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Agriculture as a Mimic of Natural Ecosystems

Workshop Report for the
RIRDC/LWRRDC/FWPRDC Joint Venture Agroforestry Program

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Foreword

Many current agricultural systems are not sustainable in the long-term due to land degradation and the high levels of resource inputs involved in production. In Australia there is an increasing perception that achieving sustainable agriculture will require dramatic departures from current practices.

Natural systems agriculture suggests that the best models for sustainable agriculture are natural ecosystems. Work at the Land Institute in Salina, Kansas was a major impetus for the comparative study of natural and agricultural ecosystems in Western Australia and for convening a workshop to bring agriculturalists and ecologists from around the world to explore the concept of natural systems.

This publication details outcomes of the workshop and presents a broad approach for the development of natural systems agriculture. This approach was developed by drawing together experimental case studies and theoretical considerations. It attempts to identify the steps required to replace as much as possible the growing external demands of existing managed systems with co-operative functions found in natural systems.

This report forms part of RIRDC's Agroforestry and Farm Trees R&D program which aims to integrate sustainable and productive agroforestry within Australian farming systems.

Peter Core
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Executive Summary

Many current agricultural systems are not sustainable in the long-term due to land degradation and the high levels of resource inputs involved in production. In Australia there is an increasing perception that achieving sustainable agriculture will require dramatic departures from current practices. This workshop, convened in Western Australia, brought agriculturalists and ecologists from around the world to explore the concept of natural systems agriculture which suggests that natural ecosystems can serve as models from which we can develop sustainable agricultural systems. This concept suggests that by examining how components of natural ecosystems affect their function, it may be possible to develop functional mimics which retain the functions of the natural system while allowing sustainable production. Theoretical considerations were coupled with long-term case studies of multi-species farming systems and specifically designed mimic systems in examining the potential for developing functional mimics for use in the agricultural systems of southern Australia. Theoretical scepticism engendered by the standard scientific approach was matched by pragmatic optimism from those that have used intuition to 'have a go'. The combination of both may provide important signposts for the future of agriculture in Australia. Key steps required for the development of natural systems agriculture emerged out of the workshop. They represent the sequence of steps required to replace, as much as possible, the growing external subsidies required of existing managed systems with co-operative functions existing in natural systems. These were

1. Identify the system functions which are currently suboptimal in the managed system.

2. Identify the suite of species which carry out these functions in the natural ecosystem.

3. Within this suite of species, identify those with key functional roles, or identify analogs of these, ie well adapted species from elsewhere with these same functional roles.

4. Identify the likely range of environmental conditions and disturbances, and select the array of species needed to confer system resilience.

5. Consider how many of these species are required for the managed system, in the context of trading-off environmental risks versus long and short term costs and benefits. For instance, is it essential to install the full suite of species immediately, or can a phased approach be employed?

6. Decide whether it is most appropriate to integrate or segregate these functions with production, that is to have diversity at field or landscape scales or a mixture of both.

7. Assemble the suite of species required to achieve functional objectives within an adoption framework that a) has clear links to end users and b) demonstrates economic viability and/or c) includes socio-economic instruments to facilitate implementation including incentives such as carbon tax trading.

8. Develop these systems in an adaptive management framework involving monitoring and the capacity to modify elements of the design as new information becomes available or as circumstances change.

1. Introduction

The most recent assessment of the state of the agricultural resource base in Australia puts the value of losses due to land degradation at $1.2 billion per annum (Industry Commission 1997). This is equivalent to 30 per cent of total annual production costs. Of this, $450 million is due to declining water quality, $300 million to soil acidity, $200 million to secondary salinity, $200 million to soil structural decline, $180 million to waterlogging and $80 million to soil erosion. This is compounded by the fact that the $900 million outlaid each year on fertilisers, accounting for 23 per cent of total production costs, has a net efficiency of around 10 per cent (Williams 1997).The combined effect of this is not only diminished earnings but also a diminishing capacity to produce in the future. On a global scale, nearly one third of the world's arable land of 1,500 million hectares has been lost to erosion and continues to be lost at a rate of more than 10 million hectares per year (Pimental 1995).

A common response to this is to take a compensatory approach. This involves accepting that erosion of the natural resource base is inevitable and then determining what action will be necessary to compensate for this within the existing production systems. Projections using CSIRO's Stocks and Flows Model suggests that it will take a 1% increase in crop yields per annum through germplasm improvement alone to compensate for Australia's lost productive capacity (Crome *et al* in press). While this level of yield increase has been achieved over the last 40 years through a combination of improvements in germplasm, fertiliser and machinery, the energy intensiveness of the latter two sources of yield improvement negate their contribution to sustainable production increase. A consequence of this approach is that conservation becomes peripheral to production and represents an additional cost.

Another response is to reject the inevitability of agriculture running down its natural resource base at the current rate and to look for alternative approaches to producing food and fibre. This involves identifying the root causes of land degradation and designing agricultural systems that avoid them. In other words, designing agricultural systems where the conservation of land, water and to some degree biodiversity is a consequence of production, not an ameliorating after-thought. Many traditional agricultural systems achieve this to a greater extent than industrial broadacre agriculture but are under increasing pressure from alternative land uses and population increase to modify the aspects that impart sustainability, particularly rotation length (Altieri 1995). Permaculture has set out specifically to design food production systems where conservation is a consequence of production within the context of a self sufficient household, where a food garden is designed around the household, arranged in zones depending on management intensity and energy requirement (Mollison 1988). The challenge still remains to incorporate these same principles of land, water and energy conservation into broadacre food production.

Natural systems agriculture takes the view that the best models for agriculture are natural ecosystems. The term was coined by scientists at Kansas State University to describe collaborative work being under taken with The Land Institute in Salina, Kansas (Jackson 1996). Since 1978, research at The Land Institute, a private non-profit research and teaching institute has been directed towards the development of high seed yielding perennial polycultures using the native mid-grass prairie as the model. In the words of their mission, they aim "..to develop ecological assemblies of edible seed-producing perennial polycultures featuring the four major guilds or functional units represented in native prairies and in roughly the same proportions” (Jackson 1996). While conventional agricultural monocultures grown in rotation rely on mimicking some of the process found in nature, they do not mimic the structure or diversity of natural systems. In the case of the Kansas prairie, the four functional groups being used as models by The Land Institute are the warm season grasses, cool season grasses, legumes and members of the sunflower family.

Table 1. Land use types by life form, product and cultural system

CULTURE	**LIFE FORM**		**PRODUCT**	**LAND USE SYSTEM**
Polyculture/ Monoculture	**Woody/ Herbaceous**	**Annual/ Perennial**	**Reproductive/ Vegetative**	
1. Polyculture	Woody	Perennial	Reproductive	Mixed Orchard
2. Polyculture	Woody	Perennial	Vegetative	Mixed Woodlot
3. Polyculture	Woody/Herb.	Pere./Ann.	Repro &Vege	Alley Cropping
4. Polyculture	Woody/Herb	Pere./Ann.	Repro &Vege.	Forest Garden/Permaculture
5. Polyculture	Herbaceous	Annual	Reproductive	Mixed Cropping
6. Polyculture	Herbaceous	Annual	Vegetative	Pasture/Mixed Horticulture
7. Polyculture	Herbaceous	Perennial	Reproductive	Multi-spp. Perennial Grain Crops
8. Polyculture	Herbaceous	Perennial	Vegetative	Pasture/ Mixed Horticulture
9. Monoculture	Woody	Perennial	Reproductive	Orchard
10. Monoculture	Woody	Perennial	Vegetative	Timber Plantation or Woodlot
11. Monoculture	Herbaceous	Annual	Reproductive	Cropping, Floriculture
12. Monoculture	Herbaceous	Annual	Vegetative	Vegetables, Silage
13. Monoculture	Herbaceous	Perennial	Reproductive	Floriculture, Pasture Seed Crops
14. Monoculture	Herbaceous	Perennial	Vegetative	Hay Crops & Grazing

adapted from Jackson (1985)

Table 1 shows land use systems classified in terms of their components (woody or herbaceous, annual or perennial), their output (flowers/fruits/seeds or vegetative) and their design and management (monoculture or polyculture).The eight types of polycultures could all be examples of natural systems agriculture where functional similarity with natural ecosystems exists, consciously or otherwise. Examples of the first six polycultures can be found amongst traditional farming systems, commonly in the tropics. The only one that does not exist yet is type 7, The Land Institute’s seed yielding perennial polyculture being developed as an alternative to type 11, high production annual crop monoculture.

The aim of developing ecological assemblies based on proportional representation of functional groups emphasises that in natural systems agriculture a mimic is not constructed on taxonomic, biogeographic or aesthetic grounds. The aim is the very pragmatic one of producing a functional mimic with commercially attractive harvestable products. This does not preclude the use of exotic species. The aim is to achieve functional mimicry regardless of the taxonomy or origin of the component plants. As an indication of this, the most promising high seed yielding perennials for inclusion in The Land Institute's first assemblies were a mixture of exotics, endemics and specially developed hybrids. Of the cool season grasses, *Leymus racemosus*, the giant wild rye of Central Asia, was the most promising. Amongst the warm season grasses, a hybrid between *Sorghum bicolor* and *Sorghum halepense* and a native progenitor of corn, eastern gammagrass, were the most promising. Legumes were represented by *Desmanthus illinoensis*, the Illinois Bundle Flower commonly found on roadsides in the Mid-West and sunflowers by the perennial *Helianthus maximilliani* (Jackson 1992). Of course, accompanying the free-trade approach to the use of plants from elsewhere in the world has to be adequate assessment of the potential for imported species to become problem weed species (Hobbs and Humphries 1995). In finding solutions to one problem, we do not want to create greater unexpected problems in the future (Tenner 1996)

The major research questions that Jackson and his co-workers set out to address in 1978 were: 1) Can perennialism and high seed yield go together, 2) Can a polyculture outyield a monoculture, 3) To what extent can such an ecosystem sponsor its own nitrogen fertility and 4) Does such an ecosystem have the ability to control insects, pathogens and weeds (Jackson 1985). By 1995 they had affirmative answers to the first two questions (Piper and Kulakow 1993, Barker and Piper 1995). In the process of demonstrating high seed yield in perennials, their results challenge life-history theory, as selection for high seed yield did not compromise allocation of carbon to roots (Pimm 1997).

Table 2. Energy ratios for five agricultural systems

Farming System	**Energy Ratio** output:input	**Source**
Semipastoral farming without tools	6:1	Cox and Atkins 1979
Semipastoral farming with tools	15:1	Cox and Atkins 1979
Modified draft horse farming	6:1	Cox and Atkins 1979
Industrial agriculture	3:1	Briggle 1980, Smil et al 1983
Natural systems agriculture	9:1	Jackson and Bender 1980

from Jackson (1996)

By 1996, there was an answer to the question of the ability of a farming system to generate its nitrogen and energy from sunlight alone. A five-year whole farm experiment demonstrated that it would require 25% of the land area to produce the energy required for traction for conventional agriculture through oilseed production. A further 25% would need to be devoted to legume crops to sponsor nitrogen fertility (Jackson pers. com.). Table 2 shows estimates of the energy ratios for five stages of agricultural development. Introducing tools increased energy returns from 6:1 to 15:1 while adding draft animals doubled the energy input for crop production, reducing the energy ratio to 6:1. Estimates for conventional wheat and corn production are typically in the order of 3:1 while natural systems agriculture, assuming it requires only one third of the energy of conventional cropping, would be expected to have a ratio of 9:1.

Recent work has also given some support to the hypothesis that perennial polycultures can control pests and diseases. Studies of insect and viral populations in monocultures and polycultures provided evidence of the role of increased diversity in suppressing pests and diseases (Piper in press, Piper, et al in press)

After 20 years, the research emphasis has now shifted to exploring community assembly rules. Is it possible to design diverse ecosystems that persist? In the first series of experiments, a four species mix comprised of one representative of each functional group failed to persist, being rapidly dominated by annual weeds. By adding a minimum of four other species from the next best selections, a near weed free mix has persisted for three years after planting. Some encouragement for the development of community assembly rules comes from computer modelling of complex systems which suggests that although persistent complex mixes are statistically rare, they can be achieved through the successive addition and loss of species (Pimm 1997).

The work of the Land Institute was a major impetus for the comparative study of natural and agricultural ecosystems in Western Australia and for convening this workshop.

2. Case studies of multi-species farming systems

The ultimate test of the concept of natural systems agriculture is whether it travels - whether the principle of perennial, multi-species agriculture based on functional mimicry of natural ecosystems has global application. To answer that question and explore the relevance of the concept to southern Australia, agriculturalists and ecologists were invited to an international workshop in Williams, SW Australia in September 1997. Those attending fell into three groups. The first group consisted of the keynote speakers who have spent a combined 30 years designing and assembling mimics of natural ecosystems. The second comprised the experimentalists whose work, while not deliberately setting out to develop mimics of natural ecosystems, has involved studying relevant aspects of the concept such as ecosystem function, functional groups and interactions between species in mixtures. The third group were scientists from a range of disciplines who were asked to critically examine some of the underlying theoretical issues.

The two key note speakers described their experience assembling mimics of two very different natural ecosystems as a basis for sustainable agriculture. Wes Jackson described the work of The Land Institute in developing a productive mimic of a perennial grassland. Jack Ewel (Institute for Pacific Islands Forestry, Hawaii) described his work mimicking successional regrowth of tropical rain forest in an attempt to develop an alternative to shifting agriculture.

Each had approached the challenge of assembling their mimics in slightly different ways. While Jackson and co-workers based their mimic on the functional groups present in the prairie with an emphasis on phenology, Ewel and co-workers based their mimic on structure. Following a detailed life-form analysis of a site at La Selva, Costa Rica prior to clearing, they set themselves the rule of substituting tree for tree, shrub for shrub and vine for vine with the added proviso that none of the species in the mimic could have got there by themselves. This exotic mimic was compared to three other treatments; (1) succession (i.e. the development of vegetation through the invasion and establishment of species from the surrounding forest, (2) a progressive monoculture (two years of corn, followed by cassava and a plantation of the tree species *Cordia alliodora*) and (3) enriched succession where the exotics in the mimic were added to the successional plots. The conclusion they came to was that where they mimicked the structure, nutrient retention followed (Ewel *et al* 1991). This work provided the first experimental evidence of functional similarity between a natural ecosystem and a simplified mimic.

The work of Jackson and Ewel was the stimulus for a multi-disciplinary research project in Western Australia. Ted Lefroy, John Pate and Murray Unkovich (University of Western Australia), Richard Stirzaker (CSIRO Land and Water, Canberra) and Todd Dawson (Cornell University, NY, USA) reported on a comparative study of water and nutrient cycling in a *Banksia prionotes* woodland, conventional cereal/legume crop rotation and an agroforestry systems featuring crop rotations between wide spaced rows of the leguminous shrub *Chamaecytisus proliferus.* The hypothesis being tested is that the alley cropping systems represents a satisfactory functional mimic particularly with respect to water use. This team is making a direct functional comparison of the three ecosystems by tracking the fate of water and nitrogen through soil and vegetation using stable isotopes, direct measurement of tree water use with the heat pulse technique and predictive modelling (Lefroy and Stirzaker 1997). Rather than use vegetative structure or functional groups to design a mimic, this novel agroforestry system had been developed by farmers in an attempt to reverse land degradation processes associated with rising water tables and wind erosion (Lefroy *et al* 1992, Lefroy and Melvin 1996).

In southern Australia, the development of agriculture has involved replacing predominantly summer active woodland, heath and forest communities with winter active, synthetic annual grasslands of crops and pastures. This asynchrony between the phenology of agricultural plant species and native vegetation has resulted in dramatic changes to the hydrologic cycle. While the deep rooted summer active component of the native vegetation draws on reserves of soil and groundwater that are recharged each winter, rainfall unused by annual crops and pastures during their six month winter/spring growing period accumulates through deep drainage and runoff to re-appear elsewhere in the landscape as waterlogging, salinity and problems associated with nutrient leaching such as acidity and eutrophication. Average drainage below the root zone of annual agricultural species in the drier areas (less than 750 mm yr^{-1}) has increased from <0.1 mm yr^{-1} to > 10 mm yr^{-1} since clearing (George *et al* 1997).

A primary reason for considering the natural systems agriculture approach in southern Australia is to develop crop and pasture production systems more closely tailored to the unique characteristics of Australia's climate and soils. The fact that very few new food plants have been domesticated in the last two hundred years emphasises the point that cultural habits do not change rapidly. Finding alternatives to the wheat that occupies 15 million hectares of Australia is not a realistic option. Rather than find a substitute for annual crops, the approach suggested by natural systems agriculture would be to return deep rooted summer active species to the agricultural landscape in roughly the same proportions that existed prior to clearing. In some cases this will preclude broadacre farming, requiring forestry, horticulture or other land use systems based on woody perennials as shown in Table 1. Assuming the natural ecosystem is a good indicator of what is required in order to restore ecosystem function, it is then up to the ingenuity of the designers to find commercially attractive products within those life form and functional constraints.

John Williams, Tom Hatton and Frank Dunnin (CSIRO Land and Water) demonstrated the value of hydrologic modelling and ecosystem-scale measurements in providing comparisons of water use by agricultural and natural vegetation systems in southern Australia and how this could be used to re-design better adapted agricultural landscapes.

The value of understanding below ground architecture of species in natural systems and potential candidates for mimic systems was emphasised by this team and echoed by the research of Pauline Grierson and Mark Adams (University of Western Australia). Deborah Neher (Biology, University of Toledo, OH, USA) described research into the way components of below ground biodiversity are likely to be affected by different land use systems

The Australian research strongly indicated that in the drier parts of Australia where open woodland was cleared for agriculture, and where recharge rates and the risk of salinity are currently highest, the re-introduction of woody perennials seems essential if any form of sustainable land use is to survive. In light of this, the African experience with agroforestry introduced a sobering note to the workshop. Chin Ong (ICRAF, Nairobi) cautioned against the uncritical adoption of agroforestry, citing the failure of alley cropping especially in the sub-humid tropics. He attributed this failure to simplistic assumptions about the complementarity of resource use between trees and crops. He pointed out that there is insufficient knowledge of the temporal and spatial patterns of resource capture for all but a handful of tree/crop combinations (Ong *et al* 1996). Brian Trenbath (Agriculture Western Australia) introduced a mathematical approach to describing the potential types of interactions between species in mixtures for those designing mimic systems (Trenbath 1983).

A long term study of Europe's oldest continuous farming system led Richard Joffre (Centre Emberger, CNRS, France) to warn against un-realistic expectations of the productivity of mixed systems designed to persist under highly variable climatic conditions. The dehesa agroforestry system of southern Spain and Portugal features the cork oak (*Quercus suber*) at densities of 2 to 10 ha $^{-1}$ in conjunction with pastures grazed by pigs, sheep and cattle. Richard pointed out that this systems had persisted for over 800 years because it was well adapted to local resource constraints and that this came at the cost of sub-optimal production (Joffre and Rambal 1993). Studies of adjacent areas of relatively undisturbed Mediterranean oak woodland suggested the dehesa represents a weak mimic of that natural ecosystem as tree densities are similar, but with commercially less desirable *Quercus spp*. selectively replaced by *Q. suber* in the dehesa.

Meine van Noordwijk (ICRAF, Indonesia) also tempered any remaining enthusiasm for complex, multistrata agroforestry systems by reminding us of the naive early view that all of the complex interactions in agroforestry systems would be positive. This view has been replaced by a more realistic appreciation of a mix of competition and complementarity. He also warned against the delusion that modest increases in biodiversity in agricultural systems would necessarily mean increased biodiversity conservation. He presented his modelling-based research into the question of whether it is better to integrate or segregate the production and conservation roles of land use, based on studies of rubber production in diverse agroforests, at intermediate production levels and high-output monocultures (van Noordwijk *et al* 1995). One question being asked is whether the objectives of biodiversity conservation and ecosystem functioning can be better met by segregating production. While agroforests may have high levels of diversity and be regarded as the ultimate in conservation farming, they are managed for production and cannot compete with a primary forest for biodiversity conservation.

These case studies showed that several different approaches are possible to the development of agriculture as a mimic of natural ecosystems, as summarised in Table 3. Of these five examples, the two that have survived the test of time both evolved through the selective exploitation and simplification of natural ecosystems with the addition of some exotic plants and animals. The dehesa system essentially represents a weak mimic of the Mediterranean oak woodland with the understorey replaced by a pasture of annual and perennial herbaceous species and the tree component selectively reduced to one species of oak. Its persistence for over 800 years is an indication that within this reduced diversity there remains a representation of key functions and a combination of sufficient diversity and management to impart resilience. The persistence of the other three systems has not been tested.

Their evolution however indicates that alternative pathways might be used to achieve the same ends. In the first case, life form and phenology are used as surrogates of function and in the second structure is used as the surrogate of function. In the third, structure was used by farmers as a likely clue to function (accessing water at depth over summer) while experimentally, function is being directly interrogated.

Table 3 Different pathways to achieving ecosystem mimics

Natural Ecosystem	**Agricultural System**	**Basis for Mimic Development**	**Mimic Status**	**Reference**
Mid-grass prairie Kansas USA	Annual crop monoculture	Functional groups	Experimental seed-producing perennial polycultures	Jackson (1985), Barker and Piper (1995)
Humid tropical forest Costa Rica	Shifting agriculture	Structure	Experimental successional mimic	Ewel *et al* (1991)
Semi-arid *Banksia* woodland SW Australia	Annual crop and pasture monocultures	Process (correcting hydrologic imbalance)	Alley farming: crops and pastures + C*hamaecytisus proliferus* treebelts	Lefroy and Stirzaker (1997), Pate *et al* (1996)
Humid tropical forest Sumatra, Indonesia	Shifting agriculture	Commercial exploitation of selected tree spp.	Damar and jungle-rubber agroforestry systems	van Noordwijk *et al* (1995)
Mediterranean oak woodland, southern Spain	Pastoralism	Commercial exploitation of *Quercus suber*	Dehesa agroforestry system	Joffre and Rambal (1993)

3. Theoretical issues involved in the adoption of natural systems agriculture

The third group of participants were asked to address the conceptual issues implicit in the concept of mimicking natural ecosystems. Bert Main (University of Western Australia) was asked to address the question “How much biodiversity is enough?” He replied with “Enough for what?”, explaining that as ecosystem functions must be understood in evolutionary terms, the question of how much biodiversity is enough can only be answered from an appreciation of the geological, climatic, biological and social events that have shaped a particular region's history (Main 1992). Wes Jackson elegantly made the same point, quoting Alexander Pope’s Epistle to Burlington, “Consult the genius of the place in all”, meaning to consult the *genius loci*, the spirit of place, or in Bert Main's terms, the history of place, in order to determine what is appropriate action for that location.

In quoting Pope, Jackson indicated that this idea of using nature as a standard or measure is not a new one. In practice it can be seen in many of the indigenous agricultural systems of the tropics. In the Western cultural tradition it can be found amongst the English Romantic poets and the writing of Virgil. Within the agricultural and scientific tradition, the concept has been advocated by writers such as Liberty Hyde Bailey (*The Holy Earth*), Albert Howard (*An Agricultural Testament*) and J. Russel Smith (*Tree Crops*) from early this century (Jackson 1992).

Jackson also pointed out that the need to adopt this approach would be greatest on what he referred to as the least forgiving parts of the landscape, where inherent fertility and water holding capacity were lowest, and the erosion of ecological capital under monocultural agriculture greatest.

John Passioura expressed this last point by suggesting that while the natural systems agriculture concept would result in very different outcomes in different parts of the world, the common thread would be that sustainable agricultural landscapes would need to take on the characteristics of mosaics in space and time if plant production systems were to be well adapted to available resources.

Richard Hobbs and Steve Morton also pursued the question of how much biodiversity was enough by examining the recent debate in ecology on the ecosystem function of biodiversity. They reiterated Bert Main's point that one of the main functions of diversity was to provide resilience to change (Main 1992), and to provide options for dealing with unusual and episodic events. The emphasis in ecology is shifting away from considering diversity of species to considering the diversity of kinds of species (Chapin *et al.* 1997), clearly indicating a convergence with the sorts of considerations being discussed in natural ecosystems agriculture.

Hobbs and Morton also discussed the changing paradigms in ecology, with greater emphasis on the dynamism and patchiness of natural ecosystems (Turner and Gardner 1991; Pickett *et al.* 1992; Fiedler *et al.* 1997; Ostfeld *et al.* 1997), and indicated the profound implications these changes had for the level of prediction possible in ecology, and for the idea of using natural ecosystems as a model. They summarised ideas presented by (Jordan 1995), who took "twenty great ideas in ecology" and interpreted these in a resource management framework. The important insight from this is that natural systems comprise many species with mutualistic or cooperative functions which are generally lost in intensively managed systems and replaced with external energy subsidies. Clearly, to reduce these subsidies again involves restoring key cooperative functions by increasing the species and/or landscape diversity.

While most presenters had concentrated on the biological and scientific constraints to developing agriculture based on natural systems, David Pannell (University of Western Australia) emphasised the social and economic constraints. He described the conditions necessary for farmers to adopt a farming systems innovation, and indicated that adoption rates were often very slow, even for clearly advantageous and profitable innovations. He concluded that with the types of complex innovations which would be necessary with natural systems agriculture, the important challenges in developed countries were to 1) find systems that are more profitable than the existing one, 2) find a way of assessing that they were in fact more profitable and 3) overcome the deep uncertainty about the technology. In developing countries there are the additional challenges of high interest rates and insecure or inequitable land tenure.

In summarising the workshop Dawson and Fry (in press) identified three characteristics of a successful mimic system. They suggested that it should:

(a) be based on a scientific understanding of the functional characteristics of the main players in the model system. Ecologists, ecohydrologists, soil scientists, and others can help agriculturalists identify the key functions and functional groups; sustainability will arise from successfully mimicking the "processes" through which those functional groups interact. It is acknowledged that 'natural' systems themselves are dynamic; the native vegetation is not an ideal but a model for adaptation to the constraints of that particular landscape.

(b) mimic variability at the landscape as well as the farm scales, ie., in a mosaic across space and time. Diversity at a farm and landscape scale can help manage soil, nutrient and water cycles, stabilise and build the soil, and reduce 'leakage' out of the system so that external inputs are minimised.

(c) be designed within an adoption framework, with clear links to the farmers who will use it. There may be long time lags between implementation and payback, so part of the mosaic should supply short-term profits for the farmer. Here, a mismatch of scales needs explicit consideration. Conventional agriculture is focused on short-term gains, with key decisions being made at the farm scale and industry scale. Sustainability is a long-term goal that operates at different, generally larger, scales. Therefore we must identify the spatial and temporal boundaries within which the key functions of the agricultural system are to 'match' the key functions of the natural system. Different kinds of decisions can be made by individuals within farm boundaries than can be made at, say, a catchment scale by some wider authority. A plan for adoption should provide a means of reconciling, in Levins' and Lewontin's words, the 'boundary of consideration' with the 'boundary of causation' (Levins and Lewontin 1985).

4. Conclusions

Drawing together the experimental case studies and theoretical considerations, a broad approach for the development of natural systems agriculture emerged from this workshop. It attempted to identify the steps required to replace as much as possible the growing external subsidies required of existing managed systems with co-operative functions found in natural systems. These steps are to:

1. Identify the system functions which are currently suboptimal in the managed system

2. Identify the suite of species which carry out these functions in the natural ecosystem

3. Within this suite of species, identify those with key functional roles, or identify analogs of these, ie well adapted species from elsewhere with these same functional roles.

4. Identify the likely range of environmental conditions and disturbances, and select the array of species needed to confer system resilience.

5. Consider how many of these species are required for the managed system, in the context of trading-off environmental risks versus long and short term costs and benefits. For instance, is it essential to install the full suite of species immediately, or can a phased approach be employed?

6. Decide whether it is most appropriate to integrate or segregate these functions with production, that is to have diversity at field or landscape scales or a mixture of both.

7. Assemble the suite of species required to achieve functional objectives within an adoption framework that a) has clear links to end users and b) demonstrates economic viability and/or c) includes socio-economic instruments to facilitate implementation including incentives such as carbon tax trading.

8. Develop these systems in an adaptive management framework that includes monitoring and the capacity to modify elements of the design as new information becomes available or as circumstances change.

A working group appointed at the workshop is currently expanding on these points into a research agenda for natural systems agriculture.

A common theme that emerged with respect to points 1 and 2 was the need for information on below ground plant architecture and activity in order to identify key functions and functional groups in natural and managed ecosystems. Point 3 extends the range of conventional economic botany or bio-prospecting to include consideration of the functional role of economic species in managed landscapes. Points 4 and 5 are directed towards the difficult question of how much biodiversity is required to impart resilience in a managed system. Point 6 poses a question which may rule out ecosystem mimicry at the field scale due to the costs of competition being greater than the benefits of added ecosystem services, or on the grounds that the benefits of biodiversity conservation at that level of integration are minimal. This question of scale emerged as a critical decision point for the application of natural systems agriculture, particularly as maintenance of ecosystems functions such as water and nutrient cycling and biodiversity conservation operated at larger scales and were often in conflict with the economic decisions crucial to the survival of farmers and foresters. Point 7 acknowledges that if these more complex farming systems are not commercially attractive in their own right or supported by incentive schemes, there is little or no hope of them being seriously considered by farmers. Point 8 emphasises that solutions like ecosystems need to be dynamic.

There was general agreement that the natural systems agriculture concept represented a promising approach to the problem of matching agricultural systems to available resources, or in Wes Jackson words, meeting the expectations of the land through the marriage of ecology and agriculture.

The workshop represented something of a watershed, in that it brought together scientists from a wide array of disciplines to explore the potential for progress in this area. The important questions to be asked do not fall neatly into the remit of any one of these disciplines - rather they inhabit the shady realms at the interface between many different disciplines. The workshop provided a useful opportunity to shine a torch on some of these areas. The workshop started with a field visit to Dean Melvin's farm near Dowerin in the wheatbelt of Western Australia. Dean provided the inspiration for the experimental work on ecosystem mimicry now underway in Western Australia by looking at the mismatch between current agricultural practices and how the native bush worked. He then put these observations into practice to develop his alley farming system, which then formed the prototype for the systems currently under close observation. The mix of local innovation by farmers coupled with the power to generalise from one system to the next, derived from scientific testing and development, is very powerful, and provides a clear signpost for the way ahead in the future.

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Appendix 1. Workshop participants

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Mr	John	Bartle	Dept. Conservation and Land Management	Perth	
Dr	Tina	Bell	Botany Department, University of Western Australia	Perth	
Mr	Andrew	Campbell	Environment Australia	Canberra	
Prof.	Todd	Dawson	Ecology and Systematics, Cornell University	Ithica, New York	USA
Mr	Frank	Dunnin	CSIRO Plant Industries	Perth	
Dr	Jack	Ewel	Institute of Pacific Island Forestry, USDA	Honolulu, Hawaii	USA
Dr	Ian	Fillery	CSIRO Plant Industries	Perth	
Ms	Rae	Fry	ABC Radio National Science Unit	Sydney	
Dr	Pauline	Grierson	Faculty of Agriculture, University of Western Australia	Perth	
Dr	John	Hamblin	CLIMA, University of Western Australia	Perth	
Dr	Tom	Hatton	CSIRO Land and Water	Perth	
Dr	Richard	Hobbs	CSIRO Wildlife and Ecology	Perth	
Dr	Wes	Jackson	The Land Institute	Salina, Kansas	USA
Dr	Richard	Joffre	Centre Emberger, CNRS	Montpellier	France
Dr	Brian	Keating	CSIRO Tropical Crops and Pastures	Townsville	
Dr	Rod	Lefroy	ACIAR	Bankok	Thailand
Mr	Ted	Lefroy	CLIMA, University of Western Australia	Perth	
Prof.	Bert	Main	Zoology Department, University of Western Australia,	Perth	
Dr	Warren	Mason	Meat Research Corporation	Sydney	
Dr	Steve	Morton	CSIRO Wildlife and Ecology	Canberra	
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Dr	Bob	Nulsen	Agriculture Western Australia	Perth	
Mr	Mike	O'Connor	Curtin University	Perth	
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Appendix 2 – Workshop report from Trends in Ecology & Evolution

Agriculture in Nature's Image

Report of an international meeting held at 'Munthoola', Williams, 2-9 September 1997

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During the past twenty or more years, ecologists have joined agricultural scientists, farmers and economists in search of sustainable solutions in contemporary agriculture. One ecologically-based approach, which has been scattered in the literature but until recently not gained momentum, is to design agricultural systems 'in nature's image'; that is, to mimic the natural functions of the biota of the region in which the agricultural system is embedded (1). In early September an international workshop, 'Agriculture as a Mimic of Natural Ecosystems', was held in Williams, SW Australia, to discuss the meaning and merits of this approach.

The working premise for what was discussed at this meeting was that the natural ecosystem of any region is adapted to key resource constraints, and therefore provides a site-specific model for sustainability if well mimicked by agriculture. Keynote speakers at the workshop were researchers who had deliberately attempted to mimic, in structural and functional terms, natural ecosystems as a basis for redesigning agriculture. Wes Jackson (The Land Institute, KA, USA) provided philosophical arguments for why we need this approach to agriculture, as well as his practical experience of constructing high-seed-yielding polycultures to mimic the perennial prairie (grassland) which once occupied the great plains of the United States (2).

Jack Ewel (Institute of Pacific Islands Forestry, HI, USA) reported on experiments in Costa Rica where he and co-workers used the successional regrowth following shifting cultivation as a template for a mimic forest (3); here the natural structure was used to mimic function. The workshop organisers, Ted Lefroy (CLIMA/University of Western Australia), Richard Hobbs (CSIRO Wildlife and Ecology, Western Australia), Michael O'Connor (Curtin University, Western Australia) and John Pate (University of Western Australia) wanted to draw together a range of perspectives and experience on mimicking natural ecosystems, but also to explore the relevance of the concept for southern Australia and develop a research agenda for that region. Here, the replacement of deep-rooted, summer-active perennial woodland and heath with shallow-rooted, winter-active annual crops has created a crisis: the rise of saline water tables threatens to wipe out large areas of farmland and remnants of native vegetation.

Chin Ong (ICRAF, Nairobi, Kenya) cautioned against a simplistic analysis of agroforestry systems. Alley cropping has largely failed in Africa, he said, because of insufficient knowledge of where the plants extracted their resources and/or their phenological patterns of resource use, and because of insufficient attention to farmers' immediate economic needs (4). David Pannell (University of Western Australia) added to this by outlining the broad range of social, economic and institutional factors which influence adoption. Richard Joffre (Centre Emberger, CNRS, Montpellier, FR) presented his analysis of the 800-year-old 'dehesa' system of southern Spain, whose sustainability derives from sub-optimal production, an adaptation to the highly variable climate of that region (5). The dehesa is one example of a system which, though managed for harvest by humans, is sufficiently adapted to local resource constraints to be maintained over time.

The importance of an historical understanding of ecosystem change was underlined by Bert Main (University of Western Australia), who asked: "How much biodiversity is enough?" In agricultural systems, "Enough for what?" is the crucial qualifier. If a mimic is to survive over time, the key functions of the existing biota must be understood in evolutionary terms; they are the response to specific geological, climatic, biological and cultural events of that region's past (6). "How much diversity?", then, is a question which can only be answered in context. Brian Trenbath (Agriculture West Australia) provided a mathematical approach to designing successful mimic systems using species mixtures which compliment one another for a higher, combined yield (7). Jack Ewel also discussed how successful mimic systems might look for species 'complementarity' (7, 8) but also gave an example of a potential tree crop where the necessary functions were adequately performed by a monoculture. In most cases, however, the "M5 rule applied" -- Making Mimics Means Managing Mixtures.

Mien van Noordwijk (ICRAF, Bogor, Indonesia) added to this approach, calling for a multifaceted and knowledge-based approach to designing mimics which fell along a continuum between 'segregated' and 'integrated' designs,(7, 9) where the goal was to find an integrated mixture with higher yielding ability. Perhaps the biggest gaps in our understanding of the differences between natural and agricultural ecosystems lie below the soil surface. Deborah Neher (Biology, University of Toledo, OH, USA) gave a picture of below-ground biological diversity, and how it may change in response to different management regimes (10). Richard Stirzaker (CSIRO Environmental Mechanics, Canberra, Australia) looked at soil structure under mixed perennial cropping systems.

In most Australian ecosystems, water and nutrients are scarce, and spatially and temporally variable. The irony here is that "leakage" of, water and nutrients is responsible for degradation problems such as salinity and soil acidification, so a finely-tuned understanding of water and nutrient dynamics is important. John Williams (CSIRO Land and Water, Canberra, Australia), Ted Lefroy, John Pate, Richard Hobbs, Michael O'Connor, Pauline Grierson and Mark Adams (University of Western Australia) are examining the natural heath, woodland and forest ecosystems of southern and western Australia; rooting structures in particular are providing some clues for the effective redesign of agriculture.

Todd Dawson (Cornell University, NY, USA), John Pate and Murray Unkovich (University of Western Australia), meanwhile, gave a reminder that the purpose of mimicking nature in agriculture is to mimic natural "functions"; and that easy-to-apply yet powerful monitoring methods will be crucial in evaluating our success in these terms; the use of stable isotopes and predictive modelling are two such methods. In fact, Tom Hatton and Frank Dunin, (CSIRO Land and Water, Perth) and Bob Nulsen (Agriculture West Australia) showed how insights gained from hydrologic model simulations (11) and ecosystem-scale measurements in southern Australia have been useful in providing a comparative perspective of water uptake between cropping systems and perennial vegetative cover.

Ultimately, the demands of the species in the system must be met as much as possible from resources available within the system. John Passioura (CSIRO Plant Industries, Canberra) pointed out that this is most likely to occur in perennial systems which persist in diverse mosaics where the 'demands' of the plants in the mosaic, closely match what the system can supply. There will be no universal recipe for implementing successful sustainable agriculture; what works for the tropics is not likely to work for south Australia because of different climatic, ecological and socioeconomic constraints. However some general ideas emerged from the presentations and discussions. Any mimic system designed with a view to sustainability should:

(a) be based on a scientific understanding of the functional characteristics of the main players in the model system. Ecologists, ecohydrologists, soil scientists, and others can help agriculturalists identify the key functions and functional groups; sustainability will arise from successfully mimicking the "processes" through which those functional groups interact. It is acknowledged that 'natural' systems themselves are dynamic; the native vegetation is not an ideal but a model for adaptation to the constraints of that particular landscape.

(b) mimic variability at the landscape as well as the farm scales, i.e., in a mosaic across space and time. Diversity at a farm and landscape scale can help manage soil, nutrient and water cycles, stabilise and build the soil, and reduce 'leakage' out of the system so that external inputs are minimised.

(c) be designed within an adoption framework, with clear links to the farmers who will use it. There may be long time lags between implementation and payback, so part of the mosaic should supply short-term profits for the farmer. Here, a mismatch of scales needs explicit consideration. Conventional agriculture is focused on short-term gains, with key decisions being made at the farm scale and industrial scale. Sustainability is a long-term goal that operates at different, generally larger, scales. Therefore we must identify the spatial and temporal boundaries within which the key functions of the agricultural system are to 'match' the key functions of the natural system. Different kinds of decisions can be made by individuals within farm boundaries than can be made at, say, a catchment scale by some wider authority. A plan for adoption should provide a means of reconciling, in Levin and Lewontin's words, the "boundary of consideration" and the "boundary of causation" (12).

It was agreed that the sustainability of mimic systems will depend on how well we work within the 'natural' ecological, geological and hydrological settings for the area under consideration. In Alexander Pope's words, we must "consult the genius of the place" to identify plant species that will provide a diversity of functional roles, accommodate environmental fluctuations and grow well in mixtures. This meeting and the book “Agriculture as a Mimic of Natural Ecosystems” (Kluwer) which will come from it represent a first bold attempt to come to terms with one of the most important issues facing humanity: how to have agriculture without eroding nature.

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Appendix 3 – Workshop Report from CSIRO's *Interactions*

Agriculture as a Mimic of Natural Ecosystems

2-6 September, Williams WA

Tom Hatton and John Williams, CSIRO Land and Water

An international conference on how we might approach agricultural design based on lessons learned from natural systems was held recently on a farm outside of Williams, WA, attended by leaders in agroforestry, ecology and agriculture from around the world. The aim was to assess the feasibility of an alternative approach to agricultural research and practice.

The motivation for the conference, organised by Ted Lefroy of the University of Western Australia, is the unsustainability of agriculture as currently practised around the world, and the apparent inability or reluctance on the part of researchers and managers to devise and adopt production systems which rely to a greater degree on contemporary sunlight while reducing land and water degradation. Given the environmental problems associated with Australian agriculture as practised, there was no shortage of local participation; CSIRO was represented by John Williams, Tom Hatton, Richard Stirzaker, John Passioura, Brian Keating, Kirsten Verburg, Ian Fillery, Frank Dunnin, Steve Morton and Richard Hobbs. The meeting was a nice balance of agricultural scientists and ecologists.

An invited speaker from the US, Wes Jackson, provided the tone and inspiration based on experiences his group have had in redesigning an agricultural system in eastern Kansas based on principles and genetics derived from the local tall grass prairie. In that case, they are searching for a polyculture of grasses and legumes with the same nutrient, energy and water cycling as the original system, but yielding grain as well. Wes' biggest impact, however, was philosophical. He reviewed the history of "nature as model," including contributions from the biblical, the poetic (Pope), the literary (Thoreau), and the scientific (Darwin, Leopold). He contrasted this approach to the Cartesian philosophy which underpins most research today.

Other speakers included Jack Ewel from the university of Hawaii, who has for the past twenty years examined reconstructed tropical ecosystems in Costa Rica and elsewhere. This research has helped clarify the degree to which diversity, structure, and function interact in terms of sustainable production. Chin Ong from ICRAF reviewed the (poor) history of agroforestry system development and adoption in Africa and Asia, and provided wise words with respect to the role that farmers must play in technological development. Richard Joffre from Montpelier provided an example of what was the only apparently sustainable agroforestry system discussed, the dehesa system of Iberia, and noted that the woodland systems of central California may have been the result of an early Spanish attempt to introduce this system to the New World. With the dehesa's widely-spaced trees, sustainable grazing, retention of upland remnant vegetation, low inputs and diverse outputs, some of us wondered how better off Australia might have been if we had been settled by the Spanish! We imported the Merino but not the understanding of the function of trees in the landscape which is central to the sustainability of the 800 year old Spanish dehesa .

The Australians demonstrated the relatively great understanding we have of the structure and function of some of our natural systems (e.g., the Banksia woodland WA), but the stark contrast between these systems and our agricultural ones in the way water and nutrients are cycled led Chin Ong to state that they are better off in Africa than we are here with respect to the environmental problems faced by agriculture.

The tone of the conference was intimate, humorous and honest. This was inspired not only by the participants but the on-farm venue (when was the last time you attended an international conference held in a shearing shed?). There were moments of collective depression over the state of the world in general, but this was balanced by a courageous optimism that we can change it for the better. The conference gave a valuable opportunity to think about, and test some of the ideas and assumptions that are part of the LWRRDC/CSIRO program “Redesign of Australian Plant Production Systems” which is seeking to design novel agricultural systems which ensure economic production and ecological sustainability by matching these systems to the unique biophysical characteristics of the Australian environment. All of us were richer for the time out to think about the ecological principles that are central to building sustainability into the Australian agricultural landscape. The most immediate outcome of the conference will be a book on the subject. In the longer term, it is hoped that the philosophy of finding inspiration in nature for sustainable agriculture will lead to innovative and attractive solutions.