutrient acquisition strategies.

The problem with this strategy is that investment in woody plant structure requires time, delaying returns to the landholder. They concluded that the greatest opportunity for agroforestry appears to be in filling niches in landscapes where resources are currently under-utilized by crops. In other words, imitate the large scale patch dynamics of savannah (or woodland) ecosystems, but avoid imitating natural systems at smaller scales as it comes with the penalty of competition in the early stages.

From annual monocultures to perennial polycultures

Matching plants to resources will require land use systems composed of a mixture of species of various life forms. Given that most species in a mixture will have to justify their inclusion on the basis of direct commercial value, farming systems will need to be based on the multiple products of perennial polycultures. A further reason for polycultures rather than single genotypes of perennials is that mixed populations of multiple genotypes are likely to both stabilize and increase productivity. As there will be little recruitment over time, mixed populations will have to be established at the initial planting (5).

Table 1. Land use types by life form, product and cultural system modified from Jackson (10)

Cultural type	Life form		Product	Land use system
1. Polyculture	woody	perennial	fruit & seed	mixed orchards
2. Polyculture	woody	perennial	vegetative	mixed woodlot
3. Polyculture	woody & herb.	annual & per.	fruit, seed & veg.	alley cropping
4. Polyculture	woody & herb.	annual & per.	fruit, seed & veg	forest garden
5. Polyculture	herbaceous	annual	fruit & seed	mixed cropping
6. Polyculture	herbaceous	annual	vegetative	pasture
7. Polyculture	herbaceous	perennial	fruit & seed	perennial grain crops
8. Polyculture	herbaceous	perennial	vegetative	pasture
9. Monoculture	woody	perennial	fruit & seed	orchard
10 Monoculture	woody	perennial	vegetative	timber plantation
11 Monoculture	herbaceous	annual	fruit & seed	cropping
12 Monoculture	herbaceous	annual	vegetative	silage
13 Monoculture	herbaceous	perennial	fruit & seed	pasture seed crop
14 Monoculture	herbaceous	perennial	vegetative	hay crops, grazing

Polycultures are not new. There are more land use systems throughout the world based on polycultures than on monocultures (Table 1), although the latter are more extensive and responsible for a far higher proportion of the world's food production. The point is that as well as studying natural ecosystems as a guide to the components and interactions in perennial polycultures, there is much to learn from traditional land use systems such as the first five types in Table 1 found in the tropics (6, 7, 8). The only land use system in Table 1 that does not exist yet is type 7 perennial grain crops, currently under development as an alternative to type 11 in The Great Plains and Pacific Northwest of the USA (9).

Balancing persistence and productivity

A trade off between persistence and productivity seems likely with perennial farming systems. Persistence will almost inevitably involve a greater investment in biological infrastructure, particularly woody above- and below-ground biomass, with a consequent decrease in harvestable product. Studies of the oldest continuous farming system in Europe, the cork oak *dehesa* of southern Spain and Portugal, suggest its ecological and economic persistence have been achieved at the cost of sub-optimal productivity as the tree density in the managed landscape is lower than in adjacent oak woodlands and managed trees are subject to lower levels of water stress (11). It has also persisted at the expense of social equity as it has relied heavily on poorly rewarded labour for maintenance and after 800 years its greatest threat appears to be European Union social policy.

The difference in net annual primary productivity between annual crops and an adjacent remnant of the pre-existing natural vegetation is illustrated in Table 2. Despite the fact that the annual crops and pastures failed to capture a third of the annual rainfall, they consistently out-produce the native vegetation. The difference is largely due to the amount of biomass the *Banksia* woodland has invested in below ground structure in order to survive over summer and buffer the high climate variability. The argument that the place of agroforestry lies in exploiting resources unused by crops at the scale of landscape patches rather than plant communities (4) is supported by the performance of the tagasaste plantation which has access to an elevated water table.

Table 2. Above-ground net annual primary productivity of annual crops and pastures, rhodes grass (*Chloris gayana*), a plantation of the fodder shrub tagasaste (*Chamaecytisus proliferus*) and *Banksia prionotes* dominant woodland at Moora, Western Australia. Source: Pate and Bell (14); Lefroy and Pate, unpubl. data.

Plant community	Annual productivity ($t\ ha^{-1}$) Mean (Range)	Biomass per unit rainfall[4] ($kg\ ha^{-1}\ mm^{-1}$)
Annual crops and pastures [1]		
wheat	4.8 (2.8-6.8)	4.0 - 17.0
lupins	5.4 (4.2-6.5)	9.2 - 18.0
sub-clover based pasture	5.5 (3.4-7.6)	7.8 - 11.4
Perennial pasture[2]		
rhodes grass	1.9	4.6
Forage trees (tagasaste)		
1996 - 1st year coppice	4.4	(10.0)
1997 - 2nd year coppice	20.1	(48.7)
Banksia woodland[3]		
Pristine	2.4	4.5
At agricultural interface (elevated water table and N)	8.4	(15.9)

1. various years from 1994 to 1997 with annual rainfall of 294, 703, 438 and 412 mm respectively
2. 1997 only
3. 1995-1997
4. numbers in brackets are for plant communities with access to a fresh (< $1 dSm^{-1}$) perched water table

The trade-off between persistence and productivity is likely to be less in the case of herbaceous perennials than with woody perennials. However the argument continues as to the importance and degree of hydrologic imbalance in the southern Australian landscape and therefore the relative importance of these two life forms. Hatton and Nulsen (12) present an argument based on modeling and ecological studies that woody perennials are the only life form capable of maintaining permanent leaf area over a sufficient proportion of the landscape. Dunnin et al. (13) present results of phase farming experiments from the western slopes of New South Wales to suggest that herbaceous perennials such as analogues of lucerne or native perennial grasses could be sufficient when used in rotation with crops.

Jackson and Jackson (9) are dissenting voices on the subject of trade-offs between perenniality and harvestable yield. Their work demonstrating that perenniality and high seed yield are not mutually exclusive trade-offs in Eastern Gamma grass *Tripsacum dactyloides* is an exciting finding that opens the door to the prospect of perennial grain agriculture. Whether their example has general applicability to other species and life forms remains to be tested. If it does, it would present a serious challenge to life history theory and highlight the dangers of eliminating possibilities for landscape redesign on the grounds of theoretical ecology.

Diversity, stability and risk

A claim often made for mixtures over monocultures is that they reduce the risk of crop failure. In a review of multiple cropping systems in India, Trenbath (8) observed that risk reduction comes at the cost of deferring short-term production for longer term stability. Van Noordwijk and Ong (6) add that the reason the debate on stability and complexity of natural and agro ecosystems is so confused is that insufficient recognition has been given to the hierarchical nature of agricultural production. They argue that the implicit assumption is often made that stability at lower hierarchical levels is necessary before stability can exist at a higher level whereas the reverse is equally likely. The question of whether diversity improves stability in food production depends on the level at which the question is posed. From the perspective of a grazing animal in a mixed plant community, a stable feed supply can be achieved from a highly variable grass legume mixture in competitive balance for soil nitrogen. While production at paddock scale and animal intake remain stable, species composition fluctuates.

At field level, stable yields can be achieved by intercropping cultivars or species that respond differently to seasonal factors that cannot be predicted at the time of sowing (8). At farm level, a farmer can attempt to balance different attractive but risky field-level enterprises by maintaining a mixed portfolio of products destined for different markets. At the regional scale, stable urban food supplies are achieved by linking highly specialized but risky farming enterprises. This results in the paradox that food choice is now more diverse than at any time in human history while production is less diverse and at greater risk of failure than ever before (6).

This question of scale emerges as a critical decision point for perennial farming systems as resource management and biodiversity conservation decisions are made at larger scales and are often in conflict with the economic decisions crucial to the survival of individual farmers. Main (15) points out that the degree of diversity required in this new landscape depends entirely on the goal in question - restoration of ecosystem services, maintaining high yields, improving yield stability. Until the scale is specified and the goals at each scale made explicit, the question of diversity cannot be addressed.

Adaptive management

If long term persistence and yield stability are likely to come at the cost of short term productivity, how can perennial farming systems ever be sufficiently attractive to be adopted by farmers? That difficulty is represented by the last step in the sequence below on steps in the development of farming systems based on an understanding of natural ecosystems, adapted from Dawson and Fry (16):

1. Identify ecosystem processes sub-optimal in managed systems.
2. Compare the form and function of natural and managed ecosystems to identify key functions and functional groups.
3. Develop commercial crops as functional analogues of endemic species. This implies extending the range of conventional bio-prospecting to include consideration of the functional role of economic species in managed landscapes.
4. Identify whether it is most appropriate to integrate or segregate these functions with production at field and landscape scales. Where the costs of competition between species in closely integrated polycultures is greater than the benefits of added ecosystem services or biodiversity conservation, the segregation of roles (production versus resource and biodiversity conservation) would be the better option.

5. Develop strategies and partnerships to overcome the obstacles facing adoption, particularly the profitability, start up costs, long lead time and difficulty of trialling of alternatives land uses.

If the last condition is not met, little will be achieved in practice despite the amount of effort put into steps 1 to 4. And yet to be overwhelmed by the last step may well be to give up before starting. An example of changing land use systems in southwestern Australia may serve to illustrate this point. Over the last decade, more than 100,000 ha of Tasmanian Bluegum (*Eucalyptus globulus*) have been established on farm land in the higher rainfall areas (> 600 mm y^{-1}) (17). Harvested on rotation for fibre and sawn timber, they represent an alternative source of income to meat, wool and milk production from farming systems based largely on annual plants. As a summer active perennial, they represent an opportunity to address the imbalance in the hydrological cycle that is a feature of annual based farming systems in this region. Catchments that now include plantings of blue gums, either segregated or integrated with conventional farming, cannot be considered as mimicking the original jarrah (*E. marginata*) forest, but could be regarded as having taken a step in that direction. In hindsight, the adoption process can be seen as having fast tracked the above steps, with 1, 3 and 5 considered and steps 2 and 4 overlooked. The key to this alternative land use becoming a viable option for farmers came with step 5, a share farming scheme that saw initially government and increasingly private enterprise in partnership with landowners. An essential part of that final step was a change in legislation to recognize contracts where one party owns the land and another party owns the trees. The landowner is paid an annuity based on the projected value of the trees at harvest while the owner of the trees bears the cost of establishment and harvest and shares the risks.

Many issues remain to be addressed such as the appropriateness of site and species selection in the face of tree deaths, vulnerability to disease, the minimal level of functional diversity and the social disruption that is occurring as tree monocultures displace people, traditional forms of land use and familiar landscapes. The point of this example is that a more sustainable and commercially viable form of land use may well evolve out of this process, something that may not have happened by simply progressing through the above steps in sequence. It certainly would not have happened without the intervention of step 5, the share farming scheme. This example suggests that solutions to complex problems at landscape scales are more likely to evolve through a process of adaptive management (18, 19) in which simulation modelling and decision support systems play a part but are not substitutes for creativity or trial and error. The process is therefore less planning in the formal sense than fishtailing into the future, attending to the finer details once social momentum is established.

Conclusion

The current debate on the necessary degree of landscape change required to match land use systems more closely to southern Australia's climate and soils appears to be centred around the question of how little can we get away with. If we take as our starting point an understanding of processes occurring in natural ecosystems, the question becomes what is required of us (10)? It is then ultimately up to the ingenuity of farmers, foresters, agronomists, and others to find commercially attractive products within those life form and functional constraints. The significant issues that have to be addressed are the degree of investment in biological infrastructure required to persist in water-limited and highly variable environments, the trade of between persistence and productivity, how to manage competition in early stage succession, the differing implications of diversity at field, farm, catchment and regional scales, whether and at what scale to integrate or segregate production and conservation and perhaps most significantly how to introduce structural and institutional arrangements to share the costs and risks associated with the transition from annual to perennial based land use systems.

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References

1. Diamond, J. 1997. Guns, Germs and Steel. (*Jonathan Cape: London*).
2. Stirzaker, R.J. 1999. *Agrofor. Sys.* **45**, 187-202.
3. Ewel, J.J., Mazzarino M.J. and Berish C.W. 1991. *Ecol. Appl.* **1**: 289-302

4. Ong, C. K. and Leakey R. R. B. 1999. *Agrofor. Sys.* **45**, 109-129.
5. Rossiter, R. C. 1989. *Proceedings 5th Australian Agronomy Conference*. Perth, p. 11
6. Van Noordwijk, M. and Ong, C.K. 1999. *Agrofor. Sys.* **45**, 131-158.
7. Altieri, M.A. 1995. Agroecology, 2nd ed. (*Westview: Boulder*)
8. Trenbath, B. R. 1999. *Agrofor. Sys.* **45**, 81-107.
9. Jackson, W. and Jackson, L. 2000. In: Agriculture as a Mimic of Natural Ecosystems. (Eds. E. C. Lefroy, R. J. Hobbs, M. H. O'Connor and J. S. Pate) (*Kluwer: Dordrecht, The Netherlands*).
10. Jackson W (1985) New Roots for Agriculture. (*University of Nebraska Press: Nebraska*)
11. 11.Joffre, R. Rambal, S. and Ratte, J.P. 1999. *Agrofor. Sys.* **45**, 57-79.
12. Hatton, T. J. and Nulsen, R. A. 1999. *Agrofor. Sys.* **45**, 203-214.
13. Dunnin, F. X., Williams, J., Verburg, K. and Keating, B. A. 1999. *Agrofor. Sys.* **45**,
14. Pate, J. S. and Bell, T. L. 1999. *Agrofor. Sys.* **45**, 303-341.
15. Main, A. R. 1999. *Agrofor. Sys.* **45**, 23-41.
16. Dawson, T. E. and Fry, R. 1998. *Trends in Ecology and Evolution* **13** (2), 50-51
17. Bureau of Rural Sciences (1999) National Plantation Inventory. (*Bureau of Rural Sciences: Canberra)*
18. Holling, C. S. 1978. In: Adaptive Environmental Assessment and Management. (*John Wiley and Sons: Chichester*)
19. Walters, C. 1986. In: Adaptive Management of Renewable Resources. (*Macmillan: New York*)