Polyculture Production

Principles, Benefits and Risks of Multiple Cropping Land Management Systems for Australia

A report for the Rural Industries Research and Development Corporation

by Larry Geno and Dr Barbara Geno

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Foreword

This comprehensive report provides a well-balanced synthesis of information available on what is termed polycultural production. Polyculture places an ecological framework to the growing of more than one crop at a time in one place. This report further:

- Provides an innovative synthesis of worldwide information not previously available on polyculture production: including multiple cropping, permaculture, agroforestry and intercropping dimensions applicable to agriculture, forestry and aquaculture management.
- Presents a strategy for sustainable land use intensification drawn from both traditional and modern practices. Polyculture is shown to offer the proverbial ‘free lunch’ by producing more from less. This technique is useful as questionable inputs are withdrawn from production under triple bottom line accountability.
- Establishes polyculture as an exemplary integrating theme for understanding both native and manipulated ecosystems and their interaction.
- Explores the science behind the benefits of polyculture, traces the conceptual development through time of the ecological theories of competition, complementarity, resource capture and plant interaction to show the transition from a static, structural understanding to a more dynamic, functional understanding of what is, at times the chaotic, nature of polyculture performance.
- Establishes a firm scientific basis for polyculture production management.
- Details desirable polyculture component characteristics and design principles for use in designing new farming systems, especially amenable to low input, organic and marginal land farming and for reducing environmental impact and enhancing ecological integrity.
- Illuminates potential barriers and constraints to wider adoption and implementation of polyculture production as being biophysical, mechanical, social, economic and institutional. The report notes present low adoption rates and the need for future research, development, communication and adoption of polyculture principles and practices.

This project was funded from RIRDC Core Funds which are provided by the Federal Government.

This report, a new addition to RIRDC’s diverse range of over 600 research publications, forms part of our Organic Produce R&D program, which aims to optimise the profitability of Australian organic production in domestic and overseas markets and to promote the utilisation of organic farming systems as a means of enhancing the sustainability of Australian agricultural systems.

Most of our publications are available for viewing, downloading or purchasing online through our website:

- downloads at www.rirdc.gov.au/reports/Index.htm
- purchases at www.rirdc.gov.au/eshop

Peter Core
Managing Director
Rural Industries Research and Development Corporation
Acknowledgments

This research is dedicated to Bill Mollison, who has long grappled with the concepts of polyculture and their holistic application under his wider concept of permaculture.

The Origins of Permaculture

In November 1959, watching marsupial browsers in the floristically simple rainforests of Tasmania, I wrote in my diary: ‘I believe that we could build systems that would function as well as this one does.’ A casual reflection, not further developed, had broken the barrier between passive observation (in an attempt to understand inter-relationships between browsers and plants) and the active creation of many similar systems that we could construct ourselves. The step from passive analysis to active management, or active creation, was critical.

I was also discovering over this period (1959-1962) that even two of these common browsers and no more than 26 woody plants species could set up a series of very complex interactions. Thus, it was the interactions of components, rather than the number of species that gave the system its flexibility. That flexibility allowed a fairly stable condition to be established through a variation in other influences, in weather and growth. The system constantly changed, but continued to function.

This, then, was both the precursor and the core of Permaculture: the realisation that we can create systems, based on analogies of natural systems, or try to improve them for productivity, and then allow the created system to demonstrate evolutions, stepping in at critical stages to manage, or add or subtract species, and observing at all times. These system analogies, if well constructed and recorded, could produce a yield that could be constantly assessed or improved and would also need minimal maintenance energy after the establishment phase.

(Mollison 1996)

About the authors

As researchers and commercial farmers for 25 years, Barbara and Larry have always sought ecological answers to the expectations of the land. Trained through PhD level in ecology and management, they have established polyculture farms in three countries, operated a national organic farm certification scheme, contributed to new crop development, grower organisations, popular and journal publications, and the advance of the concept of sustainability. Through their consulting, they endeavour to place solid, useful information in the hands of those who are on the land to develop successful models of adaptive human ecology. Barbara currently lectures at university, while Larry grows native fruit trees and consults on sustainable farm design. Barbara also is involved with the efforts of both the Centre for Australian Regional Economic Development (CARED) and the Institute of Sustainable Regional Development (ISRD) to promote sustainable solutions to regional development problems.
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Executive Summary

This innovative research project was funded under the Organic Produce Program of the Rural Industries Research and Development Corporation. Under the guidance of an industry developed five year R & D plan, RIRDC began funding research in 1998 in 7 sub-programs: communication and education, conversion processes, organic systems design, soil management, pests and diseases, plant and animal nutrition and market development.

In the 1999 cycle, RIRDC and its industry advisory panel approved funding under the systems design sub-program to Larry and Dr Barbara Geno of Agroecology Associates consultants. This sub-program recognises that most Australian production land use systems are largely an artefact of the importation of western science and economics, European industrial, monoculture, management approaches, and production systems that evolved in European conditions. RIRDC’s Organic Produce Advisory Committee believes that significant redesign of commercial production systems will be necessary to adapt to the different biophysical conditions found on the Australian continent.

The project accepts the extensive evidence already present regarding the failure of industrial monoculture approaches to provide for ecologically sustainable land use. There is no need to further detail fossil fuel energy reliance, net energy imbalance, environmental impacts, rural decline, and food quality issues that have emerged. Clearly, solutions are needed that maintain or increase food and fibre production in Australia. It is quite likely this will be achieved on a reduced land base with the use of fewer external resources in the future and needs to be without the current deleterious side effects. One solution may be a greater understanding and implementation of polyculture practices for agricultural intensification.

An extensive literature review of over 250 articles and books was conducted over a wide range of literature in subjects pertinent to polyculture: multiple cropping, permaculture, agroforestry, and intercropping in traditional peasant agriculture and current industrial production. While the practice and content of polycultures emphasise plant crop components, the overriding principles and supporting theories apply as well to forestry, aquaculture, and animal production systems. Since the ecological and physiological processes and theories generally arise from the study of natural ecosystems, polyculture offers an integrating bridge between natural and human systems, conceptually and on-the-ground. As well, the field offers an effective bridge between ecologists, agronomists and resource managers.

The literature review represents the first time the diverse threads of research have been drawn together to apply to the challenge of sustainable land use. The research strategy was generously inclusive, rather than exclusive because many different disciplines, cultures, and climatic situations contribute to this body of information.

After establishing working definitions of polyculture terms and their evolution through time, it was shown that they all contribute to the basic study of polyculture: the interaction of crop components in time and space.

As a relatively unknown area of study, a rationale for researching polyculture was advanced. It was shown that food production has always been primarily polycultural, from primitive hunting and gathering to current third world house gardens and managed agroforests. For 98.5 % of farming history, humans have produced food from integrated polycultures. In both the first and third world, polyculture practices remain important and the majority of current world farmers depend on multi-species production for their livelihood. Evidence emerged of the growing interest in polyculture indicated by the increasing amount and diversity of the literature. Briefly, the known problems of industrial monoculture practices, the differences between monoculture and polyculture production, and the general advantages of polyculture
production were addressed, concluding that it was useful to study polyculture because it might offer a better way to produce food, fin and fibre.

Accepting that sufficient rationale exists for studying polyculture approaches, the benefits of polycultural practices were elucidated by explanation of their underlying mechanisms and theory. Extensive individual case studies and broader review papers provided evidence that polycultures yield more from smaller areas and as an approach to agricultural intensification they suffer less than energy, gene, or expertise intensive strategies to increase production. Their yield is more stable over space and time than monocultures in terms of income level, stability and risk. Polycultures generally showed advantages while highlighting methodological problems in assessing subsistence versus market values and the role of full cost accounting in addressing benefits and costs. Little was found covering wider social and landscape values excepting the benefits of polycultures in addressing biodiversity needs.

With an understanding of the benefits of polyculture approaches, the detailed ecological basis for these benefits that arise out of interaction between crops and between crops and environment were addressed. The report reviewed the range of competitive and complementary interactions and the way they result in polyculture yield advantage and income risk reduction. Relevant ecological theories and their evolution through time were complemented with agronomic studies and the more recent integration of the two fields of science.

The process of resource capture by producing polycultures further explained the mechanisms behind polyculture benefits by looking at environmental resource use, including capture, utilisation, allocation, partitioning and differential use. Both structural and functional interactions were considered over both time and space. It was found that polycultures were more efficient at gathering the essential requirements of light, water, and nutrients than monocultures, particularly when tree based. The subtle interplay between complementarity and competition was seen as an essential feature of polycultures, as it is in natural ecosystems.

As many of the benefits arise from, and current research efforts directed toward, the role of polyculture practices in achieving acceptable pest control, a separate section presented this material. By understanding pest dynamics, particularly insects, the mechanisms of polyculture yield advantage were further articulated. Less, but sufficient, research was identified for disease and weed pests, especially the role of alleopathy.

With the foregoing information tools at hand, the report addresses the appropriate polyculture component characteristics and design principles necessary to design or monitor new or existing polyculture systems. The literature suggested that an increased awareness of existing biophysical conditions, appreciation of pre-existing native ecosystems and that an understanding of ecological theory and agronomic practice would assist in successful polyculture establishment through the notion of agriculture as ecosystem mimic. The substantial interest in tree crop based polycultures indicated this area to have perhaps the greatest potential in realising polyculture benefits. Of note, it appears the potential to realise polyculture benefits is scale neutral and can be achieved by any size producer, anywhere, with appropriate crop assemblies.

No 'magic bullet' is without cost or risk. The research covered risks, barriers, constraints and obstacles to successful polyculture production as physical crop and site differences and challenges to management, labour and mechanisation. As well, the social dimension, since humans are involved, is critical and the constraints preventing wider adoption of polyculture practices were addressed for research and extension, policy, information availability, and other socioeconomic dimensions. Polyculture production demands higher producer involvement and management expertise yet suffers from a lack of research and education efforts. Agricultural breeding has focused its efforts in a direction that means current crop varieties may not suit polyculture practices. In the rush to implement successful agroforestry systems, the absence of
information has caused failures, but not as many failures as have resulted from inattention to socio-economic factors. Polycultures were seen as more difficult to manage under existing mechanisation, but possible. Increased labour needs for polyculture could be seen as a barrier or as an employment opportunity. Considerable further research and extension will be needed but the very way science is currently done may be a constraint to expanding polyculture practices. Still, the conclusion was that there are few barriers that could not be overcome with determination.

A brief exploration of the popular press in Australia indicated that organic producers might be innovating in the establishment and operation of polyculture systems. Following the literature search, an extensive survey of 7000 organic and transition producers was conducted through organic certification agencies and the national alternative agriculture press. Unfortunately, less than half of the very low 1% response to the survey showed serious polycultural practices. Despite having a sample too small for representativeness or statistical treatment, useful empirical information of an indicative sort is presented as tables and summarised. As a communication tool, two scenarios of polyculture production, temperate and tropical were developed from principles, guidelines, strategies and practices arising from both the literature and survey responses. A final table of polyculture production as characterised by the literature and empirical survey as emergent properties, polyculture principles, practical strategies and expected benefits and risks indicates a need to demonstrate successful polycultures in a variety of climate and cropping systems and to undertake education efforts to enable Australian primary producers to implement polyculture systems to become more environmentally sound, better off financially and more globally competitive under ecologically sustainable development (ESD) and full cost accounting environments.
1. Introduction

1.1 Background to the Study

The aim of the Polyculture project was to make information available on polyculture systems design that is currently in existence but not widely available, through collecting, analysing and distributing the principles of successful organic polyculture farming in a report to RIRDC through the Organic Advisory Committee. The RIRDC Organic sub-program funds a program in organic systems design, one of seven programs of priority interest. Organic systems design recognises that most Australian production land use systems are largely an artifact of the importation of western science and economics, European industrial monoculture management approaches and production systems that evolved in distinctly different northern hemisphere conditions. RIRDC and other peak research institutions in Australia believe that significant redesign of commercial production systems will be necessary to adapt to the different biophysical conditions found on the Australian continent and achieve a more sustainable land use in line with ecologically sustainable development (ESD) commitments by all levels of government.

1.2 Justification of the Research

While the above mandate creates an initial justification, several other factors led to the support of the research. First, the consultants had active interest, past involvement and proven experience in researching and developing practical polyculture production systems. Second, it was known that there was a wide and disparate collection of relevant research across numerous disciplines that had not been synthesised and which might offer a useful framework, partly developed by earlier RIRDC research in Western Australia. Third, anecdotal reports in technical and popular journals (see Section 9) indicated a number of interesting reports of multiple benefits from polyculture production systems by organic growers and others. These factors indicated further exploration of the literature and organic producers was warranted.

1.3 Structure of the Report

The final report, which follows, is divided into eleven parts, numbered from two to twelve. Section 2 is concerned with defining polyculture by describing the evolution of polyculture terms, outlining the monoculture/polyculture continuum and then elaborating on the three common forms of polyculture: multiple cropping, sequential cropping and intercropping. The final part of Section 2 defines relevant terms used in this report. Then, Section 3 of the report addresses the rationale for research into the field of polyculture. Four primary reasons for the study are raised in this section of the report. In Section 4, polyculture benefits are examined as they are described in the literature and the theories and mechanisms of productivity in terms of yield advantage, income level and stability and social capital are outlined in detail.

Section 5 of the report turns to the issues of interactions, the ecological basis for polyculture. First, ecological theories relevant to polyculture interactions are discussed, then the principles of competition and complementarity are described before moving on to the issue of polyculture and landscape interactions. Section 5 finishes with an examination of the ecological principles of resource capture by crops. In Section 6 of the report, pest management covering the three topics of insect pests, diseases and weeds as the focus with particular attention given to the consequences of polyculture interactions on these important farm management challenges.

Design principles and polyculture component characteristics is the topic of Section 7. In this section the ecological approaches giving rise to design principles are discussed and some of the design issues in agroforestry are covered. In the last part of Section 7, the issues of mechanisation in polyculture are addressed through an examination of the effects on polyculture design. Section 8 deals with the risks,
barriers and obstacles to polyculture while Section 9 covers polyculture systems in Australia as reported in the popular press.

Section 10 describes the methodology of the empirical part of the project through a description of the development of the survey instrument and the construction of the sample frame and reports the survey responses along with illustrative scenarios of polyculture production grounded in the survey and literature results. Section 11 reports on overall results and discussion of these results. A summary table of polyculture principles, strategies, benefits and risks is presented and the specific outcomes and implications of the research are illuminated. Section 12 outlines the recommendations arising from the report.
2. Defining Polyculture

This section examines the range of terms used in polyculture research and the chronological evolution in their meanings. The aim of the section is to establish a clear set of working definitions for the project. Because polyculture practices evolved to fit an almost infinite number of geographical and climatic niches and a wide range of human needs, the definitions can be seen as a continuum of meanings, with individual points (specific term definitions) arising more for conceptual utility than to differentiate the factual reality on-the-ground. This continuum of terms is primarily based on the criterion of interaction: the extent to which component crops in a farming system affect or are affected by each other. These interactions can be in either time (temporal) or space (spatial) or both.

2.1 Evolution of Polyculture Terms

Although Geno (1976a) used polyculture as a potential term for alternative mixed farming, Kass (1978) first proposed the term ‘polyculture’ for the general case to include a number of different variants, which are discussed below. In his simplest definition, he proposed that:

Polyculture distinguishes ‘all of the multiple cropping situations from monoculture [cropping] and indicates that an area is being used for more than one crop at a time’.

Kass noted that the terms crop mixtures or crop associations came into use as early as 1912, and while less precise than the term polyculture, are the progenitors of the polyculture term used for the general case, as defined above. According to Francis (1986), the first organised attempt to provide guidelines for defining polyculture occurred in 1975. A Symposium on Multiple Cropping was held at the Annual Meeting of the American Society of Agronomy (ASA) where the terms to be used to describe specific cropping patterns or mixtures were based on the opinions of a wide range of specialists. A few refinements have occurred since and numerous more narrow terms have emerged within the framework to describe specific cropping systems. For the purposes of this project, the term polyculture is used under the assumption that it is the broadest, most inclusive overall term. It is also the term that is most clearly in opposition to monoculture.

A broad definition of polyculture also allows non-crop components and non-plant elements which by definition facilitates the appreciation of the multiple, diverse nature of these farming systems. Beets (1982) believed that the classification criteria for determining if a farming system can be defined as polyculture are:

1. The degree of intensification in space or the level of intimacy of the crop species.
2. The degree of intensification in time or the crop intensity over the year.
3. The relative time of planting the crop species.

2.2 Monoculture/Polyculture cropping continuum

The continuum of terms distinguishes between monoculture cropping, also commonly referred to as industrial agriculture, and polyculture, more often associated with traditional or ethnic cropping systems. This oppositional dichotomy can assist in informing the taxonomy of polyculture explored in this research project. Monoculture has been variously defined as:

- A sole crop referring to a component crop being grown alone and, unless otherwise indicated, at optimum population and spacing (Willey 1979a).
- The repetitive growing of the same sole crop on the same land. Sole crop is then defined as one crop variety grown alone in a pure stand at normal density, synonymous with solid planting and opposite to the meaning of intercropping (Francis 1986).
A minor term associated with monoculture is the term *monocropping*, occasionally occurring in the literature. This term refers to the single crop season. For example, in crop rotations, the sole crop is a monoculture for that cropping year, but the individual field could be sequentially monocropped with different species. More often than not, monocropping and monoculture are seen as synonymous even though the strictest definition of monoculture as currently used refers to sequential monocropping over time. Francis’ (1986) definition shown above is the closest.

Obviously, the purest monoculture is where the same crop is grown repetitively; say Douglas Fir forestry in the Pacific Northwest of the United States, without alternating sole crops of a different species. While sequential monocropping or rotations over time represent a step toward polyculture practices, the essential difference is that there is very little, if any, interaction of the sole crop in the given year and field with any other crop. It is important to note that sequential rotations can have impacts on later crops indirectly, such as soil structural or nutritional modification, residue content, or soil life modification from the prior crop. An example is rotation of maize and soybeans which fix nitrogen, doubtless a beneficial interaction but only indirect, thus for the purposes of this research it is in the category of monoculture.

2.3 Multiple Cropping

The next most inclusive term is *multiple cropping*. In the early literature it is often used interchangeably with intercropping, but in refinements since the late 1970s, intercropping is now seen as a subordinate concept to multiple cropping. Table 1 outlines the various definitions for multiple cropping arranged chronologically. It should be clear that an interaction between crops in time and space is the essential feature of the general term of multiple cropping, but that interaction is non-specific. It can occur during only part of the growing season, or only over part of the area.

Table 1: Definitions of Multiple Cropping

<table>
<thead>
<tr>
<th>Researcher</th>
<th>Date</th>
<th>Definition</th>
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<tbody>
<tr>
<td>Willey</td>
<td>1979a</td>
<td>[Using ‘intercropping’]…the growing of two or more crops simultaneously on the same area of ground where they are simultaneous for significant part of their growing periods.</td>
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<tr>
<td>Beets</td>
<td>1982</td>
<td>Growing more than one crop on the same piece of land during one calendar year.</td>
</tr>
<tr>
<td>Andrews &amp; Kassam</td>
<td>1976</td>
<td>The intensification of cropping in time and space dimensions. Growing two or more crops on the same field in the year</td>
</tr>
<tr>
<td>Francis</td>
<td>1986</td>
<td>Growing two or more crops on the same field any year.</td>
</tr>
<tr>
<td>Vandermeer</td>
<td>1989</td>
<td>Growing two or more crops on the same field any year.</td>
</tr>
<tr>
<td>Stinner &amp; Blair</td>
<td>1990</td>
<td>Using the same field to produce two or more crops a year.</td>
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2.4 Sequential Cropping

Following the ASA Symposium, a dichotomous classification further divided multiple cropping into sequential cropping and intercropping. These terms differentiate between the time and space dimensions of multiple cropping. Table 2 outlines the key definitions proposed for sequential cropping in the literature reviewed.

Table 2: Definitions of Sequential Cropping

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<thead>
<tr>
<th>Researcher</th>
<th>Date</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andrews &amp; Kassam</td>
<td>1976</td>
<td>Growing two or more crops in sequence on the same field per year (or per multi-year cropping periods as in arid regions). The succeeding crop is planted after the preceding crop has been harvested. Crop intensification is only in the time dimension. There is no intercrop competition. Farmers manage only one crop at a time in the same field.</td>
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</table>
Definitions for sequential cropping are fairly uniform and clear. Forms of sequential cropping can be further broken down and defined by the time element (Andrews & Kassam 1976):

- **Double cropping** - growing two crops a year in sequence.
- **Triple cropping** - growing three crops a year in sequence.
- **Quadruple cropping** - growing four crops a year in sequence.
- **Ratoon cropping** - the cultivation of crop regrowth after harvest, as in sorghum for a second crop of forage and lucerne or sugarcane over several years.

It must be noted that none of the above definitions consider whether the succeeding crop is the same or a different species. In practice, due to climate constraints, the following crop or proceeding crop is usually a different species, typically allowing a longer season to be utilised. Because sequential cropping is seen as having a fixed time limit in all but equatorial humid environments, the two or more crop periods are likely to experience different climatic conditions. Regardless, it is clearly intensification of use but without particular interactions between the crops. Sequential cropping could also be viewed as a sort of compressed rotation, especially in equatorial regions where crop species move through time, rather than space, as in the temperate climate understanding of crop rotation.

### 2.5 Intercropping

The other classification of multiple cropping is **intercropping**. Although occasionally used interchangeably with multiple cropping, the current consensus is that it is the *space dependent form of multiple cropping*. As with other terms in this research report, intercropping has a multitude of definitions. It has variously been defined as:

- Growing two or more crops simultaneously on the same field. Crop intensification is in both time and space dimensions. There is intercrop competition during all or part of the crop growth. Farmers manage more than one crop a time in the same field (Andrews & Kassam 1976).

- The growing of two or more crops simultaneously on the same field such that the period of overlap is long enough to include the vegetative stage (Gomez & Gomez 1983).

Most authors since Andrews and Kassam (1976) have used the ASA taxonomy for the broad definition of intercropping as a form of multiple cropping. In a later section of this report analysing the principles and benefits of polyculture, further distinctions are made in identifying specific types of intercropping in recognising that the resultant intensification can be variable in space and time, and that the intercropping interaction can be either, and occasionally both, competitive or complementary.

Intercropping systems comprise the largest category of multiple cropping. Intercropping farming systems are the most varied and best demonstrate the polyculture interactions described later. As such, it is the most extensively defined and segmented set of definitions within polyculture. In the earliest literature, the term was often interchangeable with or confused to varying degrees with multiple cropping and often assumed row culture only, with broadcast crops or mixed rows termed mixed cropping, another term with a different current meaning (often meant as mixed farming-multiple crops on one farm). The current consensus gives rise to the following definitions of intercropping types:
Mixed Intercropping
Mixed intercropping is growing two or more crops simultaneously with no distinct row arrangement (Andrews & Kassam 1976), ie. broadcast or random establishment as in indigenous slash and burn or fallow agriculture and current industrial grain mixtures (Gomez & Gomez 1983). It is also termed mixed cropping with a similar description (Kass 1978; Beets 1982), but with the earlier mentioned potential confusion. Willey (1979a) adds the point that there can also be rows with mixing within the row that is still termed mixed intercropping. Mixed intercrops are typically planted together but may have different crop maturation times. Obviously this type of intercropping will have the most intense interactions between crop species or varieties.

Row Intercropping
The growing of two or more crops simultaneously where one or more crops are planted in rows (Andrews & Kassam 1976). Vandermeer (1990) observes that this is the pattern of intercropping usually encountered in intensive agriculture, such as peas with canola, alternating maize and soybeans and various tree-based systems. Beets (1982) adds that it occurs ‘in a fixed pattern of spacings and rows’. Many traditional polyculturalists make use of this method.

Strip intercropping
The growing of two or more crops simultaneously in strips wide enough to permit independent cultivation but narrow enough for the crops to interact agronomically (Andrews & Kassam 1976). Vandermeer (1990) observed that this form of intercropping is more common in highly mechanised systems. Clearly, as cropping is increasingly mechanised, the distance between intercrops is increased and their potential level of interaction is decreased. This is an important consideration later in the discussion of the nature, principles and benefits of crop competition and complementarity in intercrops.

Relay intercropping
The growing of two or more crops simultaneously during part of the life cycle of each is defined as relay intercropping. A second crop is planted after the first crop has reached its reproductive stage of growth, but before it is ready for harvest (Andrews & Kassam 1976). Stinner and Blair (1990) added that there must be some overlap in the life cycles of the two crops (otherwise it would be termed sequential cropping). Kass (1978) referred to this as relay planting and added that the following crop can be seeds or seedlings. Some researchers believe that a distinguishing feature of relay intercropping is that the flowering periods of the two crops overlap- the most stringent definition, but one relevant to crop interactions.

Vandermeer (1989) observed that relay intercropping may actually include mixed, row or strip intercropping in one or both crops, since its primary categorisation variable is time. He further generalised that it may make more sense to think of three general categories: 1) sequential cropping, 2) relay intercropping and 3) full intercropping, a simplification based on the degree of physical association of the crops involved, ranging from no association (sequential), to partial association (relay), to complete association (full). Beets (1982) complemented these definitions by defining relay [inter]cropping as the planting of crops between plants or rows of an already established crop during the growing period of the first planted crop(s).

2.6 Other Relevant Terms
With the major taxonomy of polyculture thus defined, a number of other relevant terms that follow on or are variations of these types of cropping systems can be briefly defined.
**Agripastoral** Growing crops and animals contained in the same area at the same time.

**Agrisilviculture** The use of land for concurrent or sequential production of agricultural crops and forest crops (Farrell 1995).

**Agrisilvopastoral** Farming systems in which land is managed for the concurrent production of agricultural and forest crops and for the rearing of domestic animals (Farrell 1995), with a set of land use techniques implying the combination of a deliberate association of a woody component with animal husbandry and crops in the same site (Russo 1996).

**Agrobiodiversity** An expansion of the concept of biodiversity to include all plants and animals that contribute directly or indirectly to raising crops and livestock, including crops, weeds, pollinators, pests, soil microflora and microfauna, biocontrol agents that suppress crop pests and surrounding biodiversity (Srivastava & Smith 1996).

**Agroecology** Altieri (1987) has termed the application of ecology to the study, design, and management of agricultural systems as ‘agroecology’. Agroecology regards the farm system as the fundamental unit of study. In these farming systems, the mineral cycles, energy transformations, biological processes and socioeconomic relationships are investigated and analysed as a whole, with the goal of optimising the agroecosystem as a whole.

**Agroforestry** The deliberate integration, in space or time, of woody perennials with herbaceous crops and/or animals on the same land management unit (Steppler & Nair 1987 as cited in Williams & Gordon 1990).

**Agrophytocoenosis** Where growth or yield of some crops are increased when grown in concert with others (companion planting).

**Alleomediation** The possession of herbivore toxicant or repellant substances that prevent or reduce grazing.

**Alleopathy** A term coined in 1937 (Putnam and Duke 1978). Its current use refers to the detrimental effect of higher plants of one species (the donor) on the germination, growth, or development of plants of another species (the receptor).

**Alleospoly** Competition for necessary growth factors.

**Alley farming** A farming system where crops or pastures are cultivated in the alleys between rows of trees or shrubs (Kang 1990). This system can be synonymous with agrisilviculture, silvopastoral, and agrisilvopastoral. The physical pattern is the distinguishing feature.

**Aqua polyculture** The culture of more than one species of fish together in the same pond (Edwards et al. 1988). See also the crop/livestock/fish farming systems in Madamba (1980).

**Biodiversity** This term has three main dimensions: the genetic variation within species and populations, the number of species, and habitat preservation.

**Compensation** In a polyculture, if one crop suffers, the other crop(s) utilise the resources available to yield sufficient production, often more than they would on a per plant basis if sole planted at normal densities.
**Competition / Interference** The process in which two individual plants or two populations of plants interact such that at least one exerts a negative effect on the other (Vandermeer 1981; 1989).

**Cropping pattern** The yearly sequence and spatial arrangement of crops or of crops and fallow in a given area (Andrews & Kassam 1976).

**Complementarity / Facilitation** The process in which two individual plants or two populations of plants interact in such a way that at least one exerts a positive effect on the other. Double facilitation is equivalent to the ecological concept of mutualism (Vandermeer 1989). Living entities beneficially affect each other’s fitness (Burns 1993), such as rhizobium bacteria to fix nitrogen in clover and insect pollination of flowers.

**Land Equivalent Ratio (LER)** The ratio of the area needed under sole cropping to one of intercropping at the same management level to give an equal amount of yield (Andrews & Kassam 1976; Willey 1979a; Mead & Willey 1980). *Overyield* or *yield advantage* results when the production of component crops in an intercrop is higher than the sum of the appropriate equivalent monoculture crop areas, indicated by a LER greater than one (Francis 1986). LER represents the increased biological efficiency achieved by growing two crops together in the particular environment used (Mead & Willey 1980), or the more efficient utilisation of available land area (Vandermeer et al. 1984).

Because LER calculations only incorporate area and not time factors, later researchers attempted to extend the concept, largely because many tree and shrub components in polycultures grow for longer than one year. Hiebsch and McCollum (1987) proposed ATER, an area-times-time equivalency ratio to correct this conceptual inadequacy in LER by defining intercrop yield as a function of both land area and time. ATER unfortunately assumes continuous crop growth throughout the year, so Balasubramanian and Sekayange (1990) proposed a concept called area harvest equivalency ratio, AHER, as nearer to the true value of intercrop yield advantage.

Many third world researchers acknowledge that for the peasant farmer, biological efficiency of plants or most efficient utilisation of land with production measured in calories or kilograms are perhaps less important than income expectations and Chowdhury (1981) proposed expected money value, EMV is a better measure for trials on intercropping systems because it indicates the profitability of a system where LER or its successors did not. Vandermeer (1984) experimented in Ohio soybean/tomato polycultures and developed a similar relative yield total, RYT, to compare dollar values of different intercrop densities. Another term is RUE: Resource Utilization Efficiency (Trenbath 1986). This is the product of the efficiency of capture of resource by the crop plant and the efficiency of conversion into yield.

**Mixed Farming** Management of various plant or animal crops on the same farm without these being intercropped.

**Multilines / Mixtures** Mixtures are plantings of multiple varietics of a single crop (Barrett 1982; Cromartie 1981; Perrin 1980) while a multiline variety is a mixture of genetic types (lines) of a crop similar in growth characteristics but which differ in the (disease) resistance genes they carry (Trenbath 1976).

**Permaculture** As defined by Mollison (1988), ‘permaculture (permanent agriculture) is the conscious design and maintenance of agriculturally productive ecosystems which have the diversity, stability, and resilience of natural ecosystems. It is the harmonious integration of landscape and people providing their food, energy, shelter and other material and non-material needs in a sustainable way. Without permanent agriculture there is no possibility of a stable social order. Permaculture design is a system of assembling conceptual, material, and strategic components in a pattern which functions to benefit life in all its forms.’
**Rotation** The repetitive cultivation of an ordered succession of crops (or crops and fallow) on the same land. One cycle can take several years to complete (Andrews & Kassam 1976).

**Sequential agroforestry** A forestry system in which the maximum growth rates of the tree and crop components occur at different times even though both components may have been planted at the same time (Sanchez 1995).

**Silvopastoral** The adding or retention of fodder trees and shrubs in the grazing landscape (Lefroy et al. 1992) or the land management systems in which forests are managed for the production of wood and fodder as well as for the rearing of domestic animals.

**Simultaneous agroforestry** A forestry system in which tree and crop components grow at the same time and in close enough proximity for interactions to occur (Sanchez 1995).

**Sole crop** Where one crop variety is grown alone in pure stands at normal density (Andrews & Kassam 1976) and is assumed to be grown at optimum population and spacing (Willey 1979a). Vandermeer (1989) refers to this as monoculture, though it would seem closer to monocrop and he enlarges the genetics to ‘single species of crop’. Sole crop is the term most used by agronomists and can be considered equivalent to the term ‘pure stand’ as used by ecologists. Solid planting is another analogous term used by agronomists (Andrews & Kassam 1976).

**Taungya** Arising centuries ago in southern Asia from traditional slash and burn practices, this is now under further development across SE Asia as a commercial wood production system that includes crop cultivation as part of the silvicultural scheme, distinct and different from social forestry or agroforestry models (Jordon, Gajaseni & Watanabe 1992). Taungya is a system of forest plantations in which peasants plant and tend the trees in return for the right to cultivate crops between the trees for the first few years.
3. **Why Study Polyculture? A Rationale**

This section covers a brief background in rationale for the study of polyculture principles, risk, and benefits. A historical perspective on polyculture in the context of human food production is followed by discussion of the properties of polycultures as solutions to the problems of monoculture and elaboration of some of the opportunities offered by polyculture approaches from a general perspective.

### 3.1 Farming has always been predominantly polycultural

As humans moved from nomadic hunting and gathering the first agriculture appeared. Perhaps based on kitchen middens, the first domesticated plants probably appeared in the garbage heaps of primitive households, sprouting from lost or waste food gathered from the surrounding wilds. Seeds, tubers and stems found favourable conditions in the discarded plant and animal material and human excreta, as well as being physically concentrated in the village area. Opportunistic plants growing in such nutrient rich earth are likely to have been generally larger and thus more noteworthy than plants of comparable age growing away from campsites (Plucknett & Smith 1986). They would have represented the diversity of gathered plant foods as well as important dye, drug, basketry, medicinal, and tool plants. As these midden gardens were harvested, the process of plant domestication began. The improved size, yields, easier defence and proximity of the midden gardens would have inspired the first farmers to plant food intentionally. The earliest agriculture was likely based on vegetative propagation, primarily roots like cassava, taro, sweet potato, and yams because of the ease of propagation and care and the availability of food over a long period through staggered harvest. In addition, root crops that are clonally propagated retain their varietal integrity as opposed to seed crops that may have wide variation from crop to crop. Animals began to be domesticated as well, with pigs and chickens probably domesticated as scavengers (Edwards, Pullin & Gartner 1988). Plucknett and Smith (1986) added two general principles that:

1. Root crop cultivation is more biotically diverse than seed based farming and more people in the tropics depend on tuber crops for a livelihood than in temperate zones; and
2. The diversity of cropping patterns declines poleward or as altitude increases within the tropics and as rainfall amounts decrease.

Seed agriculture appeared around 3500 BC, based on wet rice culture, but did not eliminate root agriculture as much as complement the existing practices. Since that time, a myriad of polyculture farming systems have evolved around the world, with reliable subsistence being the priority. There is a wealth of anthropological ethnographic literature describing traditional polyculture practices by peasant cultures (Bradfield 1986; Thurston 1997). These polyculture production systems are still largely intact, though further evolved in much of the third world today. The history of farming systems shows that out of perhaps 10,000 years of agriculture, **humans have produced food from integrated polycultures for approximately 98.5% of farming history**.

In his extensive review of prehistoric agriculture, Deneven (1995) documented early agricultural practices, some still persisting. He believed that shifting cultivation, while certainly practiced, was difficult to document archaeologically and didn’t recognise the labour balance between clearing forest (with stone axes, often large hardwoods) and maintaining existing production areas. He suggested that ‘near-permanent cultivation rather than shifting cultivation was likely, especially on good soils’. He noted that prehistoric farmers relied on different strategies simultaneously where, over time, a plot of land might rotate through a sequence of varied forms of management and could include horticultural polyculture fields, swiddens, house gardens, managed fallows and forest manipulation of both wild and cultivated plants. The resulting anthropic forest could come to have species composition, density and distribution determined by human activity. Even now, the current unnatural concentration of economic plant species in the forests of Yucatan, Central America and elsewhere are evidence of this human interaction. Deneven
argued that agricultural methods employed in prehistoric time can serve as models for sustainable agriculture today.

Two major trends between 1300 AD and 1800 AD led to the development of the mixed farming systems characteristic of much of Western Europe and North America from 1850-1945 known as integrated crop-livestock agriculture. These trends were the reduction and final elimination of the fallow with pasture cultivation in rotation with crops providing feed for livestock. From 1850, industrial monoculture systems began based on better seed, more fertilisation and mechanisation. Since 1945, increasing specialisation, improved varieties, chemical fertilisers, pesticides, herbicides, mechanisation, feed concentrates, pelleted feed and pharmaceutical chemicals have come to define modern monoculture farming (Edwards, Pullin & Gartner 1988). Clearly, over the time humans have been growing food, monocultures are a recent anomaly while polycultures have predominated and persisted.

3.2  Most farmers in the world farm polycultures

Members of modern western society rarely appreciate the range and extent of agricultural practices around the world. Even the typical Australian farmer may imagine that most of the world is fed from farms like theirs. The reality is that human farmers have always and still do predominantly farm polycultures (Brookfield & Padoch 1994). The evidence is that intensive cropping systems are not merely a vestige of the historical roots of crop culture, but would appear to be increasing in importance in much of the world in specific situations where there is an economic, biological, environmental or social advantage (Francis 1986b). Where there is an advantage, farmers usually look favourably at adoption. Polycultures persist or are established because they are more efficient at crop production, producing income or both. Peasant intercropping is often remarkably productive. The Cropping Systems Program of the International Rice Research Institute (IRRI) studied traditional row intercropping systems of Javanese small farmers using maize and rice and found that these were from 30 to 60% more productive than monocultures and had less weed and pest problems (Allen 1974). Because it works, the majority of the world’s farmers, particularly those located in the tropical regions, depend for their food and income on multi-species agriculture (Vandermeer et al. 1998).

The nature and persistence of third world polycultures is worth exploring. They still represent the majority of land use systems in the tropics. Despite development pressure from within and without to move into industrial monoculture systems, these polycultures continue. Plucknett and Smith (1986) suggested that the original forms of polycultures can still be seen by looking at the remaining traditional cultures not yet modified by industrialisation and looked at the Kayapô Indians of the Brazilian Amazon. While they rely heavily on hunting and gathering for food, they practice an innovative, polycultural, and perhaps more sustainable agriculture. They practice an open field slash and burn agriculture common in the third world tropics that contains a high diversity of plants.

What is most remarkable is the degree that their farming is integrated with their hunting and gathering from the surrounding landscape. During their hunting trips, they commonly uproot and transplant desirable food, dye and other plants for re-establishing at their hunting camps. Through interplanting without clearing, a sizeable cluster of planted trees and shrubs accumulate around the hunting camps; at least 54 plant species have thus been semi-domesticated by the Kayapô. They also create resource islands of trees, shrubs, herbs and root crops in what was previously open grassland. These resource islands, containing at least 100 species transplanted from the forest, are built up gradually from small, mulched patches and may eventually appear to the western observer as part of the natural landscape. Trails through the forest are also planting sites for the Kayapô: a 13 km survey of a jungle trail from a village to a cleared garden revealed 185 planted trees comprising at least 15 species and approximately 1500 medicinal plants and 5500 food plants. While this is easily polyculture, it is a form of farming not always recognised and may have been more widespread and persistent than yet known.
As populations increased and pressures on land use grew, this primitive ideal evolved. With fewer and fewer wild areas, polyculturalists came to work closer to home and their plants became more domesticated. Unfortunately, actual measurements of the extent and importance of early polycultures are hard to find (Kass 1978). Little data is available prior to 1950. An early study of the history of multiple cropping systems in Taiwan (Cheng et al. 1974) notes a 19th century intensification of farming that included 5 upland species introduced from overseas, more than 30 vegetables and an astounding 1365 varieties of rice. By the mid 20th century, a polyculture using at least 30 different species produced 5 crops in 25 months of relay interplanting in Taiwan.

Numerous, traditional polycultures can be studied, many of which persist to the present. A survey of 11 fields belonging to the native Andoke and Witoto peoples of the Columbia Amazon and ranging from .5 to 1 hectare, revealed from 5 to 18 species intercropped with cassava, the main staple. In Central America, it is not uncommon to find two dozen cultivated plants in backyard gardens covering only .1 hectare (Plunkett & Smith 1986). In Southeast Mindoro Island of the Philippines, the Hanunoo people plant up to 40 species of trees, shrubs, herbs, tubers and cereals in a single field, a complex pattern that must have taken a long time to develop. Brookfield and Padoch (1994) reported on some current third world polyculturalists and argued that their farming systems are far more complex than previously thought. In 1985, the farmers of an isolated village along Peru’s Ucayali River, who normally practice 12 distinct types of agriculture, opted for 39 different combinations of those 12 kinds of agriculture. Not only is their farming system diverse and complex, it is quite adaptable, illustrated by the observation that 75% of the farmers changed their chosen combination of agricultural practices in one year from 1985-1986. In Indonesia, the interaction with the forest that was practiced by the Kayapô can be seen at a later stage of system development. As rubber tree cultivation was introduced to Java in colonial times, there was human adaption within and with these private plantation forests. Using their historical polyculture farming techniques, they began planting additional species into these plantations (and/or planting rubber trees into their complex existing agroforests) so that in recent history there are now mature, complex, rubber agroforests containing upwards of 300 species per hectare (Sanchez 1995). This is considerably higher than the 5 species per hectare typical of industrial rubber plantations and approaches the natural diversity of adjacent undisturbed forests in that locality of 420 plant species per hectare. They also contain up to 70% of the bird species present in the original rainforest.

Moving closer to the present, traditional polycultures in the Americas based on maize, squash and beans persisted for thousands of years until colonisation displaced it with European mixed farming. Historically, as recently as 1923, 60% of soybeans grown in Ohio and Illinois were row-intercropped with maize (Kass 1975). Farmers in Syria often sow several varieties of wheat in the same field (Plucknett & Smith 1986). Wolfe (1985) reported that 300,000 hectares of barley/oat mixtures are still grown in Ontario and that in Russia, the widely successful winter wheat Bezostaja, is actually a mixture of numerous varieties. Herzog (1998) reported on the European system of Streuobst where tall trees of different types and varieties of fruit belonging to different age groups are dispersed on cropland, meadows, and pastures in a rather irregular pattern. This system has been present in Europe since the 17th century. While suffering market pressure and legal regulation to eliminate them, there are still approximately one million hectares in eleven European countries remaining. They are now receiving government encouragement for the advantageous ecological and sociocultural benefits, especially biodiversity and landscape aesthetics as well as producing substantial market crops. Not only have traditional polycultures evolved and persisted around the world, substantial polycultures are conducted under the constraints of mechanised agriculture.

Liebman (1995) reported that polycultures can also be used on relatively large, mechanised, capital-intensive farms in temperature regions. Examples include:

- forage grasses or legumes interseeded into growing crops of maize, soybean, barley, oats or wheat;
• soybeans interseeded into a growing crop of wheat;
• field peas planted into a mixture with small grains for seed or forage;
• soybean strip cropped with maize or sunflower;
• grasses or legumes planted as understorey in orchards; and
• grass/legume mixtures for forage.

Recent Australian development is illustrated by the intercropping of canola and peas around Wagga Wagga (Cole 1993) and the emergence of mixed-species plantation forestry, especially rainforest cabinet timber and bushfoods. Even conventional modern monoculture farmers persist in applying diverse strategies; Gillespie, Lyson and Power (1995) found New York potato growers, using rotations with other crops, managed 36 distinct cropping systems among the 56 farmers surveyed. This evidence leads to speculation that the two polyculture anchors of diversity and complexity might simply come naturally to farmers as part of human nature and their response to varied environmental situations. Tuxill (2000) maintained that ‘biodiversity associated with traditional agriculture is no coincidence- it has arisen precisely because people have fostered it.’

The use of polycultures is a government recommendation for modern grain culture in Great Britain. To control powdery mildew losses, the use of seed genetic heterogeneity in the control of the disease is the official recommendation (Barrett 1982). Farmers are encouraged to plant a range of different varieties from different resistance groups, use different fungicides over time, and to reduce field to field infection. Similarly, early 1970s wheat breeders moved to development of ‘pyramid varieties’ using many resistance genes to escape disease.

Francis (1986b) reports that there is evidence that a number of intensive cropping systems practiced by both low-resource and high-technology farmers will continue to expand. Examples include multiple cropping and mixed farming:

• Winter wheat/soybean double cropping
• Overseeding legume cover into growing maize, wheat and soybean
• Strip cropping of maize/soybean or sorghum/soybean
• Double and triple cropping of high value vegetable crops
• Intensive use of relay and sequential systems in Asia
• Use of multi-storied perennial and perennial/annual crop mixtures in Asia
• Alley cropping and intensive terrace systems in Africa.

3.3. Interest in polycultures is growing

Considerable evidence has emerged demonstrating increased interest in the research and implementation of polyculture practices since the 1970s. In reporting on an unpublished literature search covering intercropping research on 14 major crops, Francis (1986a) noted a surge of interest in the research community. Summarising over all crops, polyculture investigations began about 1938 with the first publication. Since then the number of publications has increased dramatically from one 5 year period to the next and accelerated from 1970 on (see Figure 1).
Francis suggested that, in the context of the academic community, multiple crops have a strong attraction to the ecologist who likens their structure to the natural ecosystem in its diversity and biological stability. The agronomist and physiologist are intrigued by the potential of extending resource use through more of the year and the greater exploitation of the natural environment for food production. Economists are interested in stability of production and income. They see the benefits in the diversity of these complex systems, which provide buffering for family income through the year. The family diet which can be provided through planting a wide range of species and integrating their production with animals is of interest to the nutritionist. Social scientists are active in their search to understand the threads that link people and their goals with the potential of their environment to help them meet these goals. In his conclusion, Francis (1986b) began by reaffirming this position: ‘...there is an increasing recognition by scientists and agricultural administrators of the current and potential future importance of multiple cropping systems’. He predicted that the most promising approaches of double and sequential cropping would expand in both the developing and developed world. This faith was based on the previous idea that polyculture has been the predominant practice over time and space for human food production. As Way (1977) put it ‘there seems to be little doubt that the empirically developed mixed cropping systems which provide the livelihood of about one billion people in peasant families in the tropics contain important elements.’

3.4. Monoculture problems / Polyculture opportunities

An obvious and implicit assumption in this research is that polyculture offers some solutions to the problems of monoculture production. Abundant popular and in-depth technical reports have already documented the problem with monoculture: yield decline and instability, declining economic returns, difficulties with pests and disease, biodiversity reduction, deleterious short and long term environmental impacts, decline in food quality, non-renewable resource use, poor energetic efficiency, and the decline of rural culture and land management expertise (see Wade 1972; Geno 1976a, 1976b; Geno & Geno 1976; Merrill 1976; Way 1977, Wilkin 1977; Perrin 1980; Barrett 1982; Altieri, Letourneau & Davis 1983; Andow 1983b; Risch, Andow & Altieri 1983; Horwith 1985; Wolfe 1985; Conway 1987; Acres Australia 1990d; Geno 1995; Bolt 1996; Shiva 1996; Srivastava, Smith & Forno 1996; Gleissman 1998; Lefroy & Hobbs 1998; Ewel 1999; Tuxill 2000). Clearly, this infant child of agriculture, representing 1.5% of human farming history, is showing weakness compared with its polyculture parentage. What, then, is the difference between them?

A general comparison of the properties of monoculture versus polyculture may be useful. While predominantly addressing agriculture, it is important to remember that polyculture approaches also cover other land uses involving plants or animals, from aquaculture to wilderness management to forestry. Aldo
Leopold (as cited in Flader & Callicott 1991) spoke in 1939 of the Germans making a determined effort to get away from ‘cubistic’ forestry because experience revealed that by the third successive crop of conifers in pure stands, the microflora of the soil was disturbed and the trees quit growing in this sequential monoculture method. Cromartie (1981) reported that early in this century, foresters began to notice that insect outbreaks were apparently more frequent and more severe in pure, even-aged stands of forest trees and especially in plantations. The authors’ own experiences in Canada and the American Pacific Northwest echo these observations, as evidenced by the classic spruce budworm problem in eastern North America confirming Cromartie’s report. The current status in some areas of Oregon in sequential, clear-felled even-aged monocropping of Douglas Fir is that after the third rotation it is often impossible to re-establish forest on the site and the ecosystem reverts to a degraded shrub community due to collapse of soil structure, erosion and loss of mycorrhizal associates and their agents of dispersal following such disturbance. An example more closely related to agricultural cropping is the difficulty in establishing new orchards on the site of old orchards, especially for peaches and apples.

The differences between monoculture and polyculture have been evaluated several ways; generally by comparing basic structure and function, comparing emergent properties, opposing broader characteristics or identifying resultant impacts/conditions (performance or state based). Attempts to take a more holistic view can lead to concepts such as ecological health (Costanza 1992). Dr Stuart Hill of the University of Western Sydney, Hawkesbury (as cited in Payne 1993) outlined a comparison of conventional and alternative production systems from a strategic point of view, which effectively shows both end points and the nature of the continuum (see Table 3). Polyculture practices would fall into the redesign strategy.

Table 3: Comparison of Three Sustainable Agriculture Strategies

<table>
<thead>
<tr>
<th>Conventional</th>
<th>Efficiency</th>
<th>Substitution</th>
<th>Redesign</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Factory Farm)</td>
<td>(Low impact sustainable agriculture)</td>
<td>(Eco-agriculture)</td>
<td>(Permaculture, Natural farming)</td>
</tr>
<tr>
<td>High power</td>
<td>Conservation</td>
<td>Conservation</td>
<td>Low power</td>
</tr>
<tr>
<td>Physico-chemical (soluble fertiliser, pesticides, biotechnology)</td>
<td>Phys/chem/bio (slow release, band)</td>
<td>Biologica</td>
<td>Bio-ecological</td>
</tr>
<tr>
<td>Imported input intensive</td>
<td>Efficient use</td>
<td>Alternative inputs</td>
<td>Knowledge and skill intensive</td>
</tr>
<tr>
<td>Narrow focus. Farm as factory (linear design and mgmt)</td>
<td>Efficient factory</td>
<td>Softer factory</td>
<td>Broad focus, farm as ecosystem (integrated design &amp; mgmt)</td>
</tr>
<tr>
<td>Problems as enemies to eliminate &amp; control directly with products</td>
<td>Efficient control (monitor pest, IPM)</td>
<td>Biocontrols</td>
<td>Prevention, selective and ecological controls (indirect, process, service approach)</td>
</tr>
<tr>
<td>Maximise production Neglects maintenance; Create demand; Manipulate wants</td>
<td>Maintain production while improving maintenance</td>
<td>Improved maintenance</td>
<td>Optimise production emphasises maintenance; meets real needs</td>
</tr>
</tbody>
</table>

Adapted from Payne 1993

Additional criteria could be added. An idea that will be extensively addressed later is a recurring theme in polyculture research: that to design sustainable production systems, the characteristics of enduring natural systems should be used as a guide. Altieri, Letourneau & Davis (1983) suggested that the ‘natural vegetation of an ecosystem can be used as an architectural and botanical model for designing and structuring an agroecosystem to replace it’ and would be most likely to offer optimum sustainability. They note the structural and functional differences between natural ecosystems and agroecosystems (here seen as conventional monocultures).
These differences are depicted in Table 4.

Table 4: A Comparison of Agroecosystems and Natural Systems

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Conventional Agroecosystems</th>
<th>Natural Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net productivity</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Trophic chains</td>
<td>Single, linear</td>
<td>Complex</td>
</tr>
<tr>
<td>Species diversity</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Genetic diversity</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Mineral cycles</td>
<td>Open</td>
<td>Closed</td>
</tr>
<tr>
<td>Stability (resilience)</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Entropy</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Human control</td>
<td>Definite</td>
<td>Not needed</td>
</tr>
<tr>
<td>Temporal permanence</td>
<td>Short</td>
<td>Long</td>
</tr>
<tr>
<td>Habitat heterogeneity</td>
<td>Simple</td>
<td>Complex</td>
</tr>
<tr>
<td>Phenology</td>
<td>Synchronized</td>
<td>Seasonal</td>
</tr>
<tr>
<td>Maturity</td>
<td>Immature, early successional</td>
<td>Mature, climax</td>
</tr>
</tbody>
</table>

(Altieri, Letourneau & Davis 1983)

This sort of comparison is restricted to end points of an obvious continuum. Production systems can also be compared by choosing a particular characteristic such as biodiversity and oppose strategic practices that contribute to or diminish the quality of that character. Paoletti et al. (1992) contrast these practices in Table 5 below.

Table 5: Practices Affecting Biodiversity in Agroecosystems

<table>
<thead>
<tr>
<th>Sustained biodiversity</th>
<th>Decreased biodiversity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hedgerows; dykes with wild herbage</td>
<td>Wild vegetation removal; tubular drainage or vegetation removal</td>
</tr>
<tr>
<td>Organic sustainable farming</td>
<td>Intensive input farming</td>
</tr>
<tr>
<td>Polyculture; agroforestry;</td>
<td>Monoculture</td>
</tr>
<tr>
<td>Rotation with legumes</td>
<td>Monosuccession</td>
</tr>
<tr>
<td>Dead mulch; living mulch</td>
<td>Bare soil</td>
</tr>
<tr>
<td>Strip crops; ribbon cropping; alley cropping</td>
<td>Conventional mono cropping</td>
</tr>
<tr>
<td>Organic fertilisers; biological pest control</td>
<td>Chemical fertiliser and pest control</td>
</tr>
<tr>
<td>Plant resistance; germplasm diversity</td>
<td>Plant susceptibility; standardisation</td>
</tr>
<tr>
<td>Use of on-farm research</td>
<td>Conventional plot research</td>
</tr>
</tbody>
</table>

(Paoletti et al. 1992)

In this example, sustained biodiversity would be the strategy of the polyculturalist, decreased biodiversity the typical result of monocultures. Assuming that production systems are intended to provide products and values for human use, they can be called functions of that land use system. Vandermeer et al. (1998) theorised that there is always a choice between fulfilling these functions by a simple (one function at a time-segregated) monoculture approach or a more complex (combined functions-integrated) approach of the polyculturalist. Vandermeer’s strategic practices approach is illustrated in Table 6.
### Table 6: Integrated and Segregated Options in Land Use

<table>
<thead>
<tr>
<th>Functions</th>
<th>Segregated Option (monoculture)</th>
<th>Integrated Option (polyculture)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production of various plant products</td>
<td>A combination of annuals and trees, each for a different product</td>
<td>Multipurpose trees or crops</td>
</tr>
<tr>
<td>Production of tree and crop products</td>
<td>Separate crop fields and woodlots; sequential agroforestry systems</td>
<td>Simultaneous tree-crop agroforestry systems</td>
</tr>
<tr>
<td>Soil and water conservation and agricultural production</td>
<td>Erosion in alleys and sediment traps in contour strips; erosion on slopes; filter strips along rivers, rice fields in valleys</td>
<td>Continuous mulch cover</td>
</tr>
<tr>
<td>Productivity and risk reduction</td>
<td>Specialised farms with insurance schemes</td>
<td>Mixed farms (crop-animal-trees)</td>
</tr>
<tr>
<td>Biodiversity conservation and agricultural production</td>
<td>National parks and separate zones for intensive agriculture</td>
<td>Agroforests, multifunctional forests</td>
</tr>
<tr>
<td>Agricultural production and mitigation of greenhouse gas emissions</td>
<td>Sinks (eg. forest soils as sink) make up for sources elsewhere (eg. rice fields as source)</td>
<td>Crop and soil management to reduce on-site emissions</td>
</tr>
<tr>
<td>Food security and economic growth</td>
<td>Economic efficiency strategies; specialisation, reliance on markets</td>
<td>Self reliance strategies at national scale</td>
</tr>
</tbody>
</table>

Adapted from Vandermeer et al. 1998

A recurring theme that will be encountered later is that polycultures imply complexity, whereas monoculture demands simplicity. Similar to Paoletti et al. earlier, Conway (1985) compares the two end points by looking at how complexity can be enhanced (polyculture) or reduced (monoculture). Table 7 depicts the proposed driving forces of reduction and enhancement.

### Table 7: Proposed Forces Reducing and Enhancing Complexity in Agroecosystems

<table>
<thead>
<tr>
<th>Reducing</th>
<th>Enhancing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased awareness and reduced tolerance of competition for resources among components</td>
<td>Recognition and selection of plant-plant combinations which exhibit true complementarity in resource use and may thus have real agronomic advantages.</td>
</tr>
<tr>
<td>Mechanisation, which restricts the opportunities for planned mixed cropping, especially at the transition from manual field operations to draught animal traction, with further reductions at the transition from animal to tractor based systems</td>
<td>Appropriate technology developments in mechanisation which allow higher labour use efficiencies without a strong drive for simplifying field plant combinations.</td>
</tr>
<tr>
<td>Intensification of land use, aiming for higher economic outputs per hectare, reducing the thresholds for ‘weediness’.</td>
<td>Extensification of land use, as occurs in later stages of economic transformation of (formerly) agricultural economies, when returns to labour are higher in other sectors of the economy.</td>
</tr>
<tr>
<td>Market integration of the farm household, inducing specialisation and its ensuing segregation.</td>
<td>Effective rewards for society at large in niche markets or by effective policies for maintaining complexity in as far as it is valuable to interest groups beyond the farm.</td>
</tr>
<tr>
<td>The use of ‘hybrid’ germplasm which is not conducive to local selection and depends on a continuous external source of ‘quality’ seeds.</td>
<td>On-farm selection of germplasm and the continuous introduction of new germplasm, maintaining or enhancing the ‘transient diversity’ aspect of the farms.</td>
</tr>
<tr>
<td>Extension services and ‘projects’ which tend to reduce between-actor variation, especially in combination with ‘planning’ and ‘models’ in the sense of ‘blueprints’-usually enforced, if not by social pressure by credit schemes leaving few options.</td>
<td>Development of models which allow more location specificity in development options, adjusting credit schemes to the real qualities of the site and real objectives of the farmer instead of ‘blueprints’.</td>
</tr>
</tbody>
</table>

Adapted from Conway 1985

Some authors maintain that only key functional attributes are necessary to consider, as most other important characteristics can be covered by aggregation into these key functions. By using a systems
approach to agroecosystems analysis, Conway (1987) found after five years of fieldwork in Thailand that four functions were sufficient for the bulk of characterisation and decision-making:

1. **Productivity**- yield or net income per unit of resource.
2. **Stability**- the degree to which productivity is constant in the face of small disturbances from climate or other environmental variables.
3. **Sustainability**- the ability of a system to maintain productivity in spite of major disturbance.
4. **Equitability**- how evenly the products of an agroecosystem are distributed among its human benefactors.

Marten (1988) added a fifth function:

5. **Autonomy**- agroecosystems self-sufficiency.

These functions can be termed emergent properties, because they emerge from the system as a whole rather than from any one characteristic.

Table 8 explores agricultural development as a function of emergent agroecosystem properties.

<table>
<thead>
<tr>
<th></th>
<th>Productivity</th>
<th>Stability</th>
<th>Sustainability</th>
<th>Equitability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swidden agriculture</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Traditional cropping systems</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Improved type 1</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Improved type 2</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Ideal (best land)</td>
<td>High</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Ideal (marginal land)</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>

(Conway 1987)

With this general comparison of polyculture versus monoculture properties in mind, a clear conceptual orientation emerges: **we should study polyculture because it might be a better way to produce.** Polycultures represent potential solutions to the increasing problems of monoculture. This is of particular concern to organic farmers because, according to Edwards (1990), as chemical inputs in cropping systems are lowered, there emerges a need for innovative cultural techniques. While organic farmers initially replace chemical inputs with approved materials they often continue monoculture farming styles. Since monocultures are almost invariably prone to diseases (Altieri et al. 1983), they end up with a real challenge. While organic inputs certainly improve the sustainability of monoculture farming, the monoculture organic farm may still suffer a number of ‘ecological diseases’ associated with the intensification of food production under industrial monoculture (Altieri et al. 1983) shown in Table 9.
Table 9: Ecological Diseases

<table>
<thead>
<tr>
<th>Diseases of the ecotype</th>
<th>Diseases of the biocoenosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erosion</td>
<td>Loss of crop genetic resources</td>
</tr>
<tr>
<td>Loss of soil fertility</td>
<td>Loss of wild &amp; animal diversity</td>
</tr>
<tr>
<td>Depletion of nutrient reserves</td>
<td>Elimination of natural enemies</td>
</tr>
<tr>
<td>Salinity &amp; alkalisation</td>
<td>Pest resurgence</td>
</tr>
<tr>
<td>Loss of crop land to other uses</td>
<td>Genetic resistance to pesticides</td>
</tr>
<tr>
<td></td>
<td>Chemical contamination</td>
</tr>
<tr>
<td></td>
<td>Destruction of natural control mechanisms</td>
</tr>
</tbody>
</table>

(Altieri et al. 1983)

The challenge is to cure these diseases with organic and sustainable practices and that may preclude the continued reliance on monoculture. Under industrial and agroecological strategies, certain results can be noted and are shown in Table 10 as developed by Srivastava et al (1996).

Table 10: Industrial and Sustainable Intensification Strategies

<table>
<thead>
<tr>
<th>Industrial Agricultural Intensification</th>
<th>Sustainable Agroecological Intensification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase purchased inputs</td>
<td>More rational use of nutrients, space and energy</td>
</tr>
<tr>
<td>Increased nutrient run-off, eutrophication</td>
<td>Greater recycling of nutrients</td>
</tr>
<tr>
<td>Loss of soil micro organisms</td>
<td>Better use of biological resources to raise and maintain yields</td>
</tr>
<tr>
<td>Accelerated soil erosion/compaction</td>
<td>Effective measures for soil and water conservation</td>
</tr>
<tr>
<td>Surface and groundwater contamination</td>
<td>Effective measures for soil and water conservation</td>
</tr>
<tr>
<td>Draining of wetlands</td>
<td>Deployment of environmental corridors</td>
</tr>
<tr>
<td>Top-down prescriptive technology recommendations</td>
<td>Greater use of local and indigenous knowledge</td>
</tr>
<tr>
<td>External costs borne by society</td>
<td>Environmental costs internalised and accounted for</td>
</tr>
<tr>
<td>Decreasing domination by fewer crops</td>
<td>Old crops reintroduced, new crops developed</td>
</tr>
</tbody>
</table>

Adapted from Srivastava et al. 1996

Similarly, Vandermeer et al. (1998) believe that polyculture can be seen as an alternative to conventional agricultural intensification that results in:

- Land use degradation from natural vegetation to cultivation or of farming to plantation, grazing to cultivation;
- Increased use of external resources;
- Switch from internal to external regulation of pests and disease;
- Change in labour use (less) and management practice (prescribed rather than adaptive);
- Increased linkages with market economies
- Increased specialisation in the production processes
- Decreased number of crops or species utilised
- Decreased biodiversity
- Choice of practices driven by market forces.
Perrin (1980) echoed in Altieri et al. (1983) found that monocultures have been blamed frequently for inducing regular pest outbreaks by providing a continuous and unlimited supply of suitable host plants or microhabitats. Reliance on herbicides is a similar guaranteed problem, basically because herbicides are static and weeds evolve. Bolt (1996) described the herbicide resistance that has been confirmed in Australia for the last 19 years, more recently found to include glyphosate resistance in ryegrass. Australia has the highest incidence of herbicide resistance on the world. As of 1996, a total of 17 weed species have been discovered to have populations resistant to particular herbicides. Outbreaks now number in the thousands nationwide.

As will be described in detail later, polyculture approaches offer inherent advantages in reducing pest and weed problems by facilitating internal, self-regulating and adaptive processes, such as are operational in natural ecosystems. Altieri et al. (1983) observed that agricultural ecosystems and natural ecosystems have, under the industrial paradigm, become strikingly different in structure and function. The maintenance of an imposed order of simplified agricultural systems against the natural tendency toward entropy, diversity and stability demands energy and resources. Modern farming has become a highly dependent activity, with yields dependent on the uninterrupted availability of supplemental energy and materials.

Amador and Gliessman (1990) agree, stating that as awareness of the combined ecological and economic costs of maintaining yields in monoculture systems has grown, the search for alternatives that rely less on fossil fuel based energy and material inputs has begun to intensify. Cox and Atkins (1975) speak of the need for capitalising on natural energy and nutrient subsidies in the comprehensive planning of agroecosystems for the future. These authors believe that the development of an ecologically based strategy for agriculture in the future requires an understanding of natural ecosystems. They foresaw the evolution of new types of agroecosystems, semi-natural in character, such as game ranching, forest farming and traditional non-mechanised polycultures. More recently, Wilson (1993) reported on work by Wes Jackson at the Land Institute in Kansas where researchers believe that native perennial plants hold the clue for developing a sustainable agriculture system. At the Institute, Jackson and others hope to develop a perennial grain growing system from prairie natives that will not need cultivation, fertilisers, fossil fuel or herbicides. They even intend to grow their own oilseed fuel sufficient for mechanised harvest from within the system (see also Jackson 1980; Soule & Piper 1992).

One of the key features of natural ecosystems is their high diversity at genetic, species and landscape levels. This diversity is seriously eroded under monoculture methods. Some of this reduction in food diversity began even as humans first domesticated plants. Vietmeyer (1996) noted that although over 2000 species of plants have edible parts identified by our ancestors, only twelve crops now feed most of humanity. Similarly, only 24 animal species have ever been domesticated. Paoletti et al. (1992) differs slightly in claiming that although 150 plants are commonly eaten world-wide, only 15 plant species provide more than 90% of world food and only three (rice, maize, wheat) provide two-thirds of that. Human foods have become vastly oversimplified as a result of mechanised agriculture. Blackburn et al. (1996) note a similar story for domesticated animals, showing how some 4000 breeds of domesticated livestock developed over years for evolutionary elasticity and environmental adaptability have been increasingly eroded through industrial intensification. Shiva (1996) addresses this opposition between the goals of production and biodiversity. She believes that according to the dominant paradigm of production- diversity goes against productivity. This creates an imperative for uniformity and monoculture production. Thus production based on monocultures becomes a threat to biodiversity conservation and sustainability.

In Monocultures of the Mind, Shiva (1993) showed how traditional land use knowledge has no place in present scientific paradigms and how this knowledge in particular is discounted in third world rural development. She says: ‘Dominant scientific knowledge thus breeds a monoculture of the mind by
making space for local alternatives disappear, very much like monocultures of introduced plant varieties lead to the displacement and destruction of local diversity. [Furthermore] dominant knowledge also destroys the very conditions for alternatives to exist.’ Both agriculture and forestry examples are offered so we may understand how monocultures first inhabit the mind in our paradigms and world views and then are transferred to the ground: ‘Monocultures of the mind generate models of production which destroy diversity and legitimise that destruction as progress, growth and improvement.’

For polyculturalists lacking in sufficient arguments on the value of polyculture land use, her section on the non-sustainability of monocultures is illuminated in all three realms: social, economic and environmental and shows how monocultures do not merely displace alternatives, they destroy their own basis, are not tolerant of other systems, are not able to reproduce themselves sustainably, and destroy the genetic base required for their persistence. In her view, local knowledge diversity is just as important as biological diversity in maintaining sustainable land use systems. Way (1977) similarly noted that successful [monoculture] agriculture with its increasing emphasis on decreased diversity seems to represent a direct challenge to the principle that the stability of a community and of its constituent species is positively related to its diversity. When one sees up to 99% of some wheat areas in the United States planted to a single wheat cultivar (Barrett 1982), the extent of this trend away from diversity is of concern.

Another result of narrowing crop genetic diversity is the inability to adapt to new conditions. When plants are bred for specific uses, to depend on optimum conditions or particular inputs (fertiliser, herbicides, pesticides) or have been genetically engineered as the extreme case, their performance under alternative inputs systems such as organic growing, or in other types of farming systems will be more erratic. It is quite possible that existing monoculture crops will be genetically unsuitable for incorporating into future polycultures. As Cox and Atkin (1975) put it in reference to third world countries accepting industrial monoculture models of production, ‘the hasty implementation of fuel intensive monocultures may force many nations into commitment that has only short range potential, but may be exceedingly difficult to abandon.’ Monocultures are forced to replace the internal regulation that functions in natural ecosystems with external inputs, often fossil fuel based. Because of the genetic uniformity, most major crops are impressively uniform and vulnerable to pest and disease attack (Wade 1972). This is in marked contrast to the high natural genetic diversity of wild plants and even cultivated landraces of food plants. Successful implementation of multiple cropping necessitates a broad selection of varied genetic characteristics to build different intercrop systems. Noting that food demand globally is likely to triple in the next 50 years, Srivastava et al. (1996) expect increasing pressure on biodiversity and believe that continued progress in raising and sustaining agricultural yields hinges on better protection and harnessing of the planet’s biological riches to build land use systems that enhance biodiversity within managed landscapes.

As reported in Acres Australia (‘Salt report forces a shake-up’, 1999d), the recent release of the Murray Darling Basin report on salinity revealed serious problems in the way agriculture is practiced in Australia. At the same time, the CSIRO issued a companion document: The Effectiveness of Current Farming Systems and Dry Land Salinity. Leading CSIRO scientists are cooperating to assemble big teams for big problems. In particular, a project called ‘Reinventing Australian Plant Production Systems’ (now renamed ‘Redesigning Agriculture for Australian Landscapes or RAAL in a joint venture with LWRRDC) seeks to radically redesign Australian farming systems by tailoring crops and practices to the unique biophysical characteristics of Australia’s climate and soils by designing farming systems that mimic natural vegetation systems in each region. They accept that minor fine-tuning of existing farming systems is no longer sufficient and that new approaches like polyculture production are the only long-term response to meet both economic and environmental goals.
4. Polyculture Benefits: Theories and Mechanisms

This section reviews the literature presentation of the theory and observed benefits of employing polyculture practices in farming systems, the theory and mechanisms that give rise to those benefits and will suggest a number of guiding principles, summarised in a later section. After looking at the general ‘big picture’ design principles following on from the rationale, key areas emerging from the literature covering yield, income level and stability, and social capital benefits are covered.

4.1 The ‘Big Picture’ of benefits

Accepting that monoculture-style production has significant problems and that there exists a sufficient rationale for studying polyculture approaches, researchers have proposed general categories of benefit and utility. Kass (1978) listed categories of benefits as crop yield, productivity of various plant constituents, economic return, yield stability, social benefits, pest control, and fertiliser efficiency as recurring themes in his extensive review. These are described as fairly mechanistic, state variables, later categorisations become more dynamic and strategic. Altieri et al. (1983) thought that polycultures are generally more productive, utilise water and nutrient soil resources more efficiently, utilise photosynthetically active radiation more effectively, resist pests, epidemics and weeds better, better utilise local resources such as locally adapted open-pollinated seeds and contribute to economic stability and farmer’s direct participation in decision-making. Kotschi et al. (1986) saw multiple cropping as serving a wide range of functions:

- Provision of year-round ground cover, or at least for a longer period than monocultures, in order to protect the soil from desiccation and erosion. Reduction of seasonal work peaks as a result of the different planting and harvesting times of polyculture crops.
- Prophylactic plant protection through diversification of species and varieties.
- Increased output per unit area, particularly with low levels of external inputs since a mix of species makes better use of available nutrients and water in the soil.
- Evenly distributed provision of food (for self-reliance) and products (for market) over the year and lower production risks where if one crop fails the other crop(s) still provide a harvest (compensation).
- Improved microclimate, water balance, and internal nutrient cycling when tree crops are included.

In projecting the strategies necessary to maintain and to restore ecological health in agricultural systems, Altieri et al. (1983) make the following recommendations based on their interviews of successful California organic farmers:

- Energy and resource overuse should be curtailed.
- Production methods that restore community stability (in an ecological sense) should be employed.
- A maximum of organic matter and nutrients should be recycled.
- The best possible multiple use of the landscape should be made.
- Efficient energy flow should be ensured.
- As much food is possible should be grown locally, that is adapted to the local environment and local tastes [and reduced transport costs].
- That the technical development of such systems must contribute to rural development and social equality and may require a new socioeconomic framework.

Succinctly summarising the dynamic benefits of polyculture, Vandermeer (1990) believes they yield more, protect against risk, protect against pests, use available resources better, even out distribution of labour requirements, and provide a more balanced human diet. Later, Vandermeer et al. (1998) proposed that under conditions of global land use and climate changes, complex agricultural systems are more dependable in production and more sustainable in terms of resource conservation than simple ones.
This adaptability to variation occurs as a key benefit of polyculture farming systems. This is exactly why traditional farmers over most times and areas have farmed polyculturally: because it is adaptive to reduce risk. In observing third world polycultures, Flinn (1970) as cited in Lynam, Sanders and Mason (1986) made three generalisations about where and why polyculture is practiced:

1. Quality of the resource base, especially its homogeneity and the certainty of the correspondence between output and resource input, seems to be an important determinant of intercropping. The more variable the production conditions, due either to climate, soil variation within the farm, or pests and diseases, the more likely that intercropping will be practiced.

2. Intercropping can provide a more varied production of food from limited land area, and most evidence suggests that intercropping produces a lower variance in per area unit net income. However, the greater the marketing of farm output, the less likely that crops will be intercropped.

3. The greater the complementarity in yields between crops in association, the more likely that intercropping will occur.

In addition, intercropping is more likely to be practiced on small farms as opposed to larger ones with proportionally less intercropping of purely commercial crops, less intercropping if irrigation is available, and legumes intercropped more than other crops. Intercropping is found particularly where increasing population pressure on the land causes decrease in fallow periods, decline in fertility, or shifts to crops with lower soil fertility requirements. Kotschi (1986) illuminated an example of the enduring value of such pre-industrial polycultures because they often utilised and encouraged biological nitrogen fixation. Plants are dependent on biologically fixed nitrogen since they cannot utilise gaseous nitrogen absorbed through leaves. As late as 1959, only six percent of the nitrogen present in the world’s harvest was derived from industrial products. This has risen since then, but the relative significance of industrial nitrogen is minor in producing the world’s food. Nitrogen fixing plants in multiple cropping provide nitrogen for crops in various ways- rhizobia bacteria associated with legumes, blue-green algae in soil and paddy rice situations, ray fungi (actinomycetes) symbiots, and free-living bacteria and fungi, ie. azobacter, azosperillum. Francis (1986) sees these transitional approaches as useful now and noted that:

The growth of multiple cropping or multiple species systems in temperate (First world) countries is linked to the need for reducing nitrogen cost and soil erosion and the potential for increasing land use intensity as with double cropping.

Some examples of these would be grass/legume pastures, small grain nurse crops to establish legume forage, oats with alfalfa or clover for hay, and winter wheat/summer soybean (2 million hectares in the Southeast US). Polyculture practices are also seen to contribute to environmental restoration, particularly when woody crops are incorporated, as in agroforestry systems. Prinsley (1992) suggested agroforestry could ‘rehabilitate land from further degradation; via reduction of salinity, improvement of soil fertility, control of and prevention of soil erosion, control of waterlogging and reduction of catchment eutrophication.

In the largest sense, in any polyculture putting more plant material in the ground than monocultures, more CO₂ will be sequestered from the atmosphere and stored in plant and soil organic matter, assisting in removal of this greenhouse gas. Productive agroforestry systems and forests may offer the greatest benefit for this, but even clear-felled sequential monocultures of exotic pines leave more than half of their biomass in the ground after harvest. While trees will play an important part in both diversifying agroecosystems and in greenhouse gas removal, it is often temporary and dependent on future land uses. Sanchez (1995) further cautioned that ‘in most agroforestry systems, carbon sequestration should be considered a by-product rather than the principal objective’, even though it is among the highest of all potential land use systems in the magnitude of carbon sequestration.
4.2 Productivity: Yield advantage and stability

The intensification of production through polyculture approaches has important outcomes in terms of yield. Yield can be seen as purely the level of biological productivity or as the level of production of edible or saleable products. As well as the amount of yield, it is important to understand the impact of polyculture practices on the variability of yield from year to year and from farming system to farming system as climates, system components and environments vary. This is termed yield stability; a related concept is yield risk, which addresses the relative risk, either in terms of subsistence food or market products, of producing crops in polyculture or in sole cropping systems.

Yield Advantage

A recurring observation in the literature is that, quite simply, polycultures yield more total production and do so with greater stability and lower risk than monocultures. Vandermeer (1981) stated ‘the generalisation is that a relative yield advantage is usually obtained from a polyculture [greater] than that obtainable from separate monocultures’. Kass (1978) confirmed that ‘intercropping will produce higher yields than mixed cropping’. Trenbath (1974) believed that ‘multiple cropping yields are often higher, more consistent from season to season and more likely to be sustained over the longer term’, the first to add the element of sustainability. His early extensive review of 344 multiple cropping systems showed that their yield in biomass tended to lie above the mean of monocultures and the frequency of overyielding is significantly greater than that of under-yielding in the polyculture. Overyielding is the same as yield advantage: the system has an LER>1, meaning that the polyculture has a higher biological efficiency.

Snaydon and Harris (1981) cautiously concluded that the yield advantage of intercropping compared with pure stands is usually small (5-15%). Yield advantages of more than 20% are rare except in cases of mixtures of legumes and non-legumes or crops with very different growth periods. Greater yield improvements are possible through altering other agronomic practices. Moreover, improvement programs need to consider both in concert. There are numerous examples of specific cases of yield advantage through polyculture. Trenbath (1974) reported that yield and quality advantages had been firmly established for grass/legume mixtures for forage. This has become common practice in Australia.

Reporting on the first visit to China by western entomologists since 1949, Metcalf (1976) reported on pest management in early rice in Kwangyung province. A combination of predatory wasps, bacterial insect toxins and young ducklings were used to control insect pests, reducing chemical insecticide use from 77,000 kg in 1973 to 6,700 kg in 1975 plus an additional profitable crop of 220,000 ducks. Similarly, Cheng et al. (1974) concluded that from 1941 to 1972, multiple cropping in Taiwan (including all crops) yielded LERs of from 1.1 to 1.9, averaging 1.75. Elsewhere, LERs of up to 2.51 have been reported (Liebman 1995). Lin and Torrie (1971) reported that alternate row multistrain grain culture (alternate rows of 2-3 genotypes) resulted in more consistent yield than pure stands in Wisconsin soybeans and 3.8% higher yield. Kass (1978) reported that oat-barley mixtures were found to out yield the means of pure stand yields of oat and barley by up to 10% (New York), 15% (Michigan) and 20% (Ontario) and appeared to do better than mixtures of other small grains. He believed that mixtures of non-legumes appeared to make use of soil resources and applied nitrogen more completely than monocultures.

Cordero and McCollum (1979) found that in North Carolina, maize intercropped with soybean, snap bean or sweet potato in relay or concurrent intercropping gave total yields 20-40% higher than monocultures (LER 1.20-1.40). In studying radishes intercropped in a pear orchard, Newman (1986) showed that the pear yield was unaffected by intercropping and that radish yields approached sole crop radish yields, giving up to 2 acres of production per acre of land in the same season (LER= 1.5-2.01). Gliessman (1986) reported on traditional polycultures in Mexico where corn yields could be stimulated as much as 50% beyond monoculture yields when planted with beans and squash. LER was very high despite reductions
for squash and beans compared with sole crops. Interestingly, the system showed net gains of nitrogen in the agroecosystem biomass despite the removal of harvest. Gulden, Martin and Steiner (1998) found similar benefits to sweet corn with late summer chili crops interseeded with forage brassicas. Deneven (1995) reported on a prehistoric cultivation method that used raised beds in Peru (Lake Titacaca circa 800 B.C.) and noted a revival and restoration of over 1000 hectares of fields over 50 communities in recent times. This system reduced pests (soil fungi and nematodes) through high organic matter and competing micro organisms (as in Mexican chiampas, see Gliessman 1995) and offered potato yields of 8-16 tonnes per hectare versus only 1-6 tonnes on comparable flat surface fields.

In agroforestry situations, while increased deep root competition can make yield advantage more of a challenge, there are often yield benefits. Mohsin et al. (1999) reported on poplar-mint/lemon grass agroforestry trials in India. The poplars grow better with the intercrops than in pure stands at both juvenile and advanced ages. Total biomass was highest with mint, decreased with lemongrass, but still remained higher than that of pure stands which showed lowest biomass production. For silvopastoral systems of Acacia mangium timber trees and brachiaria pasture in Panama, Bolivar et al. (1999) found that the pasture had significantly lower crude protein and solubility in the monoculture control. The intercrop produced 28% higher total grass forage and only half the dry season dead pasture biomass than the monoculture. Not only was intercrop yield higher, but it was of higher nutritive value.

Theories of Overyielding
The reasons polycultures produce more have ecological, agronomic and cultural explanations. One of the first extensive articulations of overyielding mechanisms came from Trenbath (1974) who outlined the following likely causes:

- In field crop mixtures, competition for both light and soil resources will usually be occurring. More fully utilising either allows increased yield.
- Alleopathic effects (if present) will operate in conjunction with, but usually subordinate to, competition.
- Where different crop plants exploit the environment in different ways, it is likely the mixed population will be more productive than any monospecific population.
- Temporal displacement (where intercropped components differ in time of development or period of competition) may explain multiple cropping yield increase over equivalent monocultures.
- The components of a multiple crop may be complementary in the spatial sense by exploiting different layers of the soil with their root systems.
- Components of a multiple crop may complement each other nutritionally, by using different nutrients or different amounts of the same nutrient.
- Mechanical factors can explain overyielding (ie. one intercrop holding up another that could lodge in the wind or maize supporting bean vines).
- Mixtures generally have a greater tolerance of disease and pest attack.

Trenbath concluded that most investigators appeared satisfied that the effects observed (overyielding) were due to differential competition for light, water, nutrients or some combination with studies involving light being the most conclusive. Later work expanded beyond competition to the positive interactions of complementarity and facilitation between soil and plants and between crop components. By the 1980s, Gliessman (1986) established the positivist view that yield advantage in intercrops is most often attributed to complementary interactions between component crops with a result of more efficient use of environmental resources.
Liebman and Dyck (1993) conducted extensive literature surveys on multiple cropping with an interest in weed control outcomes. They felt the following mechanisms were important for overyielding:

1. Temporal, spatial and physiological complementarity in resource use among component crops can lead intercrops to capture more nutrients, water and light than sole crops.
2. Intercrop yield advantages can be substantial if mixture components differ in peak periods of leaf area display, nutrient sources, rooting depth, or photosynthetic responses to varying light intensity.
3. Intercrops may also show greater efficiency in converting available resources to harvestable yield, either through greater physiological efficiency or changes in the pattern of dry matter partitioning.
4. Intercropping may give yield advantages over sole cropping because of improvements in microclimatic conditions (eg. windbreak effects), provision of physical support structures (eg. for climbing crops) and reductions in pest damage through alterations in the dispersal, colonisation, feeding, and reproductive activities of pests and their natural enemies.

To better understand the mechanisms of overyielding, it may be useful to compare results over both a range of conditions as well as a range of crop combinations. Kass (1978) reported that ‘mixtures of non-legumes appeared to make use of soil and applied nitrogen more completely then do monocultures’ and ‘in mixtures of legumes and non-legumes, the nitrogen yield of mixtures was greater than that of pure-stand legumes in a significant number of experiments’. Furthermore, ‘polyculture of a legume and non-legume generally produced less total protein than did a legume alone’. However, polycultures of legumes and non-legumes always produced more total protein than a pure stand of non-legumes. Snaydon and Harris (1981) believed that the polyculture yield advantage was likely to be greatest when nutrients are deficient and when species differ in their temporal or spatial use of soil resources. Vandermeer (1981) thought that, theoretically, polyculture overyielding will be more pronounced in patchy, heterogeneous environments (different soil types, structures, nutrient status) than in uniform environments. Because industrial agriculture inputs have been used to make production environments more uniform (fertilising to cover areas of a field with low fertility), polycultural approaches can be expected to contribute to yield maintenance in any move toward low input farming systems, such as organic agriculture.

However, it is important to consider that overyielding in polycultures is not restricted to small, third world farming systems, despite the observation by Gomez and Gomez (1983) that yield advantage is generally higher with smaller farm size. Tuxill (2000) reported on the conclusions of the 1920s Russian biogeographer who studied genetic origin and diversity of crop plants. Vavilov had discovered that ‘crop genetic diversity was often particularly rich where farmers had to cope with a great deal of variability in local climate, soil conditions, and other environmental factors…such regions also contain some of the best examples of agrobiodiversity on an ecological level.’ Kranz (1981) observed that while there was an earlier belief that traditional intercropping advantage was only manifested at low levels of inputs and technology, research had since shown that there are substantial yield advantages of intercropping at medium to high levels of technology. Liebman (1995) concluded that although farmers often use polycultures without applying fertilisers or pesticides, polyculture yield advantages are not restricted to low input conditions. He cited numerous studies that report high LER values when large quantities of fertilisers and pesticides have been used. These arguments support the principle that polyculture approaches are scale-neutral and apply to any land use system, traditional intensive gardens or industrial mechanised systems.

It is useful to explore the generic role of polycultures in agricultural intensification. Kang et al. (1989) felt that the practice of alley cropping using multi-use trees for forestry hedges alternating with field crops would be a way to replace long, unproductive fallows in traditional swidden agriculture, allow productive
agriculture on marginal lands, and maintain or increase food production without expanding deleterious environmental impacts. They identified the following benefits:

- Higher crop yields.
- Deep-rooted trees recycle nutrients and build-up of organic matter.
- N-fixing trees and shrubs provide nitrogen (5 meter alleys, 5 prunings of leucaena and gliricidia provide 210 and 110 kg nitrogen per hectare per year).
- Hedge provides mulch, green manure, and forage.
- Microclimate for field crops improved and erosion reduced.
- Improved soil quality.

De Jong (1994) thought that polyculture could be seen as a means of agricultural intensification: producing more for longer from the same area. The inherent higher productivity per unit area not only increases production, but also reduces pressure on natural areas, marginal soils and input requirements. Traditional swidden cultivators in Indonesia were studied to examine their adaption to increasing population pressure and land degradation. Their response has been different than some shifting cultivators who simply reduce the fallow time before returning to an area to cultivate, reducing the fertility maintenance functions provided by the fallow and resulting in lower production. The Ngira farmers of West Kalimantan moved from rice growing and shifting cultivation of the highlands to rice growing and the planting and management of complex agroforests based on rubber, fruit trees, vines for crafts, nut trees, timber trees, and medicinals. They manage these agroforests over time to produce many crops and achieve a level of diversity (215 plant species per hectare) that almost reaches the diversity of neighbouring native forest (245 species per hectare). The result was that over a ten-year period, area in planted agroforest was slightly less than forest clearing while population grew by 28 percent. Their response to environmental degradation and population pressure provides leadership to other producers, both traditional and industrial. Similarly, in Amazonian Peru, enhancement of bush fallow by relay cropping locally adapted species into the crop mix, particularly weed suppressing ground covers and nitrogen fixing plants, led to higher productivity and faster regeneration through intensifying the species mix during cropping (Staver 1989).

Starting in the 1980s, ecologists made increasing contributions from ecological theory to explain polyculture yield advantage, in particular, explaining the mechanisms and limiting factors. Hart (1986) concluded that ‘higher production in multiple cropping (LER>1) can be explained in ecological terms of different niche requirements and the result of lower interspecific competition than intraspecific competition’. This will be explored in greater depth later in the section on interactions. Hart decided that the rules of community ecology dictate that the conventional cropping of fast growing, low diversity plants results in higher net harvestable biomass. As succession proceeds in natural or polyculture systems, diversity increases, occupying more niches (increasing the bio-efficiency of resource capture), increased interconnectedness among elements and a higher level of internal organisation. This is all at a cost to the net harvestable biomass as more structure and energy is used to maintain system connectedness. The short-term high productivity that can be gained by sequentially planting the same crop (typical industrial monoculture) that results in a deleterious effect on the resource base can be given up in exchange for long-term or lower productivity that is more self-sustaining and does not reduce the natural resource base.

**Yield Stability**

Following on from the idea that polycultures establish internal regulatory functions that replace external inputs (albeit at a cost of net harvestable yield), it is useful to look at stability of yield as well as amount of yield. Stability of yield and persistence of the farming system are key components of agricultural sustainability. Cox (1984) supported the approach of ‘strengthening the ecosystem characteristics that control fertility and productivity. In the humid tropics, this approach- the retention of the basic structure and processes that operate in mature natural ecosystems- is probably the only realistic means of
developing crop ecosystems with sustainable productivity'. Since traditional polycultures have such a long history of success, their methods and strategies are important to developing sustainable modern production. Gomez and Gomez (1983) observed that ‘traditionally, multiple cropping is used by subsistence farmers primarily to increase diversity of their products and stabilise the annual outputs’.

Numerous researchers cover the theory and mechanisms of yield stability in polycultures. Kass (1978) reported that all barley mixtures in Michigan were more stable in yield over several years than pure stands. Additionally, greater yield stability was also shown when soybeans were integrated into these intercrops than when grown alone. Trenbath (1974) suggested the axiom that the ‘biomass yield of a mixture having different components is likely to be more stable than that of the more stable of its components in monoculture’. Perrin (1977) articulated his observations on yield stability and its mechanisms by stating:

Where agriculture is capital scarce and labour-intensive, pest and disease incidence are high, multiple cropping gives higher and more dependable returns than monocropping for the following reasons.

1. More efficient use of solar radiation due to better interception of light by the foliage per unit of space (such as an intercropping) or time (such as relay or sequential cropping).
2. Positive interaction (compensation, facilitative production principle) between different plant species with mutual or at least unilateral benefits to certain physiological processes involved in crop growth and/or reproduction (ie. legumes and cereals).
3. Reduction of the apparent autotoxic effects of certain crops (self-limiting species).
4. More efficient use of soil moisture and nutrients associated with their different rooting depths of the constituent crops.
5. Maintenance of a dense canopy which smothers weeds.
6. The potential complementary growth of those crops in a mixture which suffers least from the vagaries of the environment.
7. Favourable changes in the incidence of pests and diseases and the significance of their damage.

Willey (1979a) proposed the axiom that intercropping gives higher yields in a given season and greater stability of yields in different seasons compared with sole cropping. Mead and Willey (1980) categorically stated that in intercropping systems, yields are more stable. In an earlier insight, Kayumbo (1976) postulated that:

The stability of mixed cropping systems can result from their ability to maintain yields despite pest and disease attack, achieved by growing mixtures that had a spare capacity or are able to compensate for damage caused by pests. Indeed, the economic success of many mixtures depends upon the plasticity of component crops. If one crop is damaged by insect attack, the second crop may to some extent compensate for the resulting lack of yield in the first crop.

Trenbath (1974) thought that the stability of a cropping system may be improved by multiple cropping practices because ‘within a mixed crop, compensatory growth by the stronger component will tend to increase stability of final yield total, but noted that component species needed to be carefully selected.

Willey (1981) expanded on this initial conceptualisation of the idea of compensation by asserting that the main physiological basis for greater stability of yield occurred because when ‘the multiple cropping set of one crop fails or grows poorly, another component can compensate, and such compensation cannot occur if the crops were grown separately. This is an additional effect from that of just “spreading the risk” by growing 2 crops, because the latter effect occurs whether crops are grown together or not’. Francis and Saunders (1978) observed that tropical American farmers found their highest probability of obtaining a consistent income with relatively lower investment was by growing beans and maize rather than one crop only. This strategy resulted in lower production costs, greater income stability, and a minimum of risk.
Lichner (1983) felt that intercrops normally show less variability in total biomass in yield than do sole crops. Reasons include compensatory effects among crops, reduced incidence of diseases, pests and weeds as a result of greater vegetative diversity and earlier soil cover provided by the intercrop. Not only do polycultures have inherent tendencies to stability similar to natural vegetation but also some components can have a stabilising effect on other components, particularly where tree crops are present. Stinner and Blair (1990) stated that:

Overall agroforestry stabilises cropping systems because:
- Water and wind caused erosion are reduced;
- Microclimate extremes are moderated;
- Trees can intersect air and moisture and redistribute it to soil; and
- Trees can supply and trap nutrients.

Polycultures can also affect the effective lifetime of the farming system and the resources required for production. In Africa, annual crops of millet and sorghum grown with acacia trees sustained yields for 15-20 years vs. 3-5 years with annual crops alone. Additionally, N, K and Ca increased 186%, 76%, and 22% respectively. Organic matter increased in a range from 26 to 40%. Cation exchange capacity increased from 5-20% in agroforest intercrop soils.

Related to yield stability is the notion of risk, in terms of either productivity or income or both. It could be argued that stability implies less risk. Beets (1982) thought that crop insurance was a major principle of polyculture in that if environmental factors change, some of the intercrop does well when others do poorly. He thought that for multiple cropping to be risk advantageous, the components of the crop association needed to have different environmental requirements or contrasting habits. This notion of potential compensation/complementarity will be explored further in the section on interactions. In his survey paper, Clawson (1985) concluded that traditional farmers cultivate a great variety or diversity of crops in order to maximise harvest security. This included intraspecies diversity such as different colours of maize with different maturation times. Clearly, yield risk is of most importance to subsistence farmers: if they don’t get a crop, they don’t eat. Increasingly, yield risk is also important to heavily leveraged industrial farmers who cannot afford risk of yield variability in their market crops. Even in current industrial monocultures the practices of polyculture can reduce risk. Wolfe (1985) reported that grain mixtures can generally provide a better guarantee of high yield than an a priori choice of a single best variety, largely due to the unpredictability of the growing season.

4.3 Income productivity, stability and risk

For most polyculture producers, either first or third world, a production goal is income. Just as productivity is determined by a milieu of ecological and technical factors, income is governed by a wide array of psychological, cultural, input costs and market factors. Income productivity has dimensions of level, stability, and risk.

Level of income

Economic and ecological studies of polycultures didn’t begin until the 1970s. Previously, the study of polyculture was dominated by third world anthropological researchers except for agronomic concepts emerging in the early organic agriculture of Europe and North America (see Conford 1988). As subsistence societies sought increased market participation, the income producing potential of traditional polycultures was explored. Perrin (1977) generally observed that there was a higher productivity in terms of gross income per hectare. Kass (1978) noted that planting alternating single rows as row intercropping, especially with grain and grain legumes, gave greater returns than other intercropping patterns. Kass also found that in all experiments reviewed, intercropping cotton with peanuts or maize was more profitable than growing cotton alone. In addition, associations of maize with legumes appeared to be very profitable except when high levels of nitrogen fertiliser were used. These findings added fuel to the recurring debate
in the literature about the adaptability and profitability of polyculture approaches to low input and marginal land production.

Kass (1978) concluded that there was considerable evidence that polyculture was distinctly less profitable at higher management levels, especially at high fertility levels. High input production detracts from income levels because of input costs. On inherently fertile or fertilised lands, the internal polyculture system attributes are masked, or overridden by the high fertility or nutrient inputs. In addition to management level, Kass (1978) observed that experimental findings have emphasised the importance of choice of crops and the relative prices in determining profitability of polyculture. He noted that the widespread use of peanuts in polyculture appeared economically justified because of their adaptability and high cash value. Scientists now know that legumes respond to the nitrogen needs of surrounding plants, increasing nitrogen fixation where soil levels are low or neighbouring plants require it and decreasing nitrogen fixation in highly fertile soils.

There can be a higher efficiency of production and possibly income at lower input levels (input dollars per unit of output). Francis (1986b) found that Asian upland shifting cultivation systems were very high in efficiency of yield per unit of manual labour input. Both high input efficiency and high labour efficiency usually resulted in higher income levels. By replacing inorganic fertilisers in mature coconut plantations with an under planting of improved pasture and nitrogen fixing trees, Liyang (1991) noted that when grazing income was established at a fixed amount per head per day, coconut yields were maintained, and the integrated farming system resulted in the savings of 69% on the previous cost of inorganic fertilisers. Liebman (1995) observed that net economic returns may be higher under polyculture in non-mechanised first and third world examples, pointing out the essential impact of mechanisation on yield and income efficiency. In modern mechanised production systems, the machine substitutes for the manual labour albeit at a significant dollar and energy cost, including many costs that are currently externalised under existing economic doctrine and are perhaps falsely excluded from calculations of input costs.

There are modern examples of higher income levels through polyculture. Blackburn et al. (1996) decided that livestock and wildlife can be managed together, increasing both landscape biodiversity and income. In south Kenya, cattle stocking rates only have to be reduced 20% to allow most wildlife species to prosper and generate income. The combination of livestock raising and wildlife management among the Masai generally resulted in higher incomes than if either were carried out alone. Sanchez (1995) found that domestication of indigenous trees with high value products enhanced profitability in agroforestry systems (in Africa and SE Asia) particularly those that can be marketed as ingredients of several products. The Australian native food industry is just now doing this with Australian bushfoods. Williams and Gordon (1992) discussed the common practice of intercropped annuals during the establishment of North American nut, fruit, or timber plantations for early income and more total income than establishment without annual intercrops. By intercropping black walnut nut and timber plantations with annual crops in Ontario, they found the ability to charge maintenance costs against the annual costs of the intercropped planting rather than against the eventual nut/timber production made a tremendous difference in the overall profitability of the planting. Benjamin et al. (2000) looked at corn and wheat intercropped with black walnut in the American Midwest and concluded that ‘net present values and internal rates of return showed that agroforestry systems were generally more favourable investments than traditional agriculture and farming.’

Some of the most profitable and innovative modern polycultures are currently taking place in Australia, especially agroforestry polyculture. Lefroy et al. (1992) discovered that the economic benefits of alley crop leucaena for forage were most dramatic with establishment costs paid off with only one year of improved live weight gains. Prinsley (1992) agreed that agroforestry systems producing multiple incomes from sawlogs, posts, chips and fodder contribute to diversification and increase farm income. Malajczuk
et al. (1996) found pine forestry and agroforestry producing sawlogs, sheep, wool and hay was more profitable than sheep-wool or cattle in Western Australian conditions. The observations of Struzaker and Lefroy (1997) in the sand plain areas of WA showed that when conventional sheep-wheat farms were supplemented with serradella pasture legumes and tagasaste forage shrub alleys, sheep numbers could increase by 76% and profit by 95%. **Clearly, polycultures can produce more income.**

**Income stability and risk**

Security of income level is as important as total income, both for subsistence and market polyculturalists. For the third world peasant, Kotschi (1986) noted that for the small-holder, the aspect of risk reduction is the primary attraction of multiple cropping. It means survival. Remembering that most studies of polyculture economics have been, by necessity, conducted in the third world situations where they occur, there is little evidence available from industrial first world agriculture by definition. Still, the principles should apply depending on the economic paradigm in place. Such principles arise from Francis and Sanders (1978) who stated that while multiple cropping systems are not always profitable, they do appear to be more stable over time and give a higher probability of providing the farmer with a specified level of net income. Lynam et al. (1986) echo this view in saying that:

Intercropping systems are not consistently more profitable than monoculture. Profitability depends on relative prices, costs and the degree of complementarity or competition of the activities; hence other factors affecting profitability are specific to site, time and income level. In intercropping systems net income advantages appear to be secondary to risk reduction.

Lynam et al’s comments particularly apply to farmers where subsistence food crops are an important part of the cropping system. Francis (1986) also noted that where subsistence is the primary goal, the main benefits are ‘food supply for the family, producing food with minimal investment of capital, and spreading income and food supply throughout the year.’ There is evidence that current third world polyculturalists seeking both subsistence and market income make clear and repeated choices to avoid risk and income variability. Francis and Sanders (1978) reported that small farmers in Central America ‘choose maize/bean [poly]culture to maintain low production costs, greater income stability and minimum of risk even when higher profit (but high risk) monocropping options are also available.

**4.4 Social Capital**

Besides the benefit of yield and income, polyculture can be seen to produce social benefits to both the land-holder and the surrounding community. Overall, the very practice of polyculture can be seen to benefit people rather than input manufacturers. Bradfield (1986) noted that updating traditional multiple cropping practices (as opposed to promoting monocultures) offers the potential of scale specific technologies that favour the small farmer. Addressing the question of equity, Willey (1981) found that the advantages of multiple cropping are that the benefits are achieved ‘not by means of costly inputs but by the simple expediency of growing crops together.’ Thus it offers a very genuine way in which the poorer or smaller farmer can benefit at least as much as the better endowed one. Similarly, Jodha (1981) thought intercropping research reveals its potential for greater employment. Because intercropping is often a system used on small farms, ‘any breakthrough in intercropping technology will help poor farmers more than the rich, thus better serving equity goals’ (Jodha 1981).

Polyculture practices can also be seen as facilitating and indeed depending on social and personal diversity as well as allowing varied and relatively precise adaption to environmental conditions and resources. Most landscapes are varied and uniform approaches cannot adapt to this variability, nor to the variability of individual goals and needs. Rao et al. (1981) concluded that in ‘developing India, the farmer resorts to intercropping in order to satisfy his multiple objectives simultaneously. Thus intercropping systems are essentially personal and unique to the land-holder and environment (including markets). This
is illustrated by the fact that 60 different crop combinations characterising intercropping were found in a single village.

If ecological theories relating diversity with stability are correct, human polycultures should contribute to social security. Russo (1996) found that in agroforestry systems, ‘trees, especially timber trees, represent a reserve of standing capital which is a stability factor contributing to internal security for the rural family’. Labour and employment are important social criteria to consider. Lynam et al. (1986) concluded that intercropping could reduce total labour input compared to sole cropping through an earlier and fuller canopy of crops to reduce weeding, more flexibility to adapt to seasonal labour availability and peak labour periods. Jodha’s (1981) results indicated that intercropping was able to ensure a greater and more even spread of employment of labour in India and Columbia and concluded that

...the objectives of having maximum cropped area without subsequent labour bottlenecks and yet providing maximum gainful employment for family workers are achieved through intercropping of crops with different growth cycles.

In contrast, Beets (1982) noted that one reason polycultures have higher yield and gross return per unit area was through additional input of labour. In many tropical countries, labour cannot be seen as an input because the opportunity cost of labour is very small. Therefore, the return from the farmer’s effort is more important than the amount of effort or labour required. Even where greater amounts of labour are required it is important to consider that labour spread over time may suit the farm family without excess funds to hire labour for peak periods. Deneven (1995) points out that labour intensity can actually result in less total eventual labour per unit output where landscaped methods of cultivation (terrace, padi, raised bed) have a high construction labour cost but low maintenance costs, resulting in higher overall labour efficiency. Van Mansvelt, Stobbelaar and Hendricks (1998) observed that a greater diversity of labour and jobs contributed to more diverse farm communities and noted a social psychological factor rarely mentioned: that polycultures are pleasant to look at and live in, no matter whether in the third or first world. They stated ‘the coherent diversity and pluriform but clear structure are appreciated as aesthetic and energising by visitors and those living on the European biodynamic farms studied.’ Another social benefit, according to Lamb (1997) is that by encouraging high biodiversity within and under new timber plantations, future society will have more options for modifications to management objectives if socioeconomic circumstances change during the lifetime of the plantation. Under even-aged, sequential, clear felled plantations, there are few options.
5. Interactions- The Ecological Basis of Polyculture

Accepting the foregoing evidence that polyculture approaches generally result in higher and more stable yield and income, the obvious questions are how and why? What is happening in these areas, between crops and between crops and their environment? Is this a matter of interaction in space, time or both? Are different mechanisms operating at different scales of interaction from individual to ecosystem? What happens when more than one crop is grown within a time or space? By examining theories developed and production systems observed the nature of existing polycultures can assist the design of additional potential polycultures.

Following mention of relevant ecological theories, this section covers a review of the nature, extent and result of competitive and complimentary interactions in polycultures, both within individual species (intraspecific), between species (interspecific) and community level interactions at the field scale. This discussion is followed by a section on interactions between crops and their environment in polycultures as described under various terms such as resource capture, use, efficiency, partitioning or allocation. The section concludes with a discussion of the ecosystem and landscape scale interactions that may give rise to adaptive polyculture characteristics of diversity, stability, and resilience. Since a substantial body of literature was identified detailing the result of these interactions on pest, disease and weed incidence and management, these are dealt with separately.

In general, it is accepted that polyculture crop components can be plants or animals of any kind producing fish, timber, field crops, fibre, food, forage or any commercially sold product of land use by humans. Since most research and most polycultures are largely plant based, terms will be used that apply to plants for simplicity.

5.1 Ecological theories relevant to polyculture interactions

Ecologists began to contribute ideas in the early 1900s that were later used by agronomists and others studying crop polycultures. The premise here is that the operation of the natural world will give guidelines on understanding the ecology of human constructed production systems like polycultures. One of the first observations of ecology was that of distribution and abundance: why are organisms where they are and in the numbers they are found? A common approach in the 1960s and 1970s was to evaluate population abundance and distribution by way of limiting factors, the requirements of the individual and population that encourage or delimit their numbers (see for example Krebs 1972; Odum 1971). Limiting factors in can be divided into abiotic (physical, chemical, nutritional, periodic and climactic events) and biotic (behaviour, interactions with other organisms or populations, internal genetics). The array and relative availability of limiting factors determine what can live where, and in what abundance.

The concept of ecological niche arose first from Joseph Grinnell (1917 and 1928) who used the word niche to stand for ‘the concept of the ultimate distributional unit, within which each species is held by its structural and instinctive limitations …no two species in the same general territory can occupy for long identically the same ecological niche’. Later theorists defined niche as the functional status of an organism in its community, the role or profession of an organism in its environment, and a multidimensional volume, the coordinates of which are those environmental factors that are most important to the species. In ecology, the idea of the niche gave rise to the competitive exclusion principle; basically saying that no two organisms can occupy the same niche since one will be less limited by some factor, and will out-compete the other over time. This principle allows inclusion of both abiotic and biotic limiting factors. Concepts and mathematical formulas arose to describe these types of interactions, and the ideas of competition and cooperation are central to the understanding of polyculture function and
structure. Odum (1971) summarised the possible combinations of interaction between two species (shown in Table 11) and noted the two worthy principles of ‘adaption and coevolution’. Adaption and coevolution as principles arise from these categories of interaction:

1. In the evolution and development of ecosystems negative interactions tend to be minimised in favour of positive symbiosis that enhances the survival of the interacting species; and
2. Recent or new associations are more likely to develop severe negative coactions than are older associations.

Table 11: Analysis of Two-Species Population Interactions

<table>
<thead>
<tr>
<th>Type of interaction</th>
<th>1</th>
<th>2</th>
<th>General nature of interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutralism</td>
<td>0</td>
<td>0</td>
<td>Neither population affects the other</td>
</tr>
<tr>
<td>Competition: direct interference</td>
<td>-</td>
<td>-</td>
<td>Direct inhibition of each species by the other</td>
</tr>
<tr>
<td>Competition: resource use type</td>
<td>-</td>
<td>-</td>
<td>Indirect inhibition when common resource is in short supply</td>
</tr>
<tr>
<td>Amensalism</td>
<td>-</td>
<td>0</td>
<td>Population 1 inhibited; 2 not affected</td>
</tr>
<tr>
<td>Parasitism</td>
<td>+</td>
<td>-</td>
<td>Population 1, the parasite, generally smaller than 2, the host</td>
</tr>
<tr>
<td>Predation</td>
<td>+</td>
<td>-</td>
<td>Population 1, the predator, generally larger than 2, the prey</td>
</tr>
<tr>
<td>Commensalism</td>
<td>+</td>
<td>0</td>
<td>Population 1, the commensal, benefits while 2, the host, is not affected</td>
</tr>
<tr>
<td>Proto-cooperation</td>
<td>+</td>
<td>+</td>
<td>Interaction favourable to both, not obligatory</td>
</tr>
<tr>
<td>Mutualism</td>
<td>+</td>
<td>+</td>
<td>Interaction favourable to both and obligatory</td>
</tr>
</tbody>
</table>

Researchers in polycultures began to apply these and other insights into crop ecology in the 1970s and 1980s. Willey (1979b) proposed that better use of growth resources as a result of the complementary effects between component crops was one of the major sources of yield advantage in multiple cropping and observed that temporal complementarity (as in relay cropping) is likely to produce bigger advantages than spatial complementarity (as in intercropping). Vandermeer (1981) noted that in community ecology, the coexistence of species has been explained by ecological theory since the early 1900s on the basis of the level of interference between species.

If the niches of two species are distinct enough to ensure a relatively low level of interference, the two can coexist. If the niches are not sufficiently distinct, the interface will drive one or the other to extinction over time. They coexist if the intensity with which they interact (niche overlap) is below some critical value (Vandermeer 1981).

**Thus competition and cooperation are two sides of the same coin of interaction.** Hart (1986) added to the understanding of the importance of not only the type of interaction but the intensity where he said the ‘increased yield of polycultures were explained by differences in niche requirements and lower interspecific than intra specific competition.’ In other words, species in successful polycultures compete less with the other crop than with other members of their own species, or as Vandermeer (1989) stated: ‘they compete only weakly in successful polycultures’. Vandermeer added the interesting insight that the biological explanation for intercrop yield advantage could simply be the same as the biological
explanation for species coexistence in nature, since the competition coefficients of the classic Lotka-Volterra equations are, in fact, ratios of inter to intra specific competition.

Vandermeer (1981) had earlier proposed a restatement of the ‘competitive exclusion principle’ and referred to it as ‘the interference production principle’, which he defined by stating: ‘two species will overyield if their mutual interference is sufficiently weak’. Vandermeer (1989) noted that two species are not only interacting with each other for possible scarce physical resources but that the quality, pattern, uniformity, and patchiness of the environment where the production is taking place is at least as important as competition for scarce resources. Vandermeer (1989) restated the idea as the competitive production principle, being the case where one species has an effect on the environment which causes a negative response in the other species, yet both can more efficiently utilise necessary resources when living together than when growing in monoculture. Field observations of successful traditional polycultures quickly showed that there was more than just competition occurring, weak or otherwise, to explain polyculture yield advantage.

Ecologists were aware of the variability of environmental factors, meaning that necessary and perhaps limiting resources may or may not occur in clumps or patches as opposed to uniformly across the area. When resources are patchy, they may have an effect on competition. If an environmental factor differs across a polyculture field, one species may do better at different places in the field. The field would be said to have environmental grain, that is, the environmental factors produce a ‘grainy effect’ on production. Other field observations showed cases where under supposedly high competition, some crop components did better than in sole crop plantings. The best example is in maize/bean/squash culture in Middle America where the legume component contributes (or facilitates in Vandermeer’s terms) more to the other species through nitrogen fixation than it detracts through competition. Vandermeer (1989) termed this as facilitation, or the facilitation production principle where one species may alter the environment of another positively (and not necessarily reciprocally). This corresponds to Odum’s interactions 7-9 shown in Table 11.

Once again, competition and cooperation are the two sides of the polyculture coin. Vandermeer (1989) makes it quite clear that in many polycultures both competition and facilitation are taking place and that it is possible to obtain the net result of LER>1 where the complimentary facilitation is contributing more to the interaction than the competitive interference. Thus, an LER>1 could result from lower competition or strong facilitation. Such an active process as nitrogen fixation may be a clear case of facilitation; others are more indirect, almost incidental interactions that may be seen as facilitative. Some examples are:

- Using different resources in the environment
- Using the same resources in the environment at different times
- Out-competing in certain patches of the environment.

These interactions all serve to avoid niche overlap and ensure competitive advantage. Speculating more broadly at a later date, Vandermeer (1990) felt that a taxonomy of multiple cropping could be based on degrees of association (levels of interaction) of individual crop components ranging from no association (rotation cropping) to partial association (relay intercropping) to complete association (simultaneous row intercropping). Indeed this taxonomy is inherent in the range of possible interactions illustrated in Table 11, and allows for the facilitation principle.

Some other ecological theories bear on the study of polyculture, especially those addressing diversity, productivity and sustainability. Hart (1986) noted that the rules of community ecology dictate that the cropping of fast growing, sun-loving, low diversity plants results in higher net harvestable biomass, such as those found in industrial monocultures. As succession proceeds in natural or polyculture systems, diversity increases occupying more niches (increasing bio-efficiency of resource capture), increased
interconnectedness among elements and a higher level of internal organisation. This is all at a cost to net harvestable biomass as more structure and energy is used to maintain system connectedness. Therefore, ‘short term, high productivity that can be gained by sequentially planting the same crop (typical industrial monoculture) that results in a deleterious effect on the resource base, is given up for long-term or lower productivity that is more self-sustaining and that does not reduce the natural resource base’ (Hart 1986).

Margalef (1968) and Morowitz (1968) have argued that there is a relationship between the biomass, energy flow, and diversity of biological systems and that primary productivity per unit of biomass is a decreasing function of the diversity in ecosystems. Watt (1973) articulates this in his Principle 9: ‘the diversity of any community is proportional to the biomass divided by the productivity’. This principle means that the energetic efficiency of biological systems increases with increasing organisational complexity. That is, the energy cost of maintaining a unit of biomass decreases with increasing diversity. A related principle is that energy, matter and diversity flow along a gradient of increasing diversity or organisational complexity from subsystems of lower diversity or maturity to subsystems of higher diversity or maturity. This tendency contributes to optimum system efficiency of resource use and can replace external energy inputs in conventional agriculture with internal energy cycling in polycultures.

The ecological concept of stability shows an interesting evolution over time. Traditional ecologists generally believed in the idea that nature was inherently stable, had an ideal adapted vegetation on any given site, and that it would inevitably return to that state following disturbance. A more chaotic paradigm now pervades ecology, one that says:

The natural world is characterised more by instability than permanence, by frequent disturbance that continually pushes ecosystems in alternative directions that change the composition of assemblages and spatial patterns (Hobbs & Morton 1999).

This non-equilibrium paradigm suggests that multiple stable states may exist and that some quasi-stable states can persist for long periods. Such is the current understanding of ecosystem resilience that includes but replaces the idea of static stability.

5.3 Competition and complementarity in polycultures

A discussion of research specific to polyculture can further elaborate the nature and result of these crop interactions. Willey (1979a) suggested there were three broad categories of competitive relationships in intercropping: 1) when the actual yield of each species is less than expected, termed mutual inhibition [Odum’s 2nd interaction], 2) where the yield of each species is greater than expected [termed mutual cooperation (mutualism) and is not unusual]; and 3) the most common situation, where one species yields less than expected and the other more; termed compensation. In aqua/polycultures, Edwards et al. (1988) reported that the culture of more than one species of fish together in the same pond has generally been regarded as more productive than raising individual species separately. The rationale is that fish have different trophic (feeding) and spatial niches and that with polyculture a balanced fish population with different species that complement each other can occupy all pond niches. Ong and Leakey (1999) suggest that ‘competitive interactions are more often associated with the early successional stages of an agroecosystem, while the complementary interactions occur during the late successional stages (of mature agroforests).’

Competition can also be viewed from the perspective of the individual crop component where it literally competes with itself. All farmers know if they sow a crop too thickly, the density is above optimum and both individual plant performance and total yield can be reduced. Besides direct competition for space, light, nutrients etc., some plants can be autotoxic, or toxic to their own members, usually via root exchanges. This is an artifact of evolutionary dispersion strategies to prevent the establishment of young where there is sure to be competition and for the purpose of maintaining adaptive genetic diversity. Not
only can plants exude root chemicals that discourage their own members from establishing nearby, but plants can defend themselves from competition from other species with a mechanism called alleopathy, when one population produces a substance harmful or inhibitory to a competing population, often released from leaf litter or roots.

In a review of botanical inhibitors, Whittaker (1970) concluded that higher plants synthesise substantial quantities of substances repellent or inhibitory to other organisms and that alleopathic effects have a significant influence on the rate and species sequence of plant succession and on the species composition of stable communities. Trenbath (1974) believed that while alleopathy was definitely present in polycultures, traditional farmers had clearly used components with minimal alleopathic tendencies, or the process of domestication had reduced alleopathic chemical production. He concluded that the research on alleopathy indicated that in cropping systems, its influence would be minor during the growing season in comparison to simple competition in determining intercrop yields. He also noted an interesting forestry example where foresters in NSW and Queensland reported in the 1960s that six rainforest trees, which do not form natural pure stands, showed unexpectedly poor growth in commercial monoculture plantations. Detailed experimentation with silky oak (Grevilla robusta) indicated that a water-soluble substance, apparently produced by the roots of silky oak trees, inhibited the growth of adjacent young silky oak individuals.

It is important to appreciate that plants compete in all dimensions of the environment, from space for light interception to rooting depth for water and nutrient uptake. Snaydon and Harris (1981) noted that the greatest difference with agroforestry versus other multiple cropping systems is the importance of root interactions in agroforestry and the need for increased attention to understanding the better dispersion of light within the canopy, a postulated advantage in multi-storied systems of the humid tropics. It is also important to remember that competition is a dynamic process and that competition often occurs along with complementarity.

In a review of forty papers on grass/legume or cereal/legume pasture intercrops, Ofori and Stern (1987) reported that in these intercrops, legume yields declined 50%, cereals 11% compared to sole crop plantings. When grain/legume pastures are cropped for cereal the grass is usually the dominant component due to faster, earlier growth by the grass and later shading of the legume. Where the grass is cropped by grazing, the legume can be released and become dominant over the cereal grass- a reversal of roles. They noted a few other observations of grass/legume intercrops related to their interaction:

- Density of the cereal component determines the level of combined mixture yield but the efficiency of their intercropping (as measured by LER) follows the trend of the legume component.
- Staggered sowing gives no benefit over simultaneous sowing
- Under high nitrogen applications, cereal/grass increased their share of yield over the legume component
- Nitrogen fixation by the legume is usually lower if nitrogen is applied
- Nitrogen is available from the legume for the grass during the growing season
- Leaching of nitrates in intercropping is less than as sole plantings.

Complementarity, such as the legume contribution to pasture intercrops through fixing atmospheric nitrogen is a key feature of polycultures and natural vegetation. Prior to the 1980s and 1990s, much of the focus of plant interaction in agriculture was largely on a simple mechanistic notion of competition without adequate acknowledgment of complementarity. Ong and Black (1994) suggested that the concept of resource utilisation is central to the assumption that mixtures of crops may lead to increased productivity in both intercropping and agroforestry systems. Their descriptive taxonomy of both spatial
and temporal complementarity follows Willey’s (1979a) analysis postulating that yield advantage in multiple cropping occurs when:

Component crops differ in their use of growth resources in such a way that when they are grown in combination they are better able to complement each other and so make better overall use of resources than when grown separately in terms of competition. The component crops are not competing for exactly the same resources (in space or time) and intercrop competition is less than intracrop competition.

Temporal and spatial complementarity can be differentiated from one another (Willey 1979a):

**Temporal complementarity**- Growth patterns differ in time (typically at least 30-40 days maturity difference).

- Use water at different times, particularly where the system is moisture limited.
- Where nutrients released from one component are available to complete growth of the other component.
- A time displacement that results in the capture of more resources by the intercrop rather than a change in the efficiency of utilisation.

**Spatial complementarity**- The combined leaf canopy or root system of an intercrop makes better use of available resources when grown together, such as total light interception.

- Component crops exploit different soil layers or canopy heights.
- Component crops differ in their nutrient requirements, the form of nutrients which they can readily exploit and their ability to extract them from the soil.
- One crop exploits a greater volume of soil.
- Where the total quantities of resource captured are relatively similar, but the efficiency of utilisation of the resources captured are increased in intercrops compared to the sole crops.

Willey (1979a) thought that light was the most important factor and noted that it was different from other growth resources in that it is only ‘instantaneously available and thus must be instantaneously intercepted to be of benefit’ while other resources are typically pools awaiting plant exploitation. Willey concluded that:

The greater the difference in maturity and growth factor demands of the crop components, either because of genetic difference or manipulation of planting dates, the more opportunity for greater total exploitation of growth factors and subsequent overyielding.

In another article published the same year Willey (1979b) concluded that:

Better use of growth resources as a result of complementary effects between component crops is proposed as one of the major sources of yield advantage. Temporal complementarity is likely to produce bigger advantages than spatial complementarity.

Vandermeer (1981) decided that the probability of realising an intercrop advantage should be greatest when the two crops can draw from a patchwork of resources within a field and when they demand these resources at different times. Ong and Black (1994) acknowledged that an important question was whether competitiveness and complementarity are species or site specific, as various studies suggested. It is tempting to view complementarity as merely the avoidance of competition, but there are varying elements of, if not active, at least adaptive reactions between plant species that result in positive effects as allelopathy results in negative effects on the other crop. As mentioned earlier, facilitation is an active promotion of one crop by the other, such as legume nitrogen fixation. This interactive dance of coevolution can also be more subtle. Amador and Gliessman (1990) found that maize/bean associations in Central America resulted in more nitrogen producing nodulation (to the benefit of the maize) than in sole crop plantings. In other words, the beans, although reduced in yield in the intercrop, produced extra nitrogen for the maize. Davis, Wolley and Moreno (1986) noted that:
Plants grown in intercrops can modify their pattern of growth from that in monoculture. Beans grown alone in one study varied in the number of nodes, from 15 nodes without support, to 27 nodes with a 2 meter bamboo stake, and to 28 nodes when intercropped with maize.

Thus, climbing beans are stimulated in the presence of a support to grow and branch more. Human agriculturalists have not failed to notice the nature and result of these interactions. Baker and Francis (1986) observed that traditional farmers carefully choose species for polycultures. These farmers combine species with different above ground and below ground morphologies, varying maturation dates, and varying nutrient uptake patterns in order to more completely utilise the plant growth environment. The spatial, physiological and temporal differences of combined species utilise resources more efficiently than either species alone. It is important to realise that the resulting higher productivity is a result of the synergy of the components- the individual species do not substantially demonstrate a change in their monoculture nutrient uptake patterns, response curves, or critical resource level tolerance, even though they may respond to their intercrop partners.

Indeed, modern farmers also value complementarity. Prinsley (1992) in a report of her PhD research, stated that half of the farmers in Australia practicing agroforestry are doing so for shelter benefits such as those found in various combinations:

**Pasture**
- Reduced water loss by shading or reduction in wind speed
- Temperature extremes are moderated
- Provision of habitat for predatory birds and insects.

**Crops**
- Eucalypt windbreaks increased wheat and oat yields by 25% and 45% respectively.

**Animals**
- Temperature modification
- Fertility enhancement through less heat stress
- Reduced neonatal mortality
- Increased juvenile growth
- Reduced shorn sheep losses.

### 5.4 Polyculture and landscape interactions

While polyculture production systems have been largely defined by their internal mechanisms and properties at the individual, population, community, and field scale, they also exist as a component of larger ecosystems at the landscape scale. While monoculture production systems can literally replace a natural landscape totally, the higher diversity of polyculture systems implies a wider range of interactions with other agricultural systems, natural areas, and the greater landscapes where they are used. An essential feature of such land use systems is diversity, both natural (biodiversity) and planted (agrobiodiversity). Srivastava et al. (1996) noted that 70 percent of global land is in agriculture or managed forests so the potential for increasing or decreasing diversity is largely in the hands of those already managing production systems. These researchers also calculated that only five percent of present biodiversity is in protected areas; in Germany only a third of all species found there are in protected areas. Srivastava et al. believe that in the past, efforts to promote biodiversity conservation have largely underestimated the value or contribution of agrobiodiversity. Polyculture represents a strategy of land use intensification that can contribute to biodiversity.

Smith (1996) concluded that there is a clear inverse relationship between biodiversity and intensity of land use. He suggested a classification system ranging from forest extraction-plantation systems-agroforestry-agro/pastoral systems-shifting agriculture to intensive cropping with short-cycle crops.
indicating the correlation of higher net harvestable productivity with increased negative impacts on biodiversity. He listed the following interactions between farming styles and biodiversity:

1. Most of the planet’s habitats have been modified by varying degrees of human activities.
2. A mixture of land uses usually provides the optimal use of natural resources and given area—whether at farmer or regional scales.
3. Practices can be identified within each land use system that enhance biodiversity.
4. Biodiversity is essential to system resiliency because it provides greater options for alternative approaches to agricultural production.
5. Agricultural production systems need to be resilient so that they can adjust more readily to changes in the biophysical or socioeconomic environments.
6. Land use intensity affects both on farm and offsite, typically showing higher offsite impacts with higher intensification.

Discussions of diversity have always tried to link with the result of diversity and one key result often postulated is stability. The early ecologists saw stability as a static persistence while later theorists say stability is more of a dynamic equilibrium. There is significant disagreement on the relationship of diversity and stability in both natural and agricultural systems but the general point of view is that they are mutually complementary. Diversity enhances stability and stability facilitates diversification. Cromartie (1981) concluded that the generalisation that diversity is valuable because of the stability it is thought to confer can be questioned. Although natural systems, when undisturbed and where they retain their original diversity, typically maintain a dynamic equilibrium between pests and hosts, Cromartie suggested that ‘stability by itself is not a solution if the pest population is stable at a level that causes economic loss.’ He also thought that ‘instability is characteristic of annual cropping systems because of tillage, rotations, and abandonment of fields in swidden cultures.’ His third point was that there is ‘little sound evidence to show that diversity is a cause of stability in ecological systems’. Cromartie makes the point that the value of crop diversification needs to be understood in a more refined way than the simple stability/diversity hypothesis.

Kevan (1980) seems to believe that overriding hypotheses were not particularly necessary if key parameters that could be measured were useful. He felt that ‘the relationship between the diversity of species and the numbers of individuals representing each species in an ecosystem contains basic biotic information which is indicative of ecosystemic health and can be used as diagnostic parameters.’ These indicators might also be useful as design parameters for planted polycultures. Certainly, the predominant observation of polycultures is that ‘the most important characteristic of multiple cropping systems is increased diversity, both in terms of habitat structure and species’ (Stinner & Blair 1990). The question is how does on-farm diversity interact with landscape biodiversity, a matter also taken up in the section on disease management.

In a study of European organic and biodynamic farms, van Mansvelt, Stobbelaar and Hendricks (1998) made several observations of an agrobiodiverse farming system. The complexity and interaction with landscape biodiversity (particularly bird and insect life) that organic and biodynamic farms had, in contrast with conventional farms, demonstrated the following:

- More species per plot and more different habitats
- More abundance of rare species
- Higher diversity internally
- Higher numbers of different niches
- More types of land use per farm
- Higher numbers of crop in animal species
- More species of trees and shrubs in more types of spatial arrangements.
Van Mansvelt, Stobbelaar and Hendricks concluded that these farms became more unique, as ecosystems, socioeconomically, and as part of the landscape; a farm diversity supporting wider biodiversity.

Production system diversity (agrobiodiversity) also interacts with landscape scale phenomena like climatic extremes. Tilman and Downing (1994) in an 11 year study of Minnesota grasslands, found that primary production in more diverse grazing communities is more resistant to and recovers more fully from a major drought. They found that species richness led to greater drought resistance because species-rich plots were more likely to contain some drought resistant species. Each additional species lost from grasslands had a progressively greater impact on drought resistance overall. This resilience was significantly higher in native prairie than in three planted successions of grasslands. Agroecosystem resistance to drought was shown to be an increasing but non-linear function of species diversity. For example, the progressive loss of species has a progressively greater impact on ecosystem stability, supporting the traditional view of the stability/diversity hypothesis. Another important way that the land use intensification to polyculture production can contribute to landscape biodiversity is, quite simply, that if the same amount of products come from smaller managed land areas, more land can be restored or not cleared for production. Sanchez (1995) thought that ‘the most important way agroforestry can serve biodiversity is less within the farms or landscapes but in reducing further clearing of native forest.

General landscape diversity is often characterised as a mosaic of different land use as in highly diverse fields of multiple crop systems. Stamps and Linit (1998) studied the difference between mosaic landscape and arable (monoculture)-only landscapes in Poland and found that pest populations increase, insect biomass increases, and insect diversity increases in mosaic landscapes versus arable-only landscapes. The observation that pest populations increase might be part of the reason that they also observed that natural enemy (predators) biomass was up to 70 percent higher in mosaic landscapes than in uniform landscapes, but they didn’t comment on the economic threshold impact of the residual pests. Cromartie (1981) cautioned that ‘diversity can create pest problems as well as solve them’ and that each case needs careful study.

Polyculture systems also interact with landscape resources, such as water catchments and surrounding natural resources. Wagachchi and Wiersum (1997) observed the linkage of buffalo ponds and forest gardens in Sri Lanka. They concluded that this type of silvo/aquacultural practice that links tree crops with aquaculture allows the combined management of vegetation and water resources, affecting catchment retention, erosion and sedimentation management and animal husbandry, thus illustrating the links between local enterprise management and larger scale public landscape values. This is an important aspect of current efforts in Australia to reduce salinity in the Murray Darling region; the resulting impact of individual farming practices at the landscape level. An early Australian work by Macnish (1980) observed that in the Darling Downs, the emerging practice of strip cropping alternate crops allowed for both rotation and erosion control benefits. Sometimes, landscape interactions can occur where the farming system is not particularly polycultural but utilises landscape-scale resources. Wilken (1977) reported on such landscape-scale hybrid systems in Central America where open field plantings were fertilised and mulched with forest litter with the two areas being managed for total system success.

5.5 Resource Capture

All organisms exist in an environment where they obtain the requirements of life and interact with living and non-living elements in that environment. The requirements for growth and reproduction are obtained from that environment, usually in competition or cooperation with other organisms. Those that do so with a higher efficiency usually succeed over those that are less adapted. In natural systems this is the mechanism of evolution, operating at all levels from gene to ecosystem. In polyculture cropping systems, humans seek to utilise the abilities of crop components to capture and utilise resources. Those human cultures that do so most effectively in terms of energy efficiency and dynamic stability succeed and persist, particularly if their environmental impact is moderated or is benign. This section looks at the role
of environmental resource use: capture, utilisation, allocation, partitioning and differential use, and how these mechanisms explain some of the attributes of polycultures. Again, for the sake of convenience and recognising the predominance of plant-based polycultures, most discussion is directed at plant crops.

Resource use has dimensions of both structural and functional interaction in both space and time. Liebman (1995) explains that intercropping crop species with similar growth duration produces an advantage in the utilisation of space only, whereas the association of crops with different growth durations result in a gain in total yields through better utilisation of two dimensions, space and time. Early attempts by agronomists to discover the basis for improved productivity of polycultures began by using many of the ecological techniques for investigating competition in natural communities. As discussed earlier, these investigations resulted in further understanding of competitive and complementary interaction among crop components. In the early 1970s and 1980’s, research on ecosystem functioning in polycultures began to look at resource use, especially light interception and use. Rhoades (1969), in one of the earliest works, concluded that ‘by growing two species together, we increase the extent to which the combined canopy can trap incident light energy’. The resource capture approach attempts to define complementarity in terms of the efficiency with which mixtures of species capture and utilise limiting growth resources. According to Vandermeer et al. (1998), ‘resource complementarity occurs when a mixture of species results in the capture of a greater fraction or quantity of the limiting growth resources and/or the more effective utilisation of the same resource’. He earlier (1981) held a similar view that ‘under certain conditions, a monoculture cannot utilise all the niche space available and a second crop can fit in without disturbing the first crop too much’.

While early investigations focused on the physical and spatial dimensions of resource use, such as amount of leaf area and light interception, the idea expanded to include plant interactions in nutrient uptake, below ground interactions, and temporal complementarity. The outcome of resource capture is expressed in terms of conversion efficiency and the varied allocation of resources captured. Trenbath (1986) explained resource capture in the following manner:

> In ecological terms, the morphological and physiological differences among crop species result in their ability to occupy different niches. Absolute differences include the timing of resource interception, its location, rate of absorption (light energy, water and nutrients), rate of growth, and response of yield to resource variation.

The general hypothesis is that the varied distributions of growth factors in space and time suggest that in many agricultural environments those factors could be more completely absorbed and converted to biomass by mixed stand of crops than by a pure stand. Trenbath (1986) proposed that this can be measured by RUE: Resource Utilization Efficiency. This is the product of the efficiency of capture of resource by the crop plant and the efficiency of conversion into yield. Capture efficiency is composed of interception and absorption. Conversion efficiency is composed of resource conversion into whole-plant biomass and harvest index (the proportion of plant biomass present at harvest as economic yield). Thus, resource capture in polycultures is seen as both dynamic and functional as well as static and structural. What is done with the resources is as important as how much is gathered, particularly in explaining polyculture yield advantage. Yield advantages of polycultures are often correlated with use of a greater proportion of available light, water, and nutrients (greater resource capture) or by more efficient use of a given unit of resource (greater resource conversion efficiency).

Liebman (1995) thought that these improvements in resource use reflect three phenomena: complementarity in resource use, interspecific facilitation, and changes in resource partitioning. Complementarity in resource use occurs if crops differ in the way they use environmental resources (in time or space dimensions) and when grown, complement each other and make better combined use of resources than when they are grown separately (Vandermeer 1989). In ecological terms, complementarity
minimises niche overlap among associated species and thus minimises resource competition. Liebman (1995) noted that complementarity may be regarded as:

- Temporal, where crops make major demands on resources at different times;
- Spatial, where canopies or roots capture resources in different zones; and
- Physiological, where biochemical differences exist between crops in their responses to environmental resources.

Codero and McCollum (1979) reported on a modern example of complementarity, in this case both temporal and spatial. In North Carolina, maize was used as the overstory component with soybean, snap beans, or sweet potato as the interplanted understory species in a 200 day growing season. The resultant intercrop yield advantage suggested a 20-40% increase in total productivity. Early in the season, the normally bare area under the maize was growing young beans and sweet potato, and in the later season, the physical difference in size and shape allowed increased resource capture. Codero and McCollum (1979) noted that:

> The crop yield in the final analysis is not solely a function of land area alone but of time as well (ie. yield equals quantity of product per unit of area per unit of time). The time factor must thus be considered in comparing intercrops with monocultures because ‘land occupancy’ by a given intercrop is not necessarily of the same duration as monocultures of the intercrop components.

They proposed LAD (leaf area duration), defined as the integral of leaf area over time, to correct for this partial flaw in LER.

When total crop densities are higher in polycultures, they can intercept more light especially early in the growing season. Polycultures composed of non-synchronous patterns of canopy development and different maturation times can display a greater amount of leaf area over the course of the growing season and intercept more total light energy than monocultures. Carandang (1980) thought that polycultures allow maximum utilisation of sunlight by increasing light interception by 30-40%. Where polycultures produce earlier or later canopy, evaporation of soil moisture is reduced, weeds suffer from light and moisture competition, and there is decreased rain impact erosion through canopy filtering and greater root structures. Wilson and Ludlow (1991) reported soil temperatures up to 10 degrees Centigrade cooler on forage under tree plantations in the tropics, assisting seedling survival, soil-water relations and possibly affecting the rate of litter breakdown and nitrogen mineralisation.

Sanchez (1995) suggested that agroforestry trees can provide nitrogen through two processes; biological nitrogen fixation and deep nutrient capture that is cycled back to the surface in leaf litter. For example, as much as 125 kg of nitrogen per hectare was generated in Malawi under acacia/sorghum polycultures in just four months after the onset of the rainy season. Where crop components exploit different volumes of the soil, as in agroforestry, immobile or limiting nutrients can be better utilised. Russo (1996) noted that in silvopastoral systems, deep-rooted trees explore the subsoil not normally exploited by the pasture, recycling deep nutrients in leaf litter for the surface vegetation. In time, if crops are growing at different times, they can access nutrient pools more completely. Altieri et al. (1983b) noted that ‘in intercropped agroecosystems, nutrients lost by one crop can be taken up by another, especially in agroforestry. Increased diversity in cropping systems yields larger root areas, increasing nutrient capture.’ Stirzaker (1999) looked at the relative success of irrigated horticulture and felt that even with improved management of current industrial practices, ‘the best managed lands are still likely to suffer soil degradation and leak water, nutrients and pesticides into the surrounding environment.’ However, he thought the integration of tree crops would be more appropriate at the regional scale, ‘confining the (relatively small) area of irrigated cropping to the most favourable soils and buffer the impacts from these areas with forestry or dryland sequential crops elsewhere in the landscape.’
Physiological complementarity can occur in polycultures composed of species that use C$_4$ and C$_3$ photosynthetic pathways. This is illustrated by the earlier North Carolina example of maize, a C$_4$ type plant that is better adapted to high light environments. Of course, the most common example of physiological complementarity is fixation of nitrogen by legume components, meaning that soil nitrogen is available for neighbouring non-legumes. Vandermeer (1989) reported on a 1985 experiment that demonstrated not only the direct transfer of nitrogen from soybean to maize, but also that the transfer was mediated through vesicular arbuscular mycorrhiza (VAM) fungi associated with their roots. He also reported on a 1982 study in which it was demonstrated that phosphorous was actually transferred from one species to another through mycorrizal connections.

Interspecific facilitation occurs when crop species grown in polycultures have access to resources not available in monocultures or when they enjoy improvements in microhabitat that result in greater resource conversion efficiencies (Vandermeer 1989). This is what happens when legume nitrogen is passed to non-legume crop components in a polyculture, or in increased water use efficiency of low growing crops in the shelter of taller crops acting as windbreaks. Russo (1996) claimed that ‘agroforestry systems increase the efficiency of radiation capture and utilisation of the horizontal and vertical space of the agroecosystem.’ Interspecific facilitation is especially important and discernible in agroforestry systems such as alley cropping. It can be as simple as providing productive trees for a living support system for vine crops like yams (in a physical sense of facilitation) or as is discussed later, the support of insect pest predators (in a functional sense). Farrell (1995) described four characteristics of agroforestry systems:

- **Structure**- agroforestry combines trees, crops and animals.
- **Sustainability**- using natural ecosystems as models, optimises the beneficial effects of interactions between woody species and crops or animals and helps protect the environment.
- **Increased productivity per unit of land**- by enhancing complementary relations among farm components, improved growing conditions and more efficient use of natural resources, production is greater than monoculture annuals only.
- **Socioeconomic/cultural adaptability**- agroforestry is particularly adapted to low-input, small farmers by spreading labour, production and risk.

According to Perrin (1977), if the farmer is seen as a polyculture component, tree crops have an interspecific facilitation where ‘multiple cropping presents to the farmer the most efficient exploitation of a given physical environment’, especially in spreading labour requirements over time. Farrell (1995) elaborated on the soil and microclimate benefits of agroforestry characteristics:

**Soil**
- Trees explore deeper soil profiles for nutrients and cycle them back to the surface in leaf litter
- Nutrient levels increase when trees are associated with nitrogen fixing bacteria or mycorrhiza
- Trees create higher organic levels in the soil
- Agroforestry increases soil porosity and encourages more stable soil aggregation
- Trees reduce wind speed, diffuse rain/hail to reduce erosion.

**Microclimate**
- Moderates temperature extremes
- Lower temperatures and reduced air movement leads to less evaporation
- Increased relative humidity versus open sites.

Agroforestry can also improve the local hydrology, support greater insect numbers and diversity and produce food as well as timber in many cases.
Similarly, Lefroy et al. (1992) noted the benefits of fodder silvopastoralism in Western Australia as being both nutritional and environmental; the benefits include:

- Restore deep rooting plants for water cycling
- Provide shade for animals and forbs
- Provide windbreak
- Help decrease wind and water erosion
- Increased nutrient cycling
- Provide additional nutrients (nitrogen fixing species)
- Counter surface soil compaction
- Increase landscape diversity.

Dunn et al. (1999), in considering the Western Australian situation again, suggested greater water resource capture was essential to solving environmental water leakage. They reported that lucerne in rotation with wheat crops helped through summer uptake from a rooting depth double that of wheat. However, they caution that ‘too much water use too quickly can jeopardise persistence’ and note the case of blue gum plantations in south Western Australia where ‘loss of growth rate midterm in the rotation and ultimate death of the plantation is common’, due to the need for carryover of soil water to maintain root infrastructure.

Resource partitioning in plants may change when they are grown in polycultures where greater percentages of total dry matter and nutrients are allocated to harvestable portions of crops. In this case, each unit of captured energy and nutrients results in a greater benefit to the farmer in polycultures than monocultures. For example, in arid Africa, pigeon pea grown in monoculture produces 19% of its total above ground weight as edible seed, but 32% when grown in mixtures with sorghum. Indeed, African researchers have found that increases in allocation ratios for sorghum, millet, and groundnut that occurred when they grew in polycultures were most marked under drought conditions (Willey 1985). These phenomena are likely explained by the typical stress response of many plants to divert resources to reproduction as a response to competitive or environmental pressure.

Experimental evidence shows that plant interactions below ground are normally more intense than those above ground and competition may limit uptake. According to Snaydon and Harris (1981) ‘nutrients often occur in specific zones of the soil due to particular environmental conditions (ie. leaching), management practices (ie. surface applied phosphates), or nutrient solubility.’ Parallel to these differences, and often partially in response to them, there are differences in root distribution patterns between plants and throughout the soil profile. Roots can also use soil resources differently:

- In the way that the nutrient requirement is satisfied (legumes use N₂, non-legumes use NO₃⁻ or NH₄⁺)
- Different species may differ in their requirement for a resource. There are fourfold differences between species for calcium concentration, twofold for potassium and phosphate and threefold differences for nitrogen concentration.

Schroth (1999) noted the inherent conflict in agroforestry between expected favourable effects of tree root systems (soil fertility and nutrient cycling) and competition between tree and root crops and suggest a range of management techniques to optimise root functions and stimulate facilitative and complementary interactions. Substantial research on below ground interactions has only recently been addressed (see also Auclair & Dupraz 1999). Ultimately, the knowledge of the ecological principles of plant growth can benefit polyculture production design and implementation. Kropff and Goudriaan (1994) offer this summary:
Intercropping systems can have several advantages over monoculture systems, of which the potential higher efficiency of resource use is the most important. The complexity of relationships between morphological and physiological characteristics and competitive ability of plants and mixtures has been recognised. Eco-physiological models for interplant competition for the resources—light, water and nutrients—can be used as a tool to study these complex relationships. These models are based on the assumption that competition is a dynamic process which can be understood from the distribution of the limiting resources between the competing neighbouring plants and the efficiency with which each plant uses the resources captured. Eco-physiological models may help to optimise cropping systems and to suggest optimum plant densities, planting dates, cultivar combinations, crop management practices, seeding rates, etc.
6. Pest Management

This section covers the theories and mechanisms of pest management in polycultures. Pests are taken to include insects, weeds, disease organisms (bacterial, fungal, and viral) and to a lesser degree, internal plant produced chemicals that affect its neighbours, higher order animal pests and the predators and parasites of crop pests. Accepting that observations of traditional polycultures showed increased yield and yield stability, are there phenomena beyond resource capture, compensation, resource partitioning, and complementarity in plant and environment interactions that explain this advantage? Perrin (1977) thought that changes in pest and disease incidence and their dispersion through the growing crop(s) may sometimes be of paramount importance because of the ways in which insect behaviour and population dynamics are modified by the nature of the cropping system. The earliest anthropological observations of traditional polycultures gave little attention to pests, an area outside their expertise. Agronomic and ecological studies since the 1950s have similarly lacked serious attention of pest experts, especially entomologists (see Perrin 1977). Pickett (1949) reviewed insect control and concluded generally that ‘a high variety of plants make it possible to raise fruit without pesticides, because a large enough resident population of parasitic and predacious insects can be supported by the large variety of plant species present to ensure control of any pest that might build up’. This speculation arose from the developing field of ecology.

It is important to realise that agricultural pests are not entirely new organisms, somehow a product of the practice of agriculture. Pests of all forms have always been competitors with humans for food products, even pre-agricultural. Just about every known agricultural pest has a natural occurrence where it does best in a particular niche, is adapted to certain prey/hosts and environments and is regulated within that system by an array of natural population regulation within that system by internal and external natural population regulation mechanisms (see Gliessman 1995). Pests become defined as such when they no longer are subject to their natural regulatory mechanisms and they increase in numbers causing economic or nutritional loss to the agriculturalist.

6.1 Polyculture insect pest dynamics

In response to insect problems in agriculture, ecologists began to look at the natural regulation of insects as pests. Pimental et al. (1961) were some of the earliest ecologists to experimentally establish the relationship between species diversity and complexity of association among species as being essential to the stability and balance of the community system. They concluded that species diversity plays an important role in preventing population outbreaks, in this case being insect pests of brassicas.

This idea defined much of the subsequent research on pests in polyculture, primarily from the premise that if polycultures are more diverse than monocultures; they will retain more of the natural pest regulation dynamics of natural systems. In arguing for increased attention by entomologists in understanding and improving multiple cropping systems, Perrin (1977) produced an early taxonomy of the possible and observed effects of multiple cropping on pest population dynamics. He agreed with Huffaker (1962) that the spatial dispersion of resources is a major factor in insect population dynamics. Perrin believed that the number and distribution of host plants is critical to the potential insect pest in four areas: the colonisation of the crop, the development of the pest population, the dispersal and further spread of the pest as well as the abundance of natural enemies. With regard to colonisation, the overriding point is that insects (and indeed, other pests) find their host or prey by the means of some stimulus, usually visual, olfactory or even electromagnetic infrared waves (see Callahan 1975). When the crop is common or prominent, the insect is more likely to recognise it through these stimuli and effectively colonise. Researchers cited in Perrin (1977) reported that crop density, background colour, degree of camouflage by other crop components and patchiness of the host plants were all known to influence visual stimuli receipt by insects.
Similarly, olfactory stimuli can be better dispersed in multiple species plantings as opposed to monocultures, reducing the efficiency of host identification. This can be either through making it difficult to detect the host plant or through a disturbance or repellent effect by component crops, a concept promoted by adherents of companion planting in gardening (see Chapman et al. 1986). However, when the insect is polyphagous, or capable of surviving on many plants as opposed to monophagous (specialised on one plant species) the multiple cropping of similar species could increase pest colonisation. Pest colonisation can also be affected by the presence of alternate or diversionary hosts that act as a trap crop, protecting other more susceptible or economically valuable crop components. Once a pest has colonised its host, multiple cropping systems can affect the way it feeds, mates or develops. Confusing olfactory or visual stimuli received from host and non-host may disrupt normal feeding or mating behaviour. If the insects manage reproduction, multiple cropping systems can affect their dispersal, especially for relatively immobile soil inhabiting pests that depend on plant to plant colonisation. If the pests cannot find new hosts, they are unlikely to remain pests.

The spatial effect of multiple cropping on pest numbers was the initial attempt at explanation by ecologists who later added more temporal and dynamic considerations. Perrin (1977) only established the idea that the more diverse environment created by multiple cropping could increase the number or diversity of the natural enemies of the pest. Later, Perrin (1980) advanced his points to include temporal as well as spatial diversity as mechanisms reducing pest insect numbers in polycultures. He reported that irrigation of alternate season crops could provide habitat for pests of later crops, that synchronisation of planting and harvesting resulted in even-aged stands more prone to rapid pest build-up and the role of long lived perennials in stabilising the cropping system in terms of the persistence of natural enemy/pest interactions. These early studies of pest incidence in polycultures often contained contradictory conclusions, showing a lack of sufficient theoretical construct and the wide range of species-specific interactions that could yield different results.

One of the first theories suggested by ecologists was by Root (1973) who put forward the proposition of the Resource Concentration Hypothesis which states that herbivorous pests are more likely to find and remain on hosts that are growing in dense or nearly pure stands, as in monocultures. His observation was that the spatial concentration of hosts was more important than the relative abundance of predators in controlling pest numbers, the premise behind his alternate; the Enemies Hypothesis. Root maintained that where the crop had specialised predators as well as pests specialising on the crop, both could increase rapidly. Root’s hypotheses were tested experimentally (as discussed theoretically in Cromartie 1981) by Risch (1981) in his PhD work in corn-bean-squash agroecosystems in Costa Rica and six beetle pests associated with these crops in monoculture and polyculture. Risch justified his study on the basis that ‘practical issues of agroecosystem design and more theoretical questions of plant-herbivore coevolution depend on knowing what ecological processes create reduced herbivore (pest) loads in polycultures’. His conclusion was that in this case, the resource concentration hypothesis could explain the differences in beetle abundance and that manipulations of plot characteristics such as species composition and distribution, and size and shape of the plot, could result in predictable alterations of pest abundance.

On the basis of an extensive literature review for his PhD dissertation, Andow (1983) looked wider at the question of pests in monoculture and polyculture. In his review of 17 studies of cotton, Andow found increased monoculture led to increases in 13 of the pest populations and a decrease in two. However, Andow concluded that it was not only related to the practice of monoculture but also the characteristics of the insect populations: voltinism (frequency of brood production), host range, vagility (inherent power of movement) and host finding ability. Reporting on the full literature of about 150 studies in which an effect of diversifying an agroecosystem had been observed on insect behaviour, Andow (1983b; Risch et al. 1983) noted that of 198 total herbivore species examined; 53% of the species were found to be less abundant in the more diversified system, 18% were more abundant in the diversified system, 9% showed
no difference and 20% showed a variable response. He also favoured the resource concentration hypothesis as the most appropriate theory. Andow (1983b) concluded that there were four main lines of evidence supporting the concept that insect populations should be lower in diversified agricultural systems:

1. Arising from biological control investigations of the early 1900s, the observation of increased mortality of pests by their natural enemies and the support (pollen, nectar, food) offered to the predators by a diverse local plant environment.
2. From observing traditional intercropping systems, limited conclusions supported the theory that monophagous (eating a single crop) herbivore pests decrease in intercropped systems while polyphagous pests (eating many crops) may increase.
3. Observations of forest trees in plantations and native forests showed pest outbreaks in the plantations while the same trees were not attacked to the same degree in mixed forests. The idea is one of the natural balances of natural mixed vegetation limiting pest outbreaks.
4. As ecological theory developed in the early 20th century, researchers postulated, and later proved, that natural enemies regulate the population density of their prey (crop pests), thus any disturbance from the trophic structure that decreases the intrinsic rate of increase of the predator population would lead to outbreaks of the pest prey. Also, ecologists showed that the spatial pattern of plant resources were as important in affecting herbivore populations as their enemies were i.e. when plants are more spread out they are attacked less. Furthermore, it was found that the movement and reproductive behaviour of the pests themselves rather than differential mortality by enemies, was affected by the diverse habitats where host plants were more distant, diffuse, or had side effects on the pest insect.

Risch et al. (1983) concluded that while plant diversification of agroecosystems frequently lowers pest populations, the underlying ecological mechanisms were not always known, and the actual benefit to the farmer often not quantified. They did say that the empirical and theoretical work suggested that herbivore movement patterns were more important than the activities of natural enemies in explaining the reduction of monophagous test populations in diverse annual systems, favouring the resource concentration hypothesis.

Table 12: Theories of Plant-Pest Interactions

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<thead>
<tr>
<th>Resource concentration hypothesis</th>
<th>Enemies hypothesis</th>
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<tr>
<td>The resource concentration hypothesis concerns the movement and reproductive behaviour of the pest insects themselves. Visual and chemical stimuli from host and non-host plants affect both the rate at which insects colonise habitats and their behaviour in those habitats. The total strength of the attractive stimuli for any particular pest insect determines what is called ‘resource concentration’ and it is the result of the following interacting factors: the number of host plant species present and the relative preference of the insects for each, absolute density and spatial arrangement of each host species, and interference effects from non-host plants. The lower the relative resource concentration, the more difficulty a pest insect will have in locating a host plant. Relative resource concentration also influences a probability that a pest insect will leave a habitat once it has arrived. For instance, a pest may tend to fly sooner or farther after landing on a non-host plant than a host plant, which results in the higher emigration rate from polycultures than monocultures.</td>
<td>The enemies hypothesis predicts greater numbers of insect predators and parasites in polycultures than in monocultures, which in turn better control pest populations. Polycultures supply better conditions for predators and parasites, reducing the likelihood that they will leave or become locally extinct. These conditions include: greater temporal and spatial distribution of nectar and pollen sources, both of which attract natural enemies and increase their reproductive potential; increased ground cover, which is especially important to some nocturnal insect predators; and more species of herbivorous insects that provide alternate prey when other prey are scarce or at inappropriate stages of their life cycles.</td>
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(Adapted from Risch 1983)
Ogol, Spence and Keddie (1999) studied the effect of the resource concentration theory on maize stem borers in Kenya and found that while the damage was significantly lower in the intercrop (with leucaena) the primary mechanism was the reduced yield loss per plant. In their best result with maize between 3 meter leucaena rows, yield was higher than the monocrop despite 25% fewer maize plants. Thus there is a complex interplay between insect response to resource concentration, crop response to both intercrop and pest damage, and economic yield through compensation.

Using Andow’s 1983 data, Altieri et al. (1990) used pest density instead of pest numbers to confirm the general premise that increased vegetational diversity fosters stability in the insect community. In a review of 617 studies it was noted that population densities of 66% of monophagous (specialised feeding on one species) herbivore insects decreased in the diversified system when compared with the corresponding monocultures. This was confirmed in evaluating flea beetles and aphid attacks of collards (brassicas) and showed that cultivated monocultures had the most damage and weedy polycultures with beans the least. Mechanisms suggested are both resource concentration in the former and increased predator abundance in the latter. Altieri and Liebman (1986) persisted in the observation that ‘vegetational diversity often results in significant reduction of insect pest populations’ but stressed that generalisations and recommendations would be difficult for yet untried systems. At this time, they felt that research had disproportionately focussed on insect dynamics with little attention to the effects of multiple cropping systems on disease epidemiology, and especially weed ecology, and suggested that integrated research was ‘sorely lacking’ in covering the simultaneous effects of polycultures on all biotic components of the agroecosystem. Their article was the first to address insect, disease and weed interactions and concluded that both the enemies and resource concentration theories were sound. Liebman (1995) later used review data of Andow’s and noted that in 209 published field studies, 53% of the predator and parasitoid species that act as natural enemies of crop pests were more abundant, 13% showed no difference and 26% showed a variable response in polycultures. He thus concluded that ‘use of polyculture production systems may increase the importance of predators and parasitoids as natural controls of populations of insect pests’, illustrating the growing acceptance of the functional interactions implied by the enemies hypothesis.

Altieri and Schmidt (1986) looked at the comparison of abandoned, organic and conventionally sprayed apple orchards in California and found significantly more aphids and leaf hopper pests in the sprayed orchard and higher immigration from adjacent woodland. As orchard management increased through tillage or frequent slashing, their numbers increased. They found that more natural enemies and less herbivore pests invaded organic orchards than sprayed orchards. This seems to indicate the interplay between the two theories and the point that they can both be operating at the same time: the uniform, simple sprayed orchard growth attracting pests under the resource concentration hypothesis and the higher abundance of enemies in the more vegetationally complex organic orchard. Kemp and Barrett (1989) found that in modern Ohio soybean production, uncultivated corridors in soybean fields supported increased predators and fungal pathogens of green clover worm, a soybean pest, thus favouring the enemies hypothesis. As early as 1961, Leius suggested that ‘the fecundity and longevity of certain parasites of crop pests depend on whether they have fed on certain wild flowers.’ Where invasive weeds are used to support predators, there is concern for weeds in the crop. However, Smith et al. (1999) found that the management of uncropped arable field edges to enhance biodiversity is unlikely to affect weed levels within the crop, less a problem than in herbicide managed field edges (non-invasive perennials used).

While most of the research into the mechanisms of reduced pest problems in polycultures has focussed on annual cropping patterns, Stamps and Linit (1998) observed that in temperate agrisilviculture alley cropping, insect diversity had generally increased in polycultures over monocultures. They felt that agroforestry ‘holds promise for increasing insect diversity and reducing pest problems because the combination of trees and crops provides greater niche diversity and complexity in both time and space than does polyculture of annual crops.’ Existing ecological theories based on observations of natural
systems would support this proposition. Even in conventional monocultures, Teetes (1981) thought that planting time and plant spacing could be varied as ‘part of an IPM strategy. Planting times can be changed to 1) avoid the pest, 2) synchronise insect pests with their natural enemies, 3) synchronise crop production with climatic conditions which adversely affect the pest, 4) synchronise crop production with available preferred alternate hosts of the pest, and 5) produce and destroy the crop before the insect can mature.’ These ideas can be used in intercropping as well. The principle is the temporal separation of pest and crop or the creation of biotic or abiotic factors detrimental to pests.

6.2 Disease management in polycultures

While the majority of pest-related research concerning polycultures has been on insect pests, some information exists for diseases, mostly plant related. Organisms that cause what agriculturalists call disease are pre-existing and normal components of natural systems and are seen to be causing disease when they increase in extent and subsequently impact on crops. Diseases are usually fungal or bacterial; it is accepted that fungal and bacterial interactions with plants occur that are both beneficial and detrimental to the producer’s goals.

Like plant and insect interactions, the dynamic of polycultures differ from that of monoculture disease incidence because of the temporal, spatial and species diversity of polycultures. Altieri et al. (1983b) believed that generally, polycultures buffer against disease losses by ‘delaying the onset of the disease, reducing spore dissemination or modifying micro-environmental conditions such as light, humidity, temperature and air movement’ and noted that ‘certain associated plants can function as repellents, antifeedants, growth promoters or toxicants, or enhance soil fungistasis and antibiosis that assist in controlling disease outbreaks.’ Altieri and Liebman (1986) added that below ground processes were much less well known and that component crops can also physically obstruct disease carrying insects that might affect the other crops.

Mixtures/Multilines

The bulk of the literature found on disease management benefits in polycultures was found for cereal grains. In the early 1950s, agronomists noticed increasing disease problems in serial cereal- the frequent or sequential monocropping of temperate cereal grains. Researchers had noticed the value of mixtures of different grains in their crop heterogeneity for disease control- an aspect of intra-crop diversity, or genetic diversity within the crop plants either inter or intra species. These crops in culture came to be termed mixtures or multilines.

<table>
<thead>
<tr>
<th>Table 13: Contrast Between Mixtures and Multilines</th>
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<tbody>
<tr>
<td><strong>Mixture</strong></td>
</tr>
<tr>
<td>(Crop mixture)</td>
</tr>
<tr>
<td>A heterogeneous crop of a single species (ie. different varieties of wheat)</td>
</tr>
<tr>
<td>(Species mixture)</td>
</tr>
<tr>
<td>A heterogeneous crop of more than one species (ie. oat-barley)</td>
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</tbody>
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Modified from Barrett (1982)

To further define multilines, Barrett says that a number of major genes are backcrossed into the same recurrent parent. After about eight generations of backcrossing, a series of lines is produced, each carrying a different resistance gene but identical in all other respects. This is intra-specific genetic diversity for disease resistance. Perrin (1980) observed that in their early development, multi-line cultivars were generally mechanical mixtures of individual lines with uniform genetic background, but with resistance to different disease races. The multi-line concept is now extended beyond the mixing of...
race-specific resistant lines to the mixing of resistant cultivars with different genetic backgrounds and of resistant and susceptible cultivars.

Barrett (1982) reported that field trials of early multilines provided consistent reductions on disease incidence of 50-70% over the mean of the components grown as pure stands and that the typical yield increases of 6-10% were about equal to the gains made by the introduction of fungicides. There is a longer term view to appreciate as well. Cromartie (1981) argued that planting ‘multiple varieties of a single crop bred for different lines of resistance to pests or disease is a way to both reduce the risk of damage in the short term and to minimise the probability that pests will evolve to overcome the plant’s resistance.’ Wolfe (1985) provided an excellent summary of mixture benefits including higher yield, income stability, adaptability to variable environments, disease resistance, reduced pest adaption, and suggested that three principle mechanisms were responsible for their success in disease control:

1. The decrease in the spatial density of susceptible plants.
2. The barrier effect provided by resistant plants (the flypaper effect).
3. Induced resistance, where non-pathogenic spores out-compete normally pathogenic spores for colonisation sites or growth factors.

While multilines are clearly technologically intensive, mixtures have a long traditional history. Stinner and Blair (1990) reported that ‘in the Middle East, multiple cropping with several cultigens or landraces of cereals is still relatively common’ and that ‘today in Syria, farmers often sow several varieties of wheat in the same field and harvest them together with a difficult to separate grassy weed seed for livestock feed.’ As an interesting aside, Wolfe (1985) noted that multilines cannot be registered for plant patents. Zhu et al. (2000) reported on disease control in rice through crop heterogeneity as genetically diversified rice crops planted at a landscape scale in Yunnan China. Rice blast fungus susceptible rice varieties had 89% greater yield and blast was 94% less severe than when the varieties were grown in monoculture. No fungicides were needed after year two due to 1) increased distances between plant genotypes, 2) poor environmental conditions for rust and 3) possible induced resistance due to greater diversity of pathogen populations in mixtures.

Other Disease/Polyculture Interactions
Schippers et al. (1987) concluded that in Dutch potatoes, considerable retardation of plant growth and decreased crop yield resulted from the deleterious activity of saprophytic rhizosphere microorganisms. ‘This activity increases with cropping practices such as growing the same crop frequently in the same field.’ In Thurston’s (1997) book on slash/mulch systems, he noted that both mulches and ground level intercrops could reduce the incidence and severity of soil-borne plant pathogens and their root diseases. Organic matter on the soil surface functions as a physical barrier preventing splashing of infected soil onto plant tissues. Rain splash is the second most important natural agent, after wind, in the dispersal of plant pathogenic fungi. Organic matter layers can also prevent direct contact of the foliage, fruit or vines with the soil and thus prevent diseases transmitted from the soil. When organic matter decomposes, phytotoxic or fungitoxic exudates can suppress fungi. When higher organic matter levels encourage more microbial diversity, micro organisms antagonistic to pathogens can help control disease and can compete with them for nutrients. Altieri and Liebman (1986) provided an extensive review of the effects of multiple cropping on plant diseases, noting the important interplay of insect vectors with fungal or viral diseases and how both were less successful in polycultures. They added that the microclimate modifications in polycultures could increase relative humidity and fungal infection but suggest wider plant spacing as the answer. Similarly, Liebman (1995) reported on how vining peas, when grown with grains where they climb the cereal stalks, are less infected with several diseases than when matted at ground level. He speculated that there may also be a facilitative below ground interaction in some polycultures where excretions from or microbes on the roots of one crop species may affect soil disease organisms that attack roots of an associated crop species.
6.3 Weed management in polycultures: Shade, competition and alleopathy

Like other pests, weeds become a problem when they increase in number or size to the detriment of the crop. Until then, the general conclusion is that weeds are beneficial for organic matter contribution, feed for beneficial insects, habitat for predators or parasites of crop insect pests, and general structural complexity in the system. Many farmers might agree with Altici et al. (1983) that most weed species are stimulated by the regular soil disturbances in (annual) monocultures. Polycultures, especially perennial, utilise far less soil disturbance, use canopy closure to shade weeds and use physical and chemical competition among root systems to reduce weed loads.

Liebman and Dyck (1993), in an extensive literature survey, indicated that weed population density and biomass production may be markedly reduced using crop rotation (temporal diversification) and intercropping (spatial diversification). In intercropping systems where the main crop was interplanted with ‘smother’ type associated crop species, weed biomass was lower in 47 cases, higher in 4 cases and variable in 3 cases (compared to monoculture sole crop). When intercrops were composed of two or more main crops, weed biomass in the intercrop was lower than in all of the component sole crops in 12 cases, intermediate between component sole crops in 10 cases and higher than all sole crops in 2 cases. Intercrops may demonstrate weed control advantages over sole crops in two ways. First, greater crop yield and less weed growth may be achieved if intercrops are more effective than sole crops in usurping resources from weeds or by suppressing weed growth through alleopathy. Alternatively, intercrops may provide yield advantages without suppressing weed growth if intercrops use resources that are not exploitable by weeds or convert resources to harvestable material more efficiently than sole crops.

Alleopathy is worth exploring further. Alleopathic interactions can occur between weeds, between weeds and crops, or between crops. Alleopathy is different from other interspecies competition in that the detrimental effect is not through direct competition for nutrients or space but is exerted through release of a chemical by one component. Putnam and Duke (1978) defined alleopathy as the detrimental effect of higher plants of one species on the germination, growth or development of plants of another species. Einhellig and Leather (1988) defined alleopathy simply as biochemical interactions between plants and noted that the effect can be negative or positive, include both avoidance and application protocols and have application in weed control, crop stimulation, or breeding plants for increased production of alleochemicals. They thought that both plants and micro organisms should be considered as sources and recipients of chemicals that may modify their growth, development and distribution and that plant to plant effects can occur within weeds, within crops and between crops and weeds.

Typically, these alleochemicals cycle through the soil matrix and their impact on a crop is through root contact. Alleochemicals are secondary compounds synthesised by plants and micro organisms and include phenolic compounds, coumarins, tannins, terepenoids, alkaloids, steroids and quinones. They are the result of the co-evolutionary dance between pest and host or between competing plants that result in chemical warfare so that plants can compete more successfully, dissuade feeding, colonise more freely or guarantee dispersal. Various mechanisms control the release of alleochemicals by:

- exudation of volatile chemicals from living plant parts
- leaching of soluble toxins from above ground parts through rain, fog, or dew
- exudation of water soluble toxins from below ground parts, or
- release of toxins from non-living plant parts through leaching of litter sloughed root cells, or as microbial by-products resulting from litter decomposition.

In crop production, it appears the release of toxins from plant litter or in the soil is the most important mechanism. Alleochemicals can play a useful role in cropping systems through capitalising on their functions (against insects) as repellents, anti-feedants, growth disrupters, toxicants or for diseases; fungistasis, and antibiosis against weeds by inhibiting germination, propagule development or plant growth.
Many plants produce alleopathic chemicals that allow them to out compete other weeds or crop plants. Indeed, many crops produce alleopathic chemicals. Barnes and Putnam (1983) reported that for pea growing in temperate climates, rye grain is often used as a fallow season green manure crop, largely for cover and organic matter benefits. “Spring planted living rye (to be chemically killed for a main season crop under a no-till strategy) reduced weed biomass by 94% over plots without rye.” Residues of fall planted, spring killed rye reduced weed biomass over bare ground controls. In greenhouse studies, rye root leachates reduced tomato dry weight by 25-30%, further indicating the alleopathic properties of rye and its utility as an alleopathic cover crop, tilled or chemically killed. Of course, care must be taken that the appropriate cover crop is alleopathic to the problem weeds and not to the following crop. In this case, the rye residues appear to suppress total weed growth, but not weed germination, or the growth and yield of the peas.

Gliessman (1986), in studying maize/bean/squash polycultures in Mexico, found that water extracts of air-dried squash leaves demonstrated a strong alleopathic potential. Local farmers stated that they largely plant squash in the polyculture for weed control and that the harvest of any fruit was an added bonus. The weed control derives from both shade and phytotoxicity. Amador and Gliessman (1990) concluded that for Mexican corn/bean/squash polycultures, the use of squash significantly reduces weeding time compared to monocultures due to shading and leaf run-off exudate. Einhellig and Leather’s (1988) four year study of cultivated sunflower, a known alleopathic crop, found no differences in weed biomass between plots with and without herbicide (EPTC) applications. Not only can crop alleochemicals affect other crops and weeds, but they can be autotoxic as in pigeon pea, lucerne and red clover. Many of these interactions can occur with plant residues as well as during the life of the plant. An important point is that these natural defensive or offensive compounds have generally been reduced, or at least not selected for, in modern plant breeding and that polyculturalists will do well to test a wide range of crop accessions where or if those alleopathic actions are available.

Unlike polyculture principles that seem to apply more to traditional gardens than modern farming, alleopathy has immediate application even in industrial monocultures as per the sunflower example above. For example, oats are known to be alleopathic. Lanini et al. (1992) found that during lucerne stand establishment, an oat companion crop, seeded either in rows or broadcast together, helped fight weeds and increased first-cut forage yield without negative impacts on lucerne production (at appropriate density). It proved economical and an effective alternative to chemical weed control in seedling lucerne. Oat replaces weeds in the first cutting and total forage yields were increased. The goal is to optimise planting so that crops perform in concert and pre-empt resources that might go to weeds. Similarly, Cheema et al. (2000) reported in the utility of a practice of spraying an alleopathic water extract of mature sorghum and as surface or incorporated mulch on weed control in irrigated wheat in India. Weed control was 35-50% higher and yield increased 10-21%. The most effective treatment of two foliar sprays at 30 and 60 days from planting produced an incredible marginal rate of return of 535%. This practice could be done by any Australian farmer.

Polycultures can have a range of effects on weeds beyond alleopathy. Liebman (1995) catalogued numerous mechanisms that resulted in fewer weeds, higher yield, fertility enhancement and favourable environmental impact. This is through elimination of herbicides or hand weeding, earlier and fuller canopy, erosion protection from heavy rain or running water or through a general theory of greater preventative use of resources that are then not available for weed growth. Some research questions the basic agronomic position that all weeds should be eliminated. In a study of intercropped wheat and beans in England, Bulson (1994) found that while both intercrops, either spring or winter cropped, produced higher yields and suppressed weeds, total removal of weeds did not significantly increase the yield of either intercrops or sole crops.
7. Design Principles and Polyculture Component Characteristics

In the last 20 years, researchers concluded that by studying ecological rules of natural communities and traditional polycultures, the characteristics of successful designs for new polycultures should become evident. As early as 1975, Trenbath observed that ‘complex traditional polycultures have many of the characteristics of natural plant communities: i.e. stands of individuals of uneven age or size and a wide range of species in growth habits.’ McKinnon (1976) believed that the ‘design of a farming system that is adapted, like a natural ecological community, is the first most basic objective of the farmer as designer.’ As ecologists began to articulate more explanations from natural system observations and contributed to understanding the mechanisms behind successful traditional polycultures, a substantive and recurring design principle emerged: design from nature. Altieri et al. (1983) concluded that the pre-existing natural vegetation pattern should be used as the model for agricultural systems and also (1983b) articulated the idea that ‘the natural vegetation of an ecosystem can be used as an architectural and botanical model for designing and structuring any agroecosystem to replace it’. This is an agroecosystem that ‘mimics the structure and function of natural successional ecosystems.’

Crossley et al. (1984) agreed that ‘successful agroecosystems will retain the functional properties of the natural ecosystems such as nutrient conservation mechanisms, energy storage, use and utilisation patterns, and regulation of biotic diversity.’ Hart (1986) further suggested that ‘basic ecological principles relating to population interactions should be useful as an organising framework for agronomic research on multiple cropping systems.’ In reviewing planting patterns of traditional polycultures, Baker and Francis (1986) noted for traditional polycultures that the complex patterns ‘show an amazing similarity to the natural ecosystem of the area. The diversity of species under different growth cycles mimic the natural system and take advantage of some of the same types of biological structuring and buffering that occur in the natural systems.’ Stinner and Blair (1990) considered that ‘sustainable and innovative systems should be based on ecological principles.’ Van Mansvelt (1995) thought that especially for low-input agricultures, they should ‘rely more strongly on and adapt more strongly to the local conditions of nature.’ Van Noordwijk and Ong (1999) hypothesised that there would be ‘clear advantages if man-made land use systems do not deviate greatly in their resource patterns from natural ecosystems typical of a given climatic zone’ and that ‘additional advantages would accrue if agroecosystems also maintained a substantial part of the diversity of natural systems.’

A substantial collection of papers (see Lefroy et al. 1999) explored the concept of ecosystem mimics for Western Australian agriculture to arrest significant environmental impacts of industrial practices. Their approach was more based on recognition of the existing biophysical conditions and less so on the structural and functional dynamics of the pre-existing native vegetation that maintained those conditions. They established several emerging themes or design guidelines:

1. What to mimic and why? To understand the processes occurring in natural ecosystems for improving the sustainability of agriculture.
2. Synchronising sources and sinks of water and nutrients in time and space.
3. Perennial plants in polyculture will likely be the base of successful mimics.
4. There are trade-offs between persistence and productivity, as more energy and biomass is invested in supportive infrastructure.
5. Diversity is used most often for risk reduction, but needs higher management.
6. That an evolving, adaptive management regime is required.

Ewel (1999) added some conclusions about the role of ecosystem mimicry for agricultural restoration. He suggested it is far easier to mimic specific ecosystem processes than to try to replicate all the complexity of nature if there is not a natural ecosystem or successful traditional polyculture model to emulate. He
thought it important to reduce nutrient inputs and be prepared to accept lesser, but biologically sustainable, yields, noting that the bulk of a perennial polyculture biomass is what sustains the ‘protective structure of the ecosystem’ and is a benefit not harvested as a saleable commodity (but potentially valued as equity and capital increase).

7.1 Ecological approaches to design principles

In 1997 in a workshop involving agriculturalists and ecologists, key steps were developed to undertake this process of designing with nature. In a germinal RIRDC workshop report, Lefroy and Hobbs (1998) suggested that:

Natural ecosystems can serve as models from which we can develop sustainable agricultural systems in those environments. 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 for sustainable production.

As an example of using natural systems and processes to discern the nature and design of polycultures, it is useful to look at the work of the Land Institute (see Jackson 1980; Soule & Piper 1992; Wilson 1993). Natural system agricultures, a term coined by Wes Jackson of the Land Institute, Salina Kansas, are being developed for the North American prairie ecosystem. He aims to develop ecological assemblies of edible seed perennial polycultures featuring the four major guilds or functional units represented in native prairies and in roughly the same proportions. By exploring natural community assembly rules, persistent complex mixtures of plants can be achieved through successive addition and loss of species. Jackson believes the application of a number of key design principles are required to succeed in establishing sustainable land use:

1. human[s] should farm like forests
2. use native perennial plants
3. encourage the biological processes to take over to remove the need for fossil fuel base
4. look to the previous natural vegetation and a landscape function and structure in trying to mimic those natural ecosystems
5. it is more important to be working on the problem of agriculture rather than problems in agriculture.

In another effort by Gliessman et al. (1981) the process of analogue farming is presented, where the polyculture mimics the natural vegetation. These authors used 5-15 hectare module production units in Mexico to replicate the characteristics of traditional shifting cultivation to once again achieve the diversity and stability of their productivity. A perimeter forest shelterbelt was used for windbreak, a source of natural predators and parasites for biological control, wood materials, and natural biodiversity preservation-mimicking natural forest succession and regeneration in the region. Within this was the production area combining aquaculture, raised bed (chinampas) and intensive annual and perennial cropping areas. This approach is a mimic of traditional slash and burn using the ecological processes of the region: high species diversity, highly heterogeneous environments, high structural diversity, high biomass accumulation relative to harvested output, and no chemical insecticides or fungicides. Recently, in a report from the land use committee of the Ecological Society of America, Dale et al. (2000) identified five principles of ecological science that have implications for land use and eight guidelines for land use decision making. Of particular note is the last: ‘Implement land use and management practices that are compatible with the natural potential of the area.’

7.2 Polyculture component crop characteristics

If such efforts are pervasive and successful, modern agriculture may come through its monoculture bottleneck and out the other end with a truly sustainable agriculture. As Sanchez (1995) noted, ‘the complex human-planted agroforests in Indonesia are perhaps the epitome of sustainability, with biodiversity levels approaching the levels of the original rainforest they replaced’ as well as high
harvestable productivity. In order to farm in nature’s image (to borrow Soule and Piper’s book title), the nature and characteristics of polyculture suitable crops will need exploration, keeping in mind that the existing ecosystem and nature of the site and climate are known and considered in this design effort. Early researchers had less ecological knowledge to work with and had a simple recommendation for the likely characteristics of potential polyculture components. Francis (1976) suggested that they needed to have photoperiod insensitivity, early maturity, short and non-lodging plant forms and population responsiveness. In considering light interception, Trenbath (1981) suggested a general design principle for choosing intercrop partners: intercrops should consist of a) an upper canopy of small, steeply inclined leaves with high maximum rates of leaf photosynthesis and b) a lower canopy of more horizontal leaves, arranged possibly in mosaics, with low maximum rates of leaf photosynthesis. Some examples would be maize over sweet potato or beans.

As ecologists and agronomists increasingly interacted over the mechanism of polyculture yield advantage, Vandermeer (1981) noticed that ‘the abstract conditions necessary for polyculture overyielding (LER>1) are identical to those for species coexistence in natural systems.’ Soon, more specific recommendations arose, as in Rao (1986) who recommended that when cereals are intercropped, as opposed to the more common sequential cropping, the most useful approach is to intercrop cereals with longer cycle annuals or perennials, using the first period of time to grow and harvest grain while the slower crops (pigeon pea, cassava, cotton) grow. This temporal offsetting of resource needs leads to high LERs (up to 2.00). Another option is widely practiced- the intercropping of cereals with low canopy legumes. Both summer and winter cereals are intercropped with a variety of appropriate legumes. In this case, it is the spatial and temporal differences that generate the complementarity and yield advantage, in addition to nitrogen fixation by the legumes.

Trenbath (1986) had more detailed suggestions:

1. As a guideline for choosing intercrop components where intercrops are to be grown on stored resources, components should be chosen so that earlier uptake of water and nutrients in the upper layers of the profile by one component should not be so efficient as to suppress the growth of later developing root systems of other components that are potentially more effective exploiters of the lower layers.

2. Where an intercrop is two-layered, the highest LER, based on net photosynthesis rate will probably come from combinations of a taller component having higher photosynthetic capacity and steeply inclined leaves with a shorter component having lower photosynthetic capacity in more prostrate leaves (ie. corn/beans/squash).

3. Methodologically, farmers and scientists should use process-oriented models of resource dynamics to aid understanding.

As the dynamic and functional processes became better known, this complemented the structural suggestions. Hart (1986) added that ‘for agroforestry, we need to incorporate ecological succession’ and ‘an agroecosystem is designed or managed to parallel or mimic natural ecosystem development.’ Specifically, Hart suggested planting annual, rapidly growing species, followed by woody longer-lived species, then large trees. Francis and Clegg (1990) thought the efficient transfer of energy and growth factors among crops and niches (‘functional integration’) within the system was necessary in order to maintain sustained yields, a term also known as ‘biological structuring’. De Clerck and Negreiros-Castillo (2000) added that by identifying natural succession models from the natural ecosystem, they could use plant species from traditional Mayan home gardens to design larger long-term successional agroforests to replace or enhance fallow periods in slash and burn practices, thus supporting producer income, biodiversity, and forest resources.

Stinner and Blair (1990) echoed the role of processes and concluded that ‘traits such as resource use efficiency, competitiveness, shading tolerance, and plant architecture are important considerations in developing varieties for intercropped agroecosystems.’ It is worth noting that perennial pasture differs
from polyculture grain systems where harvest periods must be different for mechanical harvest unless they are easily separated. For forestry situations, Lamb (1997) thought that timber plantations could be used to restore degraded tropical forestlands. Much of the former biodiversity could be restored by reassessing the design of the current plantation programs and applying the following strategies:

- Use of native species instead of exotic species.
- Embedding these plantation monocultures in the matrix of intact or restored forest.
- Use of several species in creation of mosaic of monocultures blocks across the landscape instead of a single plantation.
- Use of species mixtures instead of plantation monocultures.
- Fostering and managing the diverse understories that commonly develop beneath plantation canopies.

In another polyculture context, Kotschi (1986) argued that fish are very useful polyculture components because of their high-quality protein food value, often obtained from low quality and non-human food sources, their efficiency of feed conversion, and the fact that fish production usually doesn’t compete with land-based food production. He thought that the best examples were fish culture in flooded rice, extensive management through stocking in natural areas and high-density artificially fed fish farming. Edwards et al. (1988) agreed that high yield-small area options were valuable and could be integrated well with adjacent cropping or livestock activities as a general strategy. For integrating livestock in agroforestry, Sinclair (1999) points out that the addition of trees providing a vegetation structure similar to the natural ecosystem in which most domestic livestock evolved may result in benefits for animal welfare and attract price premiums for such livestock products, since these practices are perceived by consumers to be natural conditions.

In reporting on the 1997 RIRDC workshop, Passioura (1999) thought that the two main ecological ideas that stimulated discussion of ecosystem mimics were *succession* and the *impact of environmental variability*. He listed five features of natural systems that would benefit agricultural systems:

- Persistent ground cover and minimal disturbance of the soil
- Presence of deep-rooted perennials
- Seasonal releases of nutrients
- Adequate biodiversity
- Mosaic nature of land use.

Grierson and Adams (1999) added that the ‘relevant characteristics for mimic agroecosystems in south Western Australia include: high species diversity, diversity of rooting attributes, utilisation of different forms of nutrients (especially N and P) in space and time and the promotion of practices which increase soil organic matter content.

Permaculture has long attempted to provide design guidelines for sustainable land use and other goal achievement of a social nature. Mollison (1988, p. 13) articulates a number of permaculture design principles based on the assumption that ‘we can use the guiding principles and laws of natural systems and apply some of them to our consciously designed ecologies’. Mollison lists the following design principles:

1. *Work with nature*, rather than against it, by assisting rather than impeding natural elements, forces, pressures, processes, agencies and evolutions.
2. *The problem is the solution*, our fixed attitudes block the option of making a ‘problem’ an asset.
3. *Make the least change for the greatest possible effect*, and continue to do so on an iterative basis as systems are fine-tuned.

4. *The yield of a system is theoretically unlimited*, being limited only by the lack of information or imagination of the designer.

5. *Everything gardens*, a Mollisonian principle that everything makes its own garden or everything interacts with others and the environment.

6. *Principle of cyclic opportunity*, every cyclic event increases the opportunity for yield. To increase cycling is to increase yield.

7. *Principle of disorder*, order and harmony produce energy for other uses. True order may lie in apparent confusion. Neatness, tidiness, uniformity and straightness signify an energy-maintained disorder in natural systems. Such disorder consumes energy to no useful end.

8. *Principle of stability*, if it is not the number of diverse things in a design that leads to stability, it is the number of beneficial connections between these components.

9. *Principle of self-regulation*, the purpose of a functional and self-regulating design is to place the components in such a way that each serves the needs, and accepts the products of other elements.

### 7.3 Agroforestry characteristics and design principles

The literature reveals a substantial interest in tree based polycultures. Agroforestry entails a unique extension of annual production into greater above and below ground resource capture, component interactions, and persistence over longer time periods. Understanding agroforestry polycultures illustrates many of the design principles and component characteristics that apply to all polyculture production. In observing traditional polycultures, Nair (1979) suggested that ‘multiple cropping with trees as the dominant component is one of the safest and most variable and adaptive systems of land use allowing permanent and remunerative cultivation in humid tropical regions.’

Two functionally different types have been described: simultaneous and sequential. Simultaneous agroforestry is where trees and crop components grow at the same time and in close enough proximity for interactions to occur (ie. alley cropping). In sequential agroforestry, the maximum growth rates of the crop and tree components occur at different times, even though both components may have been planted at the same time and are in close proximity (ie. shifting cultivation, improved fallows, Taungya). Interactions between crop and trees are minimised as the time separation increases. In simultaneous agroforestry, the paramount objective is minimising competition in space and time. In sequential agroforestry, the components are planted at different times or planted at the same time if the growth rates are significantly different. Sequential agroforestry uses species with nutrient or water uptake in sequence and may use slash and burn or slash/mulch systems that evolve to forest-like conditions. Nair (1979) concluded that there are inherent advantages of sequential agroforestry over simultaneous agroforestry in managing competition for the farmer’s benefit. Because of the higher competitive interaction of simultaneous agroforestry, especially in arid climates, Ong and Leakey (1999) thought that ‘the greatest opportunity for simultaneous agroforestry practices is to fill niches within the landscape where resources are currently under utilised by crops’, thus mimicking the large scale patch dynamics and successional progression of a natural ecosystem. They also thought that the opportunity for significant complementarity was most likely when the species involved differed in their pattern or duration of rooting and resource capture.

Smith (1996) concluded that agroforestry offers numerous environmental benefits when compared with short-term intensive cropping; soil protection, better water and nutrient utilisation, increased wildlife niches, improved microclimate for essential soil micro-organisms, and higher biodiversity. He also suggested that monoculture plantations have significantly fewer benefits but he listed nine examples where plantations have been ‘biodiversified’ to environmental benefit. Stirzaker and Lefroy (1997), in
looking at silvopastoral and agrosilvopastoral trials in Western Australia, noted design principles and benefits and believed that successful alley farming polycultures will pay strict attention to:

- Degree of below-ground competition, especially for water by consideration of depth and salinity of water table and vertical/horizontal root distribution of the trees.
- The degree of temporal, spatial, and functional niche differentiation between the trees and annual crops.
- The relative economic value of components.
- Facilitating complementarity between crop and tree components in product differentiation, shelter values, and resource conservation.

They thought the goal is to maximise the positive interactions between trees and other crops and to minimise the negative ones. Later, Lefroy and Stirzaker (1999) took a more regional landscape scale assessment of the potential for agroforestry to assist restoration of degrading WA wheat lands. They concluded that trees would ‘need to be widely dispersed over a significant proportion of the landscape to manage deep drainage and salinity’ because significantly higher year-round leaf area index is required than could ever be found in farming systems based solely on annual plants. They suggested species needed to be chosen that offered higher returns than existing grain farming even with complementary interactions if they were to be viable economically. Hatton and Nulsen (1999) emphatically stated that, in WA, ‘effective control of recharge will only be achieved at a leaf area index approaching that of the natural state, including revegetation of most or all parts of the catchment’. They thought ‘it would be difficult to envisage sustainable systems not involving trees or other perennial vegetation.’ Ong and Leakey (1999) thought the greatest opportunity for simultaneous agroforestry practices was to ‘fill niches within the landscape where resources are currently under utilised by crops, [thus] mimicking the large scale patch dynamics and successional progression of a natural system. In choosing species, Sanchez (1995) decided that new agroforestry crop species are better suited if they offer a multiple purpose and benefit as opposed to species with single products or markets, illustrating that market diversity is also a polyculture design principle. However, Piper (1993) seemed to place the priority on plant characteristics saying that ‘in designing polycultures, because of species specific neighbourhood effects on phenology, growth and (seed) yield, interactions between particular components need to be considered.’

### 7.4 Design for mechanisation

Baker and Francis (1986) addressed the mechanical environment as criteria for polyculture design. It is also addressed in the next section on barriers to polyculture, along with suggestions on opportunities for effective polyculture within current mechanised agriculture. Baker and Francis (1986) concluded that in temperate mechanised systems, planting patterns are often determined by existing equipment used for conventional monoculture planting patterns. An easy step into polyculture, strip intercropping, depends on planting and harvesting equipment of compatible width for optimum efficiency. This may involve invoking the concept of ‘small is better’ since ‘if interactions between component crops are expected to provide benefits to total production, the narrower the strips and thus the greater the extent of plant interactions, the better, within the limits of available equipment.’ Similarly, relay cropping the second crop depends on the row spacing of the first. In the American plains, research studies and farmer experiences showed that planting summer soybeans into a growing winter wheat crop was done more easily if every third or fourth row of wheat had not been planted. This is easily done.
8. Polyculture: Risks, Barriers, Constraints, Obstacles

This section addresses the problems of polyculture, the risks undertaken by those who practice polyculture production, and barriers to those converting from monoculture to polyculture production systems. These include the physical crop and management differences inherent in polyculture production and the challenges to management, labour, and mechanisation. They also include the information, research development and extension, policy, and socioeconomic dimensions impacting on the adoption or expansion of polyculture practices.

8.1 Physical and crop constraints

Despite the fact that the majority of the world’s producers have persisted with polyculture production for thousands of years, western science really only began to look seriously at how and why it worked in the last 30 years. Early researchers looked first at simple state variables. Kass (1978) noted that Polycultures are likely to remove more N, P, K, Mg and Ca from the soil than does monoculture since more crop products are removed from the system. At that early time, Kass also saw studies that showed both an increase and decrease in pest or disease incidence under polyculture and concluded that there seemed to be ‘no clear-cut benefit or detriment from polyculture with regard to pest control’. This has since been disproved, but it indicates the nature of the initial observation in the absence of sufficient research. In fact, early researchers often did not address risks and barriers because they simply did not know enough about how the systems operated.

Altieri and Liebman (1986) believed that the effects of intensive systems on pest and weeds can neither be generalised nor predicted because of the enormous variety of systems and mechanisms. According to Baker and Francis (1986) there was a recurrent theme in the overall complexity of multiple cropping due primarily to the large number of possible and employed combinations and factors. These involved factors such as:

- **Site specific factors**- climate, socioeconomic constraints, soil properties, labour and time constraints.
- **Field operations factors**- land preparation, tillage, cultivation, weed and pest control.
- **Planning factors**- dates, patterns, densities, species, and cultivars.
- **Fertility factors**- species combinations, performance in monoculture vs. polyculture, objectives of multiple cropping systems.

They felt that relatively few scientists were currently involved in polyculture research and much more work was required. Baker and Francis also suggested a three-dimensional approach:

1. More use made of existing component crop knowledge and technologies to develop new innovative polyculture system designs, by understanding underlying processes and principles.
2. Explore mathematical and simulation modelling to guide the research and extension practice; and
3. Dramatically expand the use of the most available resource- farmers- more completely, earlier and across artificial geographic and political boundaries through communication and the on-farm participatory research approaches.

Certainly, polycultures are diverse by nature and intent. Kotschi (1986) thought that ‘optimal crop combinations are site specific and must be developed through local experimentation’ unlike modern industrial ‘prescription’ farming packages.
There are constraints at the individual plant and crop variety level based on their nature as bred crops: as evolution of crops progressed under human manipulation, crops have become considerably different than their wild progenitors. Putnam and Duke (1928) noted that allelopathic characteristics that assist plants in protective or defensive roles ‘were more likely to occur in crop predecessors or wild types.’ Indeed, plant breeders often return to wild populations in search of pest or disease resistance to reintroduce into current varieties. As crops are grown over time, selection pressures present in the wild population are no longer present. Wolfe (1985) reported that when multiline disease resistant crops are repeatedly regrown, ‘considerable drift in composition of the mixture can occur, favouring the tallest, most vigorous components almost irrespective of differences in disease reaction’ through unintentional selection through harvesting. Without continuous re-evaluation, random or unintentional genetic drift will occur, as opposed to the more consistent evolutionary pressures in nature.

Because of the long period crops have been manipulated, or perhaps, in spite of this manipulation, Regnier and Janke (1990) observed that within crop species, different cultivars have been found to differ in competitiveness. They reported that yield reductions among 10 soybean varieties intercropped with a competing stand of water hemp and green foxtail ranged from 3% to 20%. Similar differences have been observed for cotton, maize, grain sorghum, snap beans, winter wheat, and rice. In terms of weed suppression by crops, cultivars differing in production of allelochemicals have been found for oats, sunflower, cucumber, and sweet potato. They found that some soybean varieties required only half as much herbicide for good weed control and maximum yield than for the least competitive variety. While this may indicate that there is a sufficient range of crop characteristics to work with, Stinner and Blair (1990) suggest a bleak picture that ‘existing crop varieties, bred for maximum yield in response to high inputs’ provided more of an obstacle to increased adoption of intercropped agroecosystems by industrial agriculture. Similarly for animals, breeding objectives have often focused on individual and final product outcomes without the wider range of breeding criteria necessary for polyculture systems. Blackburn et al. (1996) noted that ‘animals in a specific environment have developed resistance or adaption to a full range of environmental challenges such as ticks, internal parasites, or temperature extremes.’ For the most part these characteristics have not been fully accounted for in planning and executing breeding and selection schemes in industrial or developing countries.

Not only are there genetic constraints inherent in the nature and range of present component crops, but they can also vary considerably within a single crop year. This phenotypic variability is caused by the individual’s response to its immediate environment and conditions, much like the earlier mentioned plasticity in bean internodes when intercropped. Kropff and Goudriaan (1994) concluded that the ‘actual mechanisms of competition for resource capture are complex. Plants are morphologically and physiologically extremely plastic in their response to their environment, making generalisations of plant responses difficult.’ This reinforces the principle that successful polycultures are site and species (and perhaps variety) specific. Other components of the system are also highly variable. Stamps and Linit (1998) observed that ‘in some (15% of those studied) polyculture crop systems (insect pest) herbivores had higher density in polyculture vs. comparable monoculture and that insect community dynamics in one system will not necessarily translate to other systems. As polyculture researchers became more interested in agroforestry systems in the last 20 years, they also found difficulty in translating theory based on annual polycultures to these forestry systems. Sanchez (1995) revealed that:

The frequent failure of alley cropping agroforestry trials had illustrated the significant differences between annual crops, multiple cropping and cropping with trees. Trees differ from short-cycle crops in two fundamental ways: they grow for several years and also develop extensive root systems that can capture nutrients and water at a time when crop root systems are beginning to develop. Both traits give trees a major competitive advantage.

Clearly these temporal and spatial dimensions in alley cropping need consideration to reduce competitive interactions while enhancing complementary ones.
Sanchez (1995) also thought that trees/alley crop combinations outside the tropics suffer from competition between the components and that the repeated failures of tree-based alley crop polycultures, particularly in semi-arid climates, were due to a poor understanding of intercrop competition, particularly below ground. He concluded that, while little research was available on this constraint, alley cropping with trees was most likely to work where soils are fertile, without major nutrient limitations, where rainfall was adequate during the cropping season, when land is erosion prone (this providing additional benefit) and where there is adequate land tenure and an oversupply of labour relative to scarce land.

Farrell (1995) agreed that there are fewer agroforestry options in drier climates, that the competition between components needed to be assessed, and that tree crops required financial support until bearing returns, possibly linked to longer-term land tenure. More recently, Schroth (1999) decided he could predict ‘in which manner and direction the development, distribution, and activity of roots in agroforestry systems will change as a response to a well-defined management measure’ but only in a few cases could this be predicted quantitatively. More recently, Schroth (1999) felt he could predict ‘in which manner and direction the development, distribution, and activity of roots in agroforestry systems will change as a response to a well-defined management measure’ but that only in a few cases could this be predicted quantitatively. Russo (1996) pointed out another constraint of agroforestry polycultures, that in some pastoral systems, grouped trees can attract shade loving animals, leading to compaction and erosion. Also, trees may compete with pasture for water, nutrients, light and space. Vandermeer (1998) observed that alley cropping total yield was a careful balance between facilitative and competitive interaction between crops and trees.

8.2 Polyculture management: Humans and machines as obstacles

Production polycultures are managed by human expertise, labour, and tools. There are constraints to retaining or increasing the extent of polyculture practice due to management needs, the availability of labour and its replacement: mechanisation. Initially, it might be asked why humans moved away from polyculture to monoculture. In observing actual third world examples of this change, Lynam (1986) believed that shifts occur out of intercropping to sole cropping when:

1. More control over environmental risk was obtained.
2. Farmers became more market oriented versus subsistence.
3. The cost of labour increased relative to the cost of mechanisation.

It should be noted that none of these reasons relate to the crop(s) themselves or the understanding of polyculture management- they are external impacts that are technological or economic.

The management of polycultures with the complex ecological and agronomic interactions mentioned earlier were instinctive in traditional polyculturalists: they knew how to manage them because they had always grown crops in that manner. As polycultures become more complex, or are reintroduced to industrial agricultures, these management abilities may also have to be reintroduced to producers trained and experienced only in the industrial model. Perrin (1980) thought that ‘meaningful generalisations on how to manage plant diversity for crop protection were felt to be virtually impossible since each crop/pest/climatic complex would require an individual approach.’ Gomez and Gomez (1983) agreed that ‘multiple cropping techniques generally require more resources and management capability relative to monocropping,’ generally referring to expertise rather than physical resources. Conway (1987) saw needs for ‘better and more informed management and specifically that management of ecological interactions and processes would be required to replace high inputs in sustainable multiple cropping systems’. Stinner and Blair (1990) agreed that ‘invariably, sustainable low input multiple cropping agroecosystems are more complex than high input systems; thus their management will need to be more sophisticated. Pannell (1999) also noticed a recurring theme of the ‘complexity of the systems, not only in their biology, but also in their management, in their economic impacts, and in the social attitudes and perceptions which they generate.’ He was less than hopeful from an extension/adoption perspective that such new complex
systems would succeed without public subsidy. One could argue that their uptake will also need changes to accounting standards to internalise environmental costs of industrial agriculture that are currently externalised, thus allowing fair economic competition between approaches (see also Geno 1995; 1998). Madamba (1980) concluded that new technical skills would be required for successfully expanding tropical polycultures. The essential principle here is that historical industrial production models externalised many of the system self-regulation tasks to materials: fertilisers replaced fertility management, chemical pest control replaced internal pest regulation mechanisms, chemical weed control replaced system or tillage controls, and mechanisation both required and enabled uniformity. Edwards (1990) noted that farming systems that ‘use fewer chemicals implicitly require a much better understanding of the interactions between and among inputs in agroecosystems. Lower input agriculture is more system oriented and, consequently, management intensive.’ There is a similarity to converting monoculture to polyculture production that can be seen in conventional farmers converting to organic farming: increased management capability is required.

Kirschenmann (1989) believed that ‘effective weed control continues to be one of the more challenging problems facing growers who eliminate their herbicide input, especially when a farm has had a long history of monocropping.’ Moreover, Vandermeer (1997) looked at the process from current systems and chaos theory and felt that conversion from conventional to organic or alternative agriculture may not be a linear process. The combination of ecological and economic dynamics under chaos theory shows the possible outcome of unpredictable shifts between the end states during conversion in the pattern known as intermittent chaos. This is particularly possible in those agroecosystems with the potential to be damaged ecologically or with the potential for market volatility risk. Clearly, there are human risks and barriers to adoption of polyculture practices but if the average third world peasant can manage to do so, anyone determined should be able to succeed.

Mechanisation is a major characteristic of industrial agriculture due to numerous factors and an historical development that is somewhat outside the scope of this research report. As mechanisation provides a certain increase in production efficiency, albeit at a cost in currency and energy, there will be a role for mechanisation in polycultures. Mechanisation for polyculture production started with population pressures among third world producers, dictating an intensification of production. Khanna (1973) described improved simple machines, often human or animal operated rather than motor driven that had been developed for non-mechanised agriculture. An animal drawn combine harvester (header) that cuts and bundles grain with supplementary stationary engine assistance was developed to harvest different grain crops (the Pusa reaper). There is an abundance of small hand and powered tools available even now (see Branch 1978; Carruthers & Rodriguez 1992) and sufficient knowledge of smaller scale animal powered technologies from historical times (see Partridge 1973). Kass (1978) thought that ‘intercropping posed challenges for mechanisation, both in re-engineering tractor equipment and improving animal drawn equipment for seeding, weeding and harvesting.’ He thought that while mechanisation can be more difficult, using animals to assist harvest can help. Some approaches are quite elegant- ie. maize and sugar beet harvested for silage, then the beets harvested.

In looking at early strip intercropping in the Darling Downs, Macnish (1980) noticed that there could be problems with machinery use at turning on headlands and that row orientation and length needed to be considered across farms to minimise erosion risks. Liebman and Dyck (1993) concluded that mechanisation barriers came more from the lack of attention from agriculture engineers than any inherent incompatibility between multiple cropping and mechanisation. They suggested that while intercropping is largely a practice of tropical subsistence farmers, intercropping yield advantages are not restricted to such situations, since many intercropping systems are suited to existing machinery and have been practiced by mechanised western farmers, such as barley/red clover (USA), oat/lucerne hay (USA), canola/field peas (Australia), barley/field beans (UK) and wheat/peas (Cyprus). Stinner and Blair (1990) also thought that ‘multiple cropping systems that appear most suitable for adaption to large scale industrial agriculture,
other than sequential cropping and rotations are forms of strip cropping and relay cropping as well as living mulch and overseeded relay cropping. The caution here is that the less time or space of overlap—the less functional ecological relationship between components.

Gomez and Gomez (1983) pointed out some general guidelines that management of polycultures will require different approaches due to the different strategy and characteristics of polyculture production versus monoculture:

1. The component crops of a cropping system must be planned and implemented jointly, because the management of one component crop greatly influences the productivity of the other(s).
2. The appropriate management for the same crop species may change depending on the position of the crop in the pattern.
3. The management practice for a component crop in the pattern is chosen not to maximise production of the particular crop (as in monoculture) but rather to maximise production of the whole pattern.

At the end of the day, Cordero and McCollum, as cited in Liebman (1995) have the most appropriate comment:

Any society that can land people on the moon and retrieve them safely should be able to design machinery to plant, maintain and harvest polycultures.

One feature of the human labour noted in the literature search is the near absolute absence of figures on labour use in modern polycultures, although some economic comparisons have been made. A projection for western Australian pine agroforestry in wheat/sheep regions by Malajczuk et al. (1996) suggested that agroforestry would have higher labour requirements only in the short term (to years 6 and 12) but at the 30 year rotation time, total labour requirement was about the same as the agriculture it replaced. However, in general terms, it must be accepted that polyculture production needs more minds and hands than mechanised monoculture, a matter of socioeconomic evolution. Higher labour inputs can be seen as either a constraint or as an opportunity for increased rural employment.

8.3 Polyculture constraints: Research, development and policy paradigms

This part addresses the risks and barriers in terms of information availability, current and future research strategies, research and socioeconomic policy and the way that the nature of polyculture directs research and policy planning. For polyculture options to be explored and implemented, there has to be adequate information about their performance, sufficient predictive models to ensure success, and reasonable understanding of the principles and mechanisms being used. Many authors pointed to general and specific information gaps for polyculture systems to be applied more widely. Tivy (1990) noted the ability of traditional polyculturalists to manage complexity based on inherited and learned experiences that are not normally present in existing producers without that background. Perrin (1980) thought that the current conceptual framework of society where the trend is toward linear, simplified production monoculture with increasing scale of production and automation of processes dictated by the western market for agriculture supported the commodification of agriculture. This mindset discourages producers of multiple crops. Producers are the primary beneficiary of polyculture benefits and Wolfe (1985) concluded that the ‘value of heterogenous crops is often more readily accepted by the farming community than by those who serve it’, pointing to institutional paradigm barriers. Conventional R, D & E, according to Beets (1982) looks down on polyculture since researchers often conclude that current mechanisation has limited flexibility, short season climates limit polyculture potential and that there are fewer options for dry regions.
Vandermeer (1998) later placed more responsibility on researchers, saying:

> It is possible that a bias is introduced by agricultural research which has an adequate ‘tool-box’ of experiments and models for technology development in monocultures but which is less able to deal with more complex systems.

This research responsibility extends beyond the agronomists to social and economic dimensions as well. Vandermeer (1981) noted that much of the discussion of polyculture productivity is based on mass production (kg/ha) because they are sold to distant markets due to primarily social and economic factors, ‘whereas social and economic factors do not change the operation of biological laws, they certainly determine the way those laws might be brought into practical application.’

Zinkhan and Mercer (1997), in looking at agroforestry systems in the southern USA, found that they were largely unproven in economic terms: ‘financial uncertainties associated with agroforestry are probably the most critical factor for expanding agroforestry.’ This is not to say that some barriers exist at the individual, family and community level as well. Kotschi (1986) thought that ‘the constraints and opportunities as perceived by the farm family will ultimately determine the appropriateness of practices’ for successful polyculture production. He thought practices should be promoted which show low variability of production and which minimise risk. Looking to the farmer, he suggested that systems and techniques which farmers have already developed to suit their particular circumstances must form the starting point for improved polyculture practices. Altieri et al. (1983b) believed that ‘social complications, rather than technical ones, are likely to be the major barriers against any transition from high capital/energy production systems to labour intensive, low energy consuming agricultural systems’.

Because of the results following on from some of the attitudes of farmers and their advisers as noted above, there are significant missing facts which may make it difficult to expand polycultural practices. With only 30 years of serious research, a coherent conceptual paradigm in science is just developing and much is unknown. Vandermeer (1989) considered that because polycultures are ‘more complicated than monoculture and more resistant to development of a central core of theory to guide empirical work’, it is best to use the theoretical frameworks from ecology, applying the theories of population and community ecology to polycultures. He found much the same position 10 years later, (Vandermeer et al. 1998) and observed that the sheer number of components automatically limits the style with which models can be developed for multi-species agroecosystems (at least a 32 factorial design). In modelling and experimenting with multi-species complex agroecosystems ‘it may be futile to attempt the same level of precision and the same scope for “optimisation” as in research aimed at the management of a single crop.’ When one adds the realisation that few natural ecosystems have been adequately modelled, and that the complexity of the human socioeconomic system is also overlaid on top of these considerations-it would appear that the agroecosystem is even more complicated than the unmanaged natural ecosystem.

Cromartie (1981) noted significant information gaps. In a CRC Handbook review of third world examples regarding the various ways in which increasing diversity can influence pest populations, where he noted that ‘most of the quantitative experimental work cited has not been concerned with producing crops economically, so there is little hard data available on the value of diversification in actual (industrial) agricultural situations.’ No long-term studies (as of 1981) on combined yields of intercrops in relation to pest attack seemed to be available. Further work is needed before weeds or intercrops can be recommended as a pest control strategy. Most promising is maize/beans, maize/beans/squash, tomato and tobacco with collards, white clover undersown with brassicas, and under planted cover or weeds in beans. ‘Little information is available on the effect of mixed cropping on the chemical and nutritional composition of plants’ as well.
Risch (1983) also noted significant missing information in a review of 150 papers on the effects of intercropping on pest control, though advances have been made since:

1. Lack of experimental evidence demonstrating that reduced pest numbers in the intercrop resulted in higher yield.
2. Lack of experimental evidence demonstrating the ecological mechanisms responsible for the intercrop effect.

Perrin (1977) gave four reasons why he thought entomologists had been slow to contribute to the study of polyculture practices:

1. The belief that multiple cropping as traditionally practiced is outdated, unproductive, and thus only a transitional phase in the trend toward monoculture.
2. The general neglect of cultural methods of pest control since the appearance of second-generation insecticides.
3. The belief that meaningful manipulations to diversify had to be on a large scale and inter-rather than intra-crop vegetation due to the well developed migratory and host seeking powers of most insects.
4. The extrapolation of theoretical arguments on diversity/stability relationships from natural to artificial ecosystems without recognising the unique nature and the ability to manipulate the human agroecosystem.

Most of these preconceptions are shown by Perrin to be inadequate and erroneous generalisations. Baker and Francis (1986) echo these concerns in looking at the knowledge base for polyculture. They suggest that:

The literature on multiple cropping advantage generally addresses complementarity far more than competition. Often both are occurring and to further complicate clear conclusions, are often site and farmer specific. This gives rise to conflicting reports. The site-specific factors influence results, and the success or failure of multiple cropping systems relative to polycultures are often not discernible or are attributable to more than one cause. It is not enough to simply document multiple cropping yield advantage or gross nutrient uptake advantages. One must know why such advantages occur in order to understand and improve multiple cropping systems. This is why process orientated research is needed.

For example, many authors point out that the majority of competition/complementarity studies address themselves to above ground interactions; with below ground interactions and the processes involved only recently receiving research interest (see Snaydon & Harris 1981; Sanchez 1995; Stirzaker & Lefroy 1997; Ong & Leakey 1999). Vandermeer et al. (1994) proposed and progressed the modelling of tomato/soybeans intercropped in Michigan by a significant degree based on experimental, if not production, fields, using a variable competition hypothesis. This sort of ecologically based model has important potential utility for polyculture design. But Sanchez (1995) cautioned that ‘modelling in agroforestry is still in its infancy, in terms of both mechanistic and simulation models.’ He saw the need to move from descriptive knowledge based work to process oriented quantification research and noted that while methods for evaluating soil biological processes had advanced, several important parameters such as microbial biomass and labile organic phosphorous pools still lacked replicability and threshold or control level information.

Some of the lack of information and research results from the way research, development and extension is conducted. Lynam et al. (1986) suggested that:

Multiple cropping research stresses the whole system and its interactions, thereby moving away from the component, disciplinary emphasis predominantly found on the experiment station. This more holistic approach of ‘farming systems research’ includes the farm and farmer in research design and trial, often on-farm. Thus a fundamental change in the organisation of agricultural research must occur.
However, farming systems research requires that farms can be categorised or grouped within similar criteria. Since so much of successful polyculture is site, species and farmer specific, it is likely to be limited by the need to be practice and process focused. As Rao (1986) found:

The location specificity of cropping system technologies, imposed by differences in agroclimatic and socioeconomic characteristics demands multi-location on-farm testing to adapt recommendations of on-station research. Because of socio-economic differences among farmers, no single system is likely to fulfil the objectives of all farmers in a given environment; future research needs to create an array of cropping systems options to optimise farmer choice.

Sanchez (1995) agreed and once again pointed out the value of on-farm participation in research, by stating:

The socio-economic dimension of agroforestry is complex because of aspects related to temporal and spatial variability, scale factors, the multiplicity of products and services, and the economic, social and ecological processes involved.

He felt that process-oriented research on socioeconomic complexity should be strengthened, particularly research on how communities react to changes in policy and environments, and that ‘characterisation and diagnosis of potential agroforestry systems for farmers should be participatory, analytical, multidisciplinary, and firmly based in relevant indigenous knowledge [as well as] conducted in an iterative manner to establish behavioural change.’

Significant barriers to increasing polyculture in practice appear within the research and advisory institutions. These bodies- like most research and scientific organisations- are dominated by a narrow approach to science, predominantly pursuing traditional reductionist science that seeks to identify simple cause-effect relationships, as confirmed for adoption of sustainable practices in Queensland cane farming (Geno 1996). At the foundation of modern science is the concept of reductionism, the attempt to isolate a minimum set of factors (preferably one) that appears to have a controlling influence on a particular situation or process. The desired outcome is usually the identification of a single, repeatable, measurable factor. Underlying reductionism is the belief that the whole can be understood as the sum of its parts. The weakness of this approach is its inability to deal with the immense complexity of relationships within agroecological systems. Interactions amongst a multiplicity of components, side effects, externalities, and long-term consequences are often overlooked.

Modern science also relies heavily on the myth of objectivity and assumes that scientists can be above nature and, being free of nature’s constraints, gain an ‘objective viewpoint’. Belief in the separateness of human scientists and nature implies that scientists can see nature without self-involvement and without value prejudice because natural/agricultural systems are something other, something outside of self. Objectivity has come to mean trusting only carefully controlled, measurable, quantifiable results and finds no place for qualitative subjective assessments. Furthermore, a preoccupation with objective science in research removes the potential for that science to develop a life nurturing role which admits responsibility, supports ethical values, requires self-involvement and is therefore inherently subjective. Successful achievement of polyculture in practice will require multi-disciplinary, systems based approaches in research along with recognition of underlying life supporting values. This will require a major cultural and operational change within research institutions.

In the economic dimension, there is inherent conflict in polyculture research and policy because some polycultures are meeting need (subsistence) values and some are meeting market values. Risch (1983) suggested that because R&D to study the benefits of intercropping does not result in a commercial product, like a pesticide, there is little incentive on the part of private industry to fund such research. Like biological control research, the responsibility may lie with public R&D agencies, particularly since benefits of polyculture production extend beyond the individual enterprise to wider, public landscape values. He also felt that ‘the economic system acts as a brake on research that may produce social benefits.
but does not produce marketable commodities.’ The development costs of agricultural machinery and other intercrop technologies may lead to an agriculture somewhat less profitable in the short run although the long-term social benefits may weigh strongly in their favour. Risch’s fear was that economic motivations would solely prevail. Lynam, Sanders and Mason (1986) noticed that the ‘cost side of multiple cropping is not is rigorously considered as the benefit side.’ Sanchez (1995) added that a priority research area for advancing agroforestry polycultures was the ‘valuation of environmental externalities’ (see also Geno 1995, 1996).

Some changes need to occur in larger institutions as well. Stinner and Blair (1990) noted that a major factor in the adoption of multiple cropping systems is agricultural infrastructure, including governmental policies that affect farmer’s decisions on cropping practices. One place to focus on the values of science and the institutions is in breeding. As crops evolved from the wild under human care, they came to be selected for specific criteria either intentionally or incidentally. The plants needed for successful polycultures may not be available among current crop varieties and assessment for this goal has rarely been made. Barrett (1982) identified some institutional barriers to crop breeding for polyculture:

While cereal multilines in Europe in the 1970s showed disease resistance and yield increases sufficient to expand commercially, the EEC regulations prevented sale of mixtures to guarantee seed ‘purity’ and they took until 1979 to change the regulations. In Denmark, a country which depends heavily on its pig industry, only animals from designated elite herds, subject to performance testing, by state-run stations can be used for breeding.

Smith and Francis (1986) concluded that most crop breeding has been done for and in monoculture situations. A number of breeding criteria become clearly more important in breeding components for polycultures, such as:

1. Variation among and between species
2. Crop maturity time, both late and early
3. Photoperiod sensitivity and insensitivity, for planting time flexibility
4. Plant morphology for above ground architectural complementarity
5. Root system properties
6. Insect and disease resistance in polycultures
7. Cultivar uniformity

Of course, normal monoculture breeding traits would also be sought:

1. Adaption to the target environment
2. Suitability to farmer or market needs
3. Responsiveness to favourable environmental changes
4. Tolerance or resistance to insects or disease
5. Reasonably high and stable yield.

They believed that many breeding methods currently used for monocultures will be useful, but stress the potential value of measuring yield reduction from monoculture to polyculture as a selection criteria, using correlation analysis, analysis of variance, regression analysis and reciprocal recurrent selection. Little of this work is being done.

Rao (1986) thought that ‘new criteria for breeding crop plants will be necessary for successful expansion of multiple cropping.’ Davis et al. (1986) argued that ‘breeding cultivars especially for a cropping system is justified if the interaction between genotypes and different cropping systems is highly significant or if selection is carried out more efficiently in intercropping rather than in sole cropping.’ This supports Trenbath (1981), who thought that ‘special attention needs to be given to shade adaption in short stature plants and multi-crops.’

9.1 Introduction

From a general reading of the national organic and alternative agriculture press in Australia, it is apparent that while current organic producers are largely replacing synthetic inputs with accepted ‘organic ones’, they are still largely engaging in an agriculture which is input/output focussed. As Kirschenmann (1989) suggested:

There is a tendency on the part of some farmers to construe new approaches to farming as simply adapting new techniques to what they have always done. This is a pitfall to avoid.

For the most part, organic agriculture has sought to replace techniques and materials which are not organic with techniques which are; even the organic standards have this type of focus. However, the popular press also reports on innovative approaches taking place, some of which transcend the input/output solutions and seek to create new farming systems design. This section summarises anecdotal reports in the popular press regarding polyculture innovators, both organic and non-organic that led to pursuing the survey.

9.2 A Summary of Polyculture Innovators

‘Companion planting a growing enterprise’ 1990
Companion planting of herbs and crops is being used at larger scales in agriculture after evolving from organic gardening. Government research trails are using companion plants to deter pests from vegetable crops. Herbs can repel or attract insects or directly stimulate the plants. Interplanting or alternate rows are used. The herbs can also benefit the crop through deep taproot nutrient cycling, fine surface rooting to hold soil and attract birds, butterflies and bees.

Holyoake 1992
In central Victorian wheat-sheep country, an innovative conventional farmer has found he can diversify his farming system. Not only does he plant multiple species pastures, but he has found he can plant grain into standing (grazed) lucerne fields, direct drilling on top of the lucerne at the usual density for ‘2 crops in one go’. Lucerne is often established under open field grain crops as well.

‘Ugly apples’ 1992
At an organic apple orchard in the Adelaide Hills, hundreds of chickens and geese assist with manuring and pest control. This approach solves some of the pest and disease problems while providing another source of income through sales of the animal products.

Cole 1993
At the Wagga Wagga Agricultural Research Institute, a unique row intercropping trial is proving to have interesting results. Field peas and canola are planted and harvested together. The peas aid nitrogen fertility and climb on the canola, reducing ground contact staining, harvest losses from lodging, ground contact diseases, and smothering by the pea canopy. The canola is planted at half rate, is easily separated after harvest, and adds an extra $100/ha/yr in income. The researchers say ‘peaola’ is widely used in Canada.

Lillington 1993
On 200 acres of red basalt soils in central Victoria, a certified organic grower integrates grazing, annual vegetables and tree crops. The animals are seen as particularly useful in nutrient recycling, weed seed
control, mowing and additional income. Tree crops include nuts, fruit and fodder species and assist in deep nutrient recycling, removal of water that would contribute to down catchment salinity, animal and annual crop windbreak shelter, income diversification, bird and beneficial insect habitat and fire resistant breaks. Crops are usually grown in blocks in alternate rows, moving about the farm in 3-4 year rotations with long term grazing.

*Marshall 1993*
On the Fleurieu Peninsula south of Adelaide, a grower leaves weeds in snow pea blocks using them as a natural trellis, increasing organic matter returns after cropping, and habitat for beneficial insects. Interplanting annual vegetables assists with pest and disease control and stabilises income risk.

*Worsfold 1993*
In converting a 171 ha monoculture dairy farm, extensive tree plantings were used as dairy cattle were reduced by producing milk, royal jelly from bees, firewood, Christmas trees, seeds, nursery stock, timber, tree fodder, orchard fruit, chickens, macadamia with tourism and teaching opportunities. The managers report that increasing diversity yields a greater economic stability than dairy alone.

*Woodman 1993*
In the Darling Ranges outside Perth, certified organic growers operate a 20 acre polyculture of stone fruit, citrus, pears, persimmons, pistachios, apples and nashi fruit interspersed with pecan, eucalypts, acacias, vegetables and flowers. Foliage and flowers are important products, often from nut, fruit or vegetable plants. They see abundant natural predators.

*Woodman 1994*
On a 7.5 acre certified organic property in Western Australia, the owners follow a Permaculture food forest model to produce vegetables, fruit, eggs, and water plant crops using integration to reduce inputs. The chickens ‘plough and manure’ the soil, vegetables maintain fertility between orchard rows as the trees grow and wet areas are used to benefit. They report reducing pest damage, increased wildlife density and an increasing and stable income.

‘Sunny Creek Farm- Diversity at every level’ 1995; Marshall 1999b
In Gippsland since 1981, certified organic growers have maximised diversity on their 10 hectare block under a permaculture food forest model. ‘Chestnut trees spread over apples which in turn over-grow mixed berries, often with cane berries over strawberries in a multi-level system’. Value adding of fruit is used to diversify income and utilise seconds. The diversity of the plantings yields the most important benefit to them: stability of income. The extensive interplanting in and between the tree rows is done for shade, weed control and crop variety. But one difficulty is the differing management requirements for different fruits and nuts on the farm. As active experimentalists, they have 250 different fruit and nut varieties on the farm. One result of the diversity is that their labour requirements are well spread out. One disadvantage is the abundant food supply for wildlife pests.

*Eisley 1996*
Cattle producers in NE NSW are turning to some cropping to level out variable beef prices. Soybean diversification is growing rapidly including multiple cropping options. Compared to beef returning $108/ha/yr, the same area devoted to sequential summer soybean-oat crops for winter fattening came out to $570/ha/yr. Besides improving income and soil fertility, aerial seeding of oats and rye grass a few weeks before the soybeans were harvested (relay intercropping) allowed a rapid turnover, with cattle grazing just four weeks after the beans are harvested.
Roberts 1997
Near Lismore in NE NSW, an interplanting of banana and avocado increases health of both. There is less chance of phytophera root rot in the avocados as the bananas take up excess water in the wet times. Grasses and planted legumes also transpire excess water and provide mulch.

Marshall 1998
North of Adelaide, a permaculture food forest of 15 hectares is certified organic and maximises diversity of products for both sale and teaching material. Differential grazing by native animals as well as grazing animals and poultry is integrated with 160 varieties of nuts and fruit, which are sold regionally. Certain weeds are encouraged for deep nutrient cycling, annual weed control, animal feed and as mimics of natural plant guilds.

‘Delighting in the quandong challenge’ 1999a
South Australia wheat, citrus and grape growers are establishing a polyculture of quandong, wattle and sandalwood. The quandong produce tasty native fruit, the wattles produce nitrogen and an edible seed while the sandalwood produces a valuable aromatic wood. The wattle and some native planted ground covers serve as hosts for the obligate parasite quandongs and sandalwoods.

‘Coupling forestry and bushfoods’ 1999b
On the Sunshine Coast of Queensland, 10 hectares are planted out in a diverse analogue forest of 20,000 timber and native food trees. Mixing fast and slow growing timber species spreads out work and income while thinning out the growing agroforest. Understorey, edge and groundcover bushfoods complement the ecology and the income. They value-add with regional direct marketing. Short term interplanting with pigeon pea provides mulch and adds nitrogen and improves soil tilth.

‘Broadcast polyculture’ means variety and continuity’ 1999c
Outside Melbourne, a manual non-row vegetable and fruit polyculture is developing. Using 17 years of experience, 4 ha of stone and pome fruit were under sown with a mixture of vegetables and short-lived fruit crops. Up to 100 different fruit and vegetable lines are grown for local and regional markets. The mixed species broadcast seeding results in product diversity, staggered maturity and crop succession in each area following planting. While there are minor problems with accuracy of distribution and sowing depth of seed and density that is too high; the heavy broadcast sowing limits early weed growth. Longer-lived vegetables come off later in each area in a relay cropping method. Brassicas are ratoon cropped, with new broccoli and cabbage heads growing after the main crop in cut from the root.

‘Polyculture on six levels and growing’ 1999e
Near Young NSW, six different enterprises are integrated on 32 hectares: six hectares of orchard, cattle, sheep, pigs, turkeys, meat birds and contract poultry processing. Waste recycling is optimised between the enterprises for nutrient retention and all products are sold from the farm direct to customers. Animals are commonly used in orchard management and are often managed under short-term intensive rotation grazing patterns. The interactions between orchard, pasture and animal crops vary widely and are managed intensively in a ‘portable polyculture’ style with a high number of possible combinations.

Marshall 1999a
In the central NSW coast, a certified organic grower alternates commercial flower rows with vegetable rows and leaves unmown areas of weeds to provide habitat for beneficial insects. He uses a diversity of grazing animals (6 types) for assistance with weed control in both production and rotation areas.

These anecdotal reports indicated that polyculture practices are being used by alternative and conventional producers to some degree in Australia. They also present novel techniques not described in the literature. These observations tend to support the hypothesis of the research and justify the wider survey of producers.
10. The Survey Questionnaire-Construction and Distribution

10.1 Survey development and administration

With the literature search completed, a survey questionnaire was constructed to address the following questions and hypotheses:

1. **To what extent do Australian organic producers use polyculture practices compared to other areas of the world, now and in the past?**

2. **To what degree are certified organic producers innovating in the adoption of polyculture practices?**

3. **What benefits and risks do Australian producers see in their polyculture practices, what guiding principles do they employ, and what useful indicators are being used to monitor these features?**

4. **Is there a significant difference in the adoption of polyculture practices between organic and other producers?**

5. **What body of information exists within Australian producers on the principles, risks and benefits of polyculture production that expands into new areas not revealed by the literature search?**

Initial consultations conducted with a wide range of expert opinion indicated that the task of identifying commercial polyculture farmers would be difficult because they appeared to be scarce. A strategy not dissimilar to that faced by any hunter or fisher of scarce prey was developed to cast a wide net. Accepting that there are some 1600 certified organic/biodynamic producers in Australia, the consultants decided to survey the entire population as the most exhaustive approach. It became clear that there are a significant number of non-certified producers who still use alternative farming approaches (often labelled transitional, minimum input, sustainable, permacultural, conservation farmers, etc). In order to reach these transitional producers and conventional producers as well as certified organic producers, a total of 7000 survey questionnaires were distributed usually accompanied by background articles. The following list was used:

- 4000 questionnaires inserted into and article printed in *Acres Australia*.
- 2500 distributed through organic certification agencies, either in their newsletters or by direct mail.
- 500 by direct mail to small regional groups, key individuals, information networks, organic input manufacturers, relevant researchers, conventional rural press, organic produce marketers and others who might know of survey candidates.

The key goal was to physically put a questionnaire in the hands of every certified grower. This was accomplished with the full cooperation of currently AQIS accredited organic certifiers with the exception of the Biodynamic Research Institute, who declined to participate. We believe that some of their producers may have discovered the project through the other outlets for the questionnaire.

The secondary goal of reaching transitional producers can be considered to be met by the *Acres Australia* insertion. As the only substantial national magazine covering alternative agriculture, it was the most
likely instrument for that purpose. Background and promotional articles were submitted and published in
two dozen magazines, newspapers, email networks, websites, and newsletters in the hope of soliciting
enquiries for the questionnaire.

The questionnaires and articles were distributed during the first two weeks of June, with a deadline for
returning questionnaires of 15 July, giving respondents a month to reply.

10.2 Response to the Survey

As of 21 July 2000, allowing five weeks for survey returns, a total of 125 responses were received. Late
returns added another 14 responses, giving a total response rate for the 7000 piece questionnaire
distribution of 1.8%. This low response rate was disappointing and could be due to a large number of
different factors:

- That the survey was not understood,
- That those not returning recognised that they were not engaged in polyculture production,
- That they decided that the literature definitions of polyculture did not describe their practices
  (such as livestock on pasture, rotation farmers),
- That they were too new to farming to offer a valid reply,
- That they were practicing polyculture but were unaware of this fact,
- That they were practicing polyculture but were not aware of the risks and benefits of doing so and
  therefore did not feel qualified to reply,
- That they were too busy to reply,
- That they were not producing polyculture crops which were commercial,
- That they were not interested in the survey,
- That the organic industry as a whole is ‘over-surveyed’ and that they were experiencing survey
  fatigue.

Ten surveys were returned blank; with only critical comments about the value of government funded
research (indicating possible survey fatigue) or simply to request information about the survey results.

The structure of the questionnaire contained some latent minor faults: the page for assessing and reporting
risks was printed on the back page and many respondents appeared to miss this section when filling out
the questionnaire. One term, agripastoral, was legitimately described in the literature to apply to animal
production within crop production area (ie. grazing under orchard) but was not included in the survey
definitions of polyculture. Such practices were described and may have come under ‘agroforestry’ but
they were small in number (3 respondents). These systems usually only occur with confined livestock
and/or tree crops for obvious reasons. The content of the questionnaire may have been too technical or
conceptually difficult for some producers to understand, but the fact that those practicing polyculture
production often completed the survey with comprehensive reports and obvious understanding leads the
consultants to believe that this facet acted as a ‘filter’. Those who were doing polyculture understood the
survey, those who weren’t did not. The original proposal included funds for survey validation cycles that
were reduced on the final project funding. Limited knowledge of polyculture practice adoption amongst
the surveyed population was identified as a known risk in the research contract.

Guided by the literature definitions of polyculture, total responses were sorted to two sets- proto-
polyculturalists (68) and polyculturalists (71). Thus polycultural organic and sustainable producers
constituted only 1.01% of the total survey population and half of the responses to the survey. Therefore,
the initial assumption of the research project that organic growers are innovating in the development and
adoption of polyculture practices was not supported by the research findings. This is further evidenced by
the observation that of the polycultural respondents, about half were fairly rudimentary in the level of
sophistication of their polycultural system. Most were short term market gardens, often sequentially cropped with minimal crop interaction or grain cropping with undersown pasture amendment or were minor extensions of common rotations and many had questionable observations as to principles, benefits or risks of their polyculture system.

The small population of valid polyculturalists constrained a planned element of the research to conduct on-farm interviews of ‘best farmers’ to evaluate real versus perceived risks and benefits of polyculture practices on the ground to attempt to elucidate further principles not found in the literature. Indeed, this research project has clearly demonstrated that many of the risks and benefits are more clearly defined in the literature than previously believed or currently known by producers. After consultation with RIRDC, it was agreed to use the following strategy to structure the discussion of results:

1. Review and report on proto-polycultural responses with an eye to polycultural or related organic principles employed, and list practices that are ‘close’ to polyculture as defined in the literature.
2. Review and report on polyculture responses, extracting stated or implicit principles used, suggested guidelines used by the producers in their management and an assessment of their specific practices for matching to literature definitions and to illustrate specific or novel practices of possible interest.
3. To demonstrate the applicability and risk of organic polyculture systems in diversifying agricultural systems through the use of scenarios of polyculture production being suggestive future visions of the transition to and operation of successful polyculture production firmly grounded in both the literature and survey information.

This approach allows the presentation of information that is descriptive, indicative, suggestive and illustrative, if not definitive. With this caveat in mind, the consultants collated, analysed and tabulated the survey content in several ways to meet the research goal of ‘to collect, analyse and distribute the principles of successful organic polyculture farming’. In addition, two scenarios of polyculture production were generated as an integrating explanatory ‘big picture’ to further articulate principles and practices from both the literature and survey results.

The results of the empirical survey guided by conclusions drawn from the literature are reported in the next section.

10.3 Proto-polycultural responses and discussion

Despite the fact that these respondents failed to meet the definitions of polyculturalist, these responses often indicated that idea was understood. Several respondents indicated that they were ‘almost polycultural’ but lacked time, experience, commerciality or observed benefits or risks to report. A considerable number reported well known, if not polycultural practices: rotation, green manure, mulching, permaculture principles, hoping that they met the definition of polyculture. Intuitively, the consultants felt many proto-polyculturalists ‘wanted’ to be polycultural.

Their reported guidelines and implied principles tended to focus on soil health firstly, then the role of natural models and the importance of farmer involvement. Most were already evident from the literature but one: ‘employ high human presence’. This put a slightly different light on the literature which discussed increased use of intuition, reapplication of lost and traditional skills, and the challenges of increased management requirements. Even proto-polyculturalists saw the need and value of increased human presence for observation and management, and not particularly as a constraint. Their responses to guidelines and principles used follow as quotes or have been slightly paraphrased for clarity:

- Use intuition
- Work with nature systems/spirits
• Improve soil to increase crop health
• High human presence needed
• Soil is always protected
• Plant random like nature
• Use diverse crops for diverse markets
• Increase complexity
• Grow what is suited to conditions.

In the reported practices, proto-polyculturalists showed the overall tendency to be just that: often ‘almost’ polycultural. Numerous production systems could evolve to functioning polycultures if commerciality was achieved, if the system was fully implemented as planned, if all crops in the system were sold, when the system was producing later, or when the results over time were gave sufficient observations to report. Many reported known organic practices, nitrogen inoculation, timely weeding, rotations (many), companion planting, remineralisation, permaculture techniques (many) and green manures/cover crop use (many). Specific proto-polycultural practices follow for illustration:

**Horticulture**
- Row intercrop pinto pea under pineapple (cover crop)
- Row intercrop tea tree/permanent herbs (new)
- Sweet potato understory in market garden
- Row intercropping bushfood trees (not yet commercial)
- Row intercropping mixed fruit trees (planned)
- In row intercrop of herbs, flowers, raspberries under fruit trees (new).

**Animal Culture**
- Row intercrops of lab lab/forage sorghum hybrids for beef grazing
- Sheep under macadamia
- Geese on pasture under citrus
- Cattle under timber rows (new)
- Savory type holistic cell grazing system.
- Sheep and garlic under pecans and macadamia (new)
- Legume/root vegetable/grain/grass planted pasture for dairy.

**Broadacre**
- Cereal undersown with clover/lucerne for following pasture
- Wide spaced agroforestry, pine over wheat (new)
- Pea/sugarcane row intercrop
- Pasture under grapes or orchard
- Timber, tea tree, flowers, bushfood mixed species rows (new).

Overall, proto-polyculturalists evidenced a fairly rudimentary understanding of polyculture knowledge, appeared to be seeking the simple outcomes of better space utilisation, diversity of crops for market and labour matching, or were using systems where all crops were contributing to total system success rather than the strict literature definition that all components were commercial. Just as in present subsistence polyculture, what is being measured is not always what is important to the practitioner, a limitation in the way that science is conducted.

**10.4 Polycultural Responses**

Of the 71 responses containing polyculture practices under the definitions of the research study, the majority were mixed market gardens or tree crop culture. This is in keeping with the bias in organic agriculture toward such crops. The remainder, in order of frequency, were livestock, grain or mixed
farming systems. By the definitions and in order of number of respondents reporting, they termed themselves in the following way:

- Row intercropping (25)
- Sequential cropping (23)
- Intercropping (16)
- Agroforestry (11)
- Silvopastoral (8)
- Agrisilvicultural (6)
- Relay intercropping (5)
- Strip intercropping (4)
- Agrisilvopastoral (3)
- Agripastoral (2)
- Mixture (2)
- Mixed intercropping (2).

It should be noted that some respondents employed several polyculture systems and that some farming systems bridged several literature definitions. Of the two most prevalent, sequential cropping was most often represented by short term cycling of vegetables through a market garden situation or as grain rotations with variable intensity of crop interactions. Similarly, row intercropping was commonly found with alternate vegetable and/or tree crop rows but was supplemented by a number of grain/lucerne cropping practices. The sequential cropping was often part of a longer rotation pattern. Polyculturalists showed a high level of development of in-row polycultures including vegetables, herbs, fruit, nut, mulch, and even occasionally including animals. These intensive approaches, largely hand harvested, would come closest to the traditional polyculture of home agroforest gardens. There were far fewer examples of mechanised polyculture.

Principles of polyculture production, either reported as guidelines followed or from their description of the farming system often duplicated but occasionally expanded on the principles arising from the literature. The most reported principles were those of permaculture, as illustrated by the statement: ‘All elements work together to give wide benefits’.

Indeed, numerous respondents objected to our request for the 5 most important benefits, saying that they all applied, or that it was difficult to pick the 5 most important. One termed the concept of yield as ‘the sum of component parts over time’ rather than the conventional definition of single crop production quantity. Again, numerous principles of organic farming were included, even though not particularly relevant to polyculture: minimise tillage, keep soil covered, use legumes where possible, alternate leafy and root crops, never plant the same crop twice, decrease nutrients leaving the property, maximise the lifespan of non-biodegradable inputs or the respondent argued that animals were essential in any farming system.

The polycultural respondents were closest to the literature in noting the increased biological efficiency; ‘polyculture = maximum sunlight capture for maximum carbon fixation and nutrient cycling and maximum biodiversity’ in the understanding of ecosystem mimic/analoge approaches, ‘work in cooperation with the ecology’ and ‘only grow crops which do well in the local natural conditions’ and ‘minimise monoculture’. Economic viability was clearly important to polyculturalists and often the reason they used these practices was for lower income risk or higher income per unit area. This was illustrated by some statements such as, ‘for me, big time farming is out due to low or no profits’, ‘I’m busy looking for ideas to get away from common cropping to use less land more profitably’ and ‘[polyculture] has less risk than any other system tried’, though it is difficult to distinguish yield risk from income risk in practice.
They clearly identified some external constraints to successful polyculture such as ‘climatic conditions are the sleeper in dryer areas’ (a constraint for grain crops), ‘2\textsuperscript{nd} and 3\textsuperscript{rd} generation [seed] needed for soil and species adaption’ and ‘very slow development [building biological infrastructure] needs freedom from economic constraints’. Some respondents noted the role of intuition, observation, and adjustment in achieving success, and acknowledged that management input varied over time, and that their system was site specific. Many of the observed benefits related to simple architectural aspects of polyculture where more intensive use of the same space could be achieved or described structural phenomena as in ‘the rye acts as a trellis for vetch for easier reaping’.

Specific practices reported or implied by the responses are of interest, and follow. None appeared in multiples except for in-row multi-species culture of vegetables, fruit or other crops.

\textit{Reported polyculture practices}

\textit{Horticultural}
- Three crop rotation of mulch crops under orchard rows
- Alternating ‘good, bug’ rows of native and exotic annuals for beneficial insect support in market garden
- In row intercropping (multi-species rows) in market garden or orchard
- Capers/herbs under olives alternating with rows of wattle/tagasaste or pistachio
- Simultaneous and sequential strawberry under caneberry
- Mixed fruit/nut orchard, herbs between trees, vegetables between tree rows

\textit{Broadacre/Animal}
- Grain undersown with pulse or forage legume
- Poultry, pork and beef on perennial multi-species pasture
- Rabbit, ducks, geese or chicken production under orchard
- Mixed intercrop of carrot, silverbeet, pumpkin, rockmelon for chicken forage

\textbf{10.5 Scenarios of Successful Polyculture: Temperate and tropical}

This section uses the tool of the grounded scenario. It is a technique of synthesis and communication that facilitates decision-making in the absence of certainty. While the project identified a substantial body of knowledge in polyculture production, the survey result provided insufficient on-ground examples in Australia for clear generalisation or specific models to follow. The scenario is used to illustrate principles from both the literature and in the context of the empirical data collected from the polyculturalist survey responses. It enables integration of observations from both information sources into a holistic, and hopefully, predictive ‘big picture’ of how polyculture might work in practice. A scenario is also useful in making theoretical concepts understandable to the average land-holder, ‘a picture is worth a thousand words’.

To cover all possible ranges of cropping systems, climates and farm business scales completely would be impossible. Therefore, two specific, indicative farms are used to form the scenarios—a temperate grain/livestock farm and a tropical sugarcane/horticulture operation. This should be sufficient to cover most of the principles from the literature and the reported practices from survey responses. It is written in the second person, as if the writer was a reporter, looking over the shoulder of Peter and Paula through the transition to polyculture production over the next 20 years.

This is not intended as specific farm advice, nor as necessarily optimum or correct for any one farm or farmer. It should be seen as a technique that provides a story, albeit well grounded in the literature and survey research results that illustrate how a polyculture farm might function in the future. Hopefully, it will build understanding, imagination, and innovation in sustainable land-use in Australia.
This is what it might look like…

**Temperate**

Peter and Paula Poly grew up on farms in the cool western tableland slopes. When they took over her family’s farm 20 years ago, it was a typical wheat/sheep/cattle operation of the time. Peter had done some university and had increased his awareness of the environmental impacts of modern monoculture farming styles. As well, Paula had watched her local community decline as farms became larger, private and state monoculture forestry plantations absorbed good land and commodity export crops attracted lower and lower market prices due to the forces of globalisation. All these factors had constrained her family’s ability to maintain their input and land reclamation costs. When Peter learned that they were exporting eight kilograms of soil down the creek for every kilograms of wheat sold, he convinced Paula that they needed to find a better way.

Fortunately, they stumbled on a dog-eared copy of a 10 year old RIRDC report on polyculture production principles, benefits and risks. While it was a bit thick going, they both slowly picked up some useful ideas and applied them to their operation. Some nearby organic farmers pointed out the traditional organic practices that they used for soil management and Peter knew that healthy soil would make it easier to produce healthy crops. Paula observed that their cropping pattern of single wheat crops only utilised part of the season and that not only was the land essentially bare for many months, even at maturity the plants only fully colonised the fields for a couple of months. As they were in a higher rainfall area, they often established summer crops or pastures after wheat. Peter noticed that some local farmers had always undersown their wheat plantings with pasture species to grow on for grazing after the wheat was harvested in a mixed intercrop. This used more of the sun and water and minimised erosion exposure. Paula was in charge of the animals and she had often remarked that the follow-on planted pastures after wheat never had the growth of the undersown pasture areas and suffered more from summer droughts.

Peter tried earlier winter sowing of the wheat, looked at different wheat varieties and came up with a disease resistant mixture of short maturity so they could get undersown legume pastures out sooner in the summer. This improved resource capture and dramatically reduced weed problems as opposed to wheat only or wheat-plow-out to pasture. The cattle loved it and the sheep were happy to help clean up. Some of the richer areas in their region supported dairies, often on irrigated ryegrass and clover pastures. The dairy people had told Paula about problems of pasture re-establishment due to herbicide resistance, the high cost of inputs, and declining animal health. When she put pen to paper, it turned out that they would be better off agisting their best permanent pastures (by now a complex mix of native and introduced grasses and legumes) and reducing the beef herd to run with the sheep on their hill country. Remembering that one of the key polyculture principles was **Land use intensification**, Peter started thinking about other modifications of his wheat growing. He found markets for some unusual pulses that he could grow with the wheat. With careful selection of varieties he could harvest them at the same time, cleaning to separate. He even got an additional undersown pasture establishment in the same season, if it was a good one. The local farmers’ group that they had stated to work with were impressed, and a field day was held to mutual benefit.

Remembering the second polyculture principle: **Build diverse complexity**, Peter suggested alternating the wheat subsystems with other cropping mixes as a mosaic of differently cropped fields across the farm. They experimented with other grains, pulses, and mustards. As they were slowly shifting to organic practices, Peter learned that much of the world’s canola was genetically modified and that there would be a real market for organic, non-GMO canola oil. Knowing enough by now that he could include a legume in the planting, and that the dairies were always in need of high protein supplements and good hay, he finally decided that canola and peas, planted and harvested together without need for machinery modifications, could be a go and would generate a useful harvest regardless of season.
Paula had been thinking about the history of her land, about what was there before and how it might have worked. She had an intuitive belief that another principle of polyculture: Polyculture is natural, just plain made sense. In her area the reasonably deep volcanic soils had supported open eucalypt and box forest with considerable grassy understorey, generally maintained by occasional fires. In the remnant areas around them she had noticed different species in the gullies and riversides and how they supported abundant birds and insects. She started to think about how they could construct producing systems that were analogues of, or mimic the native vegetation. Peter wasn’t about to let her plant gum trees across the wheat paddocks but she had some ideas. When Peter approached her about various pest problems, she exclaimed: ‘Of course! We’ve got no trees for the birds that eat insects to live in.’ On further reflection, they began to realise the potential landscape benefits beyond the farm level that they could contribute to and profit by.

They started working out a whole farm plan that would maintain or increase biodiversity and establish wind breaks for paddock and pasture, as well as lambing areas. They would also consider possible perennial trees and vines for inter-row planting in shelterbelts and agroforestry alley forage cropping in the paddocks. Paula slowly convinced Peter that wide spaced agroforestry of veneer peeler pines and fast growing eucalypts wouldn’t interfere with either cropping or pasture uses in the paddocks and they started establishing these crops. Paula remembered a local berry processor that needed strawberries and they started cropping strawberries in sequential cropping with swedes, turnips and sorghum were offered to the nearby dairy farmers for their cattle. Peter found good success with summer soybean for certified organic seed followed by aerial seeded barley but relying on barley germinating before soybean harvest didn’t always meet with the right rainfall patterns. Relay intercropping can be difficult with machines, they found.

Peter and Paula also experimented with barley/oats and lucerne or safflower under or after wheat and really started to ask themselves- why did the old folks just grow wheat? This is much more interesting! Paula started to investigate grapes and olives as alley rows in the cropping paddocks. If they produced good crops then they would also be able to provide employment for some of the young people in the area, just like in the old days when farms were more profitable and labour intensive. However, she was concerned that the markets were too distant and the bulk commodity prices might not support the need for hired labour. Peter kept on emphasising the legumes in his cereal crops and found vetch and lupin useful, though sometimes only to graze if the season wasn’t right. He always found a market for his oat/vetch hay. Wheat and lupins seemed to always work well, as did medic under cereal followed by grazing. He was most impressed by his improving soil tilth, lower weed problems, and reduced erosion from keeping the soil covered.

Paula started expanding her animal populations with all the varied and nutritious feed available. She had good success with poultry, pork and beef on perennial multi-species pastures but concentrated on portable chicken pens rotated through pasture paddocks to meet an excellent market for free range organic eggs in the cities. She was particularly pleased, as were the chickens, by the pasture gardens of carrot, silverbeet, pumpkin and rockmelons. She notices far less parasite problems in her livestock because of frequent movement and a rich variety of feed. Remembering the polyculture principle to Design the farm as an analog mimic of the pre-existing native system, she concluded that grazing animals were much more nomadic in the past and that the more she moved her animals around, the more this replicated natural nomadic foraging. She also learned that she had more options available for pasture management, faster animal growth, and healthier soils. Now, if only she didn’t have to listen to Peter’s complaints about the fencing work! Due to the more varied, higher production and the premiums from organic status, their income had risen and was more stable. They had been able to hire a couple of locals to help manage their increasing complexity. One was an older farmer, forced out before Peter and Paula took over the farm. He was bemused by the new systems but saw that they worked and contributed his knowledge about soils,
climate and machinery that he thought no one would ever need again. He remembered how clean fields were after a rye crop and Peter started using more rye after confirming its alleopathic effects to clear up weed problems that shade or tillage didn’t manage.

Paula started working on some new agroforestry rows for the cropping paddocks of wattle seed, carob, olive, pistachio and timber but about that time I moved away and didn’t see them for a few years. I heard they got an incredible offer for their farm and were considering moving north to the tropics. I’ll have to keep in touch with their progress…

**Tropical**

Peter and Paula Poly moved north to farm sugarcane and horticultural crops. After 14 years on their temperate grain and livestock farm, they wanted a change and a new challenge. Peter and Paula were particularly interested in the longer season in the tropics and the expanded range of potential crops they could use. Because their temperate farm had been developed under polyculture practices and had demonstrated higher and more stable incomes and yield, much lower input costs, fewer offsite impacts, and received premium prices for their certified products, they were able to sell the farm easily at a price considerably higher than their conventional monoculture neighbours. This price had also been driven up by the biodiversity tax incentives brought in by the federal government. The buyer’s bank was more than willing to fund the purchase, recognising that sustainable and diverse operations were likely to persist and grow over time. Peter had heard that some of their old neighbours had been unable to get out at any price, as their degraded farms couldn’t cover costs or the banks were unwilling to lend on properties of questionable health or durability.

Peter had become comfortable with the nature of plant crop interactions in his polyculture farming approach and saw the opportunity to expand these in the longer tropical growing season with more reliable moisture. He knew the eastern coastal plain was some of the richest land on the continent and he hungered for some rich basaltic soils to play in. Paula had always gardened fruit trees and vegetables, including some local market sales and had become more interested in native forestry, especially native rainforest fruits. She wasn’t sure if the hot, wet tropics wouldn’t be a mess of insect and fungus disease risks but knew that most tropical farmers use polyculture techniques to minimise these problems.

Her first project on the new place was to fully research the history of the land, the original native vegetation, and the parameters of the climate. Fortunately, they had considerable uncleared native rainforest up the back and along the creeks to learn from, as well as a number of local people who could help identify plants. Unfortunately, the cane lands had a long history of continual cane and suffered compaction, low organic matter, some organochlorine contamination and some apparently intractable insect problems. Peter reckoned he knew what to do to set it right, and with the extra money from their old farm they could make it through the 3-4 year conversion period, particularly if they booted up some fast annual vegetables for cash flow. Paula had done some research into Asian markets and felt they could meet quality, price and timing requirements for a variety of vegetables.

Peter set to work on the bulk of the cane lands, fast cycling green manure crops using deep ripping and extensive rock remineralisation with an eye to a long term alley cropping agroforestry system using cane/vegetable rotations in the alleys with alternate and sometimes mixed rows of high value rainforest timbers and native bushfood fruits in the rows. This would give them a high diversity of crops, income, spread out the labour requirements and provide internal nutrient cycling and resource capture opportunities. Paula felt that the structural complexity would offer abundant habitat for birds, bats, and insects that would largely control their existing and potential pest problems and Peter recognised that the deep rooted tree rows would cycle up deep nutrients from the subsoil that the previous cane was unable to utilise. They planted the forestry rows first, including substantial tropical fruits and bushfood fruits as mixed species rows and continued to work up the cane lands for the first two years, alternating production
and regeneration on a rapid basis with the adoption of short ratoon cane varieties. Even in producing cane, Peter put peas down the interrows.

Paula was the first to recognise that the previous rainforest was essentially self-mulching with leaf litter drop in the dry season so she heavily mulched the new trees with nearby cane plants, cut, dried and raked to the rows. At this immature stage, she expected to have to physically protect the young trees from wallabies, trap rats and watch for insects until the native predators and alternate feeds in their reserve areas along the creeks (recently fenced off) became established. She reckoned if she was going to be out there, she might as well grow a salable crop as well, so the tree rows were complexed with a variety of vegetables for sale and quite a few trials to judge best varieties, season and market acceptance. She had already thought that some on-site value adding might be necessary to increase returns and generate a storable product and had already identified a cooperative inspected kitchen in the region. She was excited to start forging links in their new community.

Peter was relieved that he would not have much of a job redesigning the line of equipment he bought with the farm. The previous owner had already gone to contract harvesting and most of the existing equipment could be used with a few modifications and exchanges. He established the cane alleys in harvester width multiples of at least two widths to allow for cutting up to the tree rows and negotiated some billet blower modifications with the harvest contractor to feed trailing bins. There would have to be only small changes to the cane growing machinery or practices. Like many northern growers, Peter was committed to green harvest: harvesting without burning, leaving tops and leaves as a protective mulch with multiple benefits both on and off site. He knew the locals had dramatically reduced pest problems, drought risk and soil compaction. Because he did not burn the cane paddocks, he was free to intercrop with vegetables and tree rows. He knew it would assist their eventual approval under the organic certification program as long as they could meet their expanded biodiversity and landscape impact standards.

Fortunately, the various government and industry extension officials had recently joined forces into a battalion of bureaucrats willing to pass on their understanding of holistic sustainable land use systems. They felt Peter and Paula would make a good demonstration of the polyculture principles that they now supported. By working in multidisciplinary teams, considering the nature and operation of the original vegetation of the area and its dynamic, they had developed a wide array of land use options that could be utilised in the region. Several traditional polyculture experts had joined them from Indonesia and Papua New Guinea and were welcomed for their knowledge and experience. Peter and Paula had already committed themselves to being a demonstration farm and to communicate their successes and failures to the broader community.

During their first rainy season, Peter appreciated the deep tillage work he had done, as there was much less erosion due to higher organic matter, higher penetration rates, and the run-off collection dams he had built for dry season irrigation filled clean. Paula was saddened by some tree loss in some of the lower areas and suggested some modest berms be dozed up to give wet year drainage. Looking back at the rain forest remnants, she understood that only maturity would provide the extensive root systems and natural drainage characteristic of the rainforest, as well as their superb ability to pump out large quantities of water as transpiration. Peter thought he might as well turn the problem into the solution and suggested some drains to another dam would serve the tree rows, provide irrigation, and establish another possible aquaculture site while it supported local wildlife. After some argument, they did both.

While building bird roosts and bat boxes one rainy season, Peter and Paula began designing their vegetable polyculture. The limitations of site, conditions, available genetics, and market price and demand had reduced their list of possible crops but they felt they could still grow at least 4-5 different vegetables each season. They chose an alternate row intercropping model that offered harvest efficiency up the rows and diversity across the rows. They understood that with short term annuals there is less
chance to build long-term functional interactions and they concentrated on a structural, architectural
design that focused on resource capture and income maximisation. They thought they could sometimes
manage sequential intercropping with fast greens under longer-term vegetables like tomato or capsicum,
but that this would be most suited to hand harvested types. Paula had identified a local aboriginal
community who had developed a harvesting business serving wild and plantation bushfood markets and
they indicated they could also help with the vegetables. Because of the premium prices they receive and
the stability and diversity of their income, Peter and Paula were able to employ several locals as well and
often hosted overseas travellers under the Willing Workers on Organic Farms (WWOOF) program.

As they neared the end of their first five years, Paul and Peter felt that they were making the transition to
the new place reasonably well. Their early experience in the south had been very useful as most of the
principles still applied: **Intensify land use, Build diverse complexity, Accept that polyculture is
natural, Rely on self-regulation mechanisms, and Design native ecosystem mimics.** Peter wasn’t sure
if the cane would continue. He thought it was a poor analog to the previous contiguous rain forest that had
evolved in the area, and the price of sugar had remained suppressed due to competition from other
countries with lower land use standards. Once again, he turned a problem into the solution by announcing
he was going to produce a line of rainforest fruit-flavoured liqueurs and cordials for export! After a
month in the shop, he announced he could do it all on-farm with freeze concentration of farm pressed
cane juice, an on-site kitchen and some extra labour. Paula thought this idea a bit mad but set to
identifying markets and penciling out the numbers. Later, I sampled some of their new products and
found them exquisite and they have since been met by enthusiastic markets.

At this stage, the final economic outcome is unclear. Peter is convinced that the sheer diversity of their
enterprises will mean success, since he attends to the basic principles and requirements of native and
sustainable polycultures. Their early cash flow is sufficient, their input costs quite low, and they will gain
premium prices and a higher proportion of retail price than simple monoculture commodity producers.
They’re perfectly happy to be investing in biological structuring because they know it will pay off later.
Peter and Paula now feel confident that their children will have a farming future. Paula has started
breeding her own adapted vegetable varieties based on some Asian imports. Peter is retreating from the
tree rows with his cane and starting to replace it with high-value cabinet timber rows with vegetable
intercrops planned for the first few years. With the extra income from their biodiversity conservation
payments, they are working on aquaculture systems. For their efforts in building community links,
communicating their model and demonstrating the wider landscape benefits of their approach, they were
recently awarded the ‘**Ecological Farmer of the Year**’ award by RIRDC as well as winning the $6000
prize for the most innovative business plan.

I can hardly wait to come back and see them in a few years…
11. Results and Discussion

The initial premise that organic producers would be most likely to be innovating in the development of polyculture production systems was over optimistic on the part of RIRDC and the consultants, perhaps based on anecdotal popular press reporting. The project found far less polyculture practice among organic producers than expected, though survey results offer some interesting observations and expanded usefully on the literature research.

Early in the investigation it became clear that there was a significant body of research results relevant to polyculture production from a wide diversity of fields of study. Moreover, it became clear that little had been done to synthesise these related threads of knowledge and that Australia was quite behind the rest of the world (except for the field of agroforestry) in acknowledging existing research or in undertaking new research oriented to polyculture production. The survey produced considerably less than expected in terms of a response rate and new information, while the literature search proved to be a rich source of information and was considerably more extensive than expected. The consultants believe that despite the necessity of weighting the final report more on the literature and less on the empirical results of the survey, that the objectives of the research have been substantively met. To attempt to generalise upon such a small number of respondents would be to expand this study in an anecdotal rather than scientific manner, lacking in a reasonable pool of individuals in order to isolate exemplars. Even within the generous terms by which qualitative sample selection is conducted, following a large survey with a follow-up of a few individuals from a very low response rate would be very dubious scientific practice. Nevertheless, that data which was collected does contain useful information for the organic industry if only to illustrate ‘what is not’ rather than ‘what is’.

There were inherent limitations in the study that may appear to be excluding some facets of agriculture or land management. As any mixed pasture could be termed a ‘polyculture’, and due to the fact that the pasture crop itself is not a sold product, the study, and most of the literature, did not address grazing systems in a substantial way. Similarly, many useful or organic practices, like green manures, underseeded following cover crops, rotations, permaculture or revegetation situations were not included as the criteria for the study was polyculture production of commercial crops for sale. The research study and the literature tended to be dominated by vegetable, fruit and grain cropping with a lesser but significant contribution covering agroforestry, animal interaction and legume forage and pulse production. Little was found in the literature on polyculture options for plantation forestry, aquaculture or fibre crops. While survey responses were dominated by mixed market gardens, the lack of reporting on observed interactions indicated that if polyculture principles were in operation, they were brief or not observed.

11.1 Summary of principles, strategies, benefits and risks

Arising from the literature and the questionnaires that were returned to the consultants, a number of principles, strategies, and benefits of polyculture production could be identified. These are presented in Table 14 in tabular form and they are structured according to emergent ecosystem property and the polyculture principle which they support. Table 14 is grounded largely in the literature but makes ‘common sense’ use of the guidelines uncovered by the empirical survey.
Table 14: Properties, Principles, Strategies and Benefits of Polyculture

<table>
<thead>
<tr>
<th>Emergent Ecosystem Property: Productivity</th>
<th>Polyculture Principle: Intensify land use</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strategy</strong></td>
<td><strong>Benefit</strong></td>
</tr>
<tr>
<td>Produce more with less</td>
<td>Higher, more stable yield and income</td>
</tr>
<tr>
<td>Nutrient &amp; maximise sunlight capture</td>
<td>Higher biological efficiency</td>
</tr>
<tr>
<td>Increase biological efficiency</td>
<td>Less waste, leakage</td>
</tr>
<tr>
<td>Higher land use diversity</td>
<td>Contributes to biodiversity conservation</td>
</tr>
<tr>
<td>More efficient utilisation of land</td>
<td>Higher energy efficiency</td>
</tr>
<tr>
<td>Apply to any land use</td>
<td>Integrate native and agric system management</td>
</tr>
<tr>
<td>Soil is always protected.</td>
<td>Enhanced soil and plant health with reduced erosion, decreased weed problems.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Emergent Ecosystem Property: Stability</th>
<th>Polyculture Principle: Build diverse complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strategy</strong></td>
<td><strong>Benefit</strong></td>
</tr>
<tr>
<td>Seek multiple benefit</td>
<td>Less market or yield risk &amp; multiple values served</td>
</tr>
<tr>
<td>Integrate functions</td>
<td>Stability of yield, income resilience of agroecosystem</td>
</tr>
<tr>
<td>Increase complexity; Multiple function</td>
<td>Serves multiple values/produces multiple outcomes</td>
</tr>
<tr>
<td>Diverse crops for diverse markets</td>
<td>Income risk reduced</td>
</tr>
<tr>
<td>Diverse crops for variable climates.</td>
<td>Decreased climatic risk.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Emergent Ecosystem Property: Equitability</th>
<th>Polyculture Principle: Polyculture is natural</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strategy</strong></td>
<td><strong>Benefit</strong></td>
</tr>
<tr>
<td>Both small and large, poor and rich can be polycultural</td>
<td>Higher social and individual diversity</td>
</tr>
<tr>
<td>Respect intuition and use traditional knowledge</td>
<td>Return of value in human instinct, expertise; Relearn lost skills, existing knowledge utilised</td>
</tr>
<tr>
<td>Apply to any climate/environment/enterprise scale</td>
<td>Socially just technique, widely applicable</td>
</tr>
<tr>
<td>Adaptable to varied sites &amp; goals</td>
<td>Higher labour efficiency; optimum landholder options</td>
</tr>
<tr>
<td>Treat as opportunity, not vestige</td>
<td>Monoculture now seen as 100 yr anomaly in a long history</td>
</tr>
<tr>
<td>Increase human presence</td>
<td>Increased employment; more knowledgeable land managers.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Emergent Ecosystem Property: Autonomy</th>
<th>Polyculture Principle: Seek self-regulation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strategy</strong></td>
<td><strong>Benefit</strong></td>
</tr>
<tr>
<td>Biotic process replaces external materials</td>
<td>Reduced input costs; reduced energy use</td>
</tr>
<tr>
<td>Internal nutrient and energy recycling</td>
<td>Reduced environmental impacts</td>
</tr>
<tr>
<td>Optimise resource capture</td>
<td>Improved resource use; inherent resource conservation</td>
</tr>
<tr>
<td>Seek farm self-reliance.</td>
<td>Reduced risk.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Emergent Ecosystem Property: Sustainability</th>
<th>Polyculture Principle: Design analog land-use as ecosystem mimic</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strategy</strong></td>
<td><strong>Benefit</strong></td>
</tr>
<tr>
<td>Design from nature using ecological principles</td>
<td>Resilience of natural systems gained</td>
</tr>
<tr>
<td>Farm in nature’s image</td>
<td>Existing ecosystems services used and maintained</td>
</tr>
<tr>
<td>Use permaculture principles</td>
<td>Same as above</td>
</tr>
<tr>
<td>Use pre-existing native vegetation as model</td>
<td>Agroecosystem persistence; natural strategies &amp; processes retained</td>
</tr>
<tr>
<td>Use traditional knowledge of the place or from similar biophysical situations</td>
<td>Knowledge base utilised</td>
</tr>
<tr>
<td>Utilise natural and proven properties of ecosystem succession in production</td>
<td>Co-evolved complimentary production, reduced risk</td>
</tr>
<tr>
<td>Integrate native and managed ecosystem operation under common ecological theories</td>
<td>Integrated theme for management across all environmental wider landscape values met</td>
</tr>
<tr>
<td>Grow what is suited to the site.</td>
<td>Adapted production.</td>
</tr>
</tbody>
</table>
The risk of taking up or practicing polyculture principles was addressed in both the literature search and survey. Section 8 addressed those risks identified in the literature and survey responses did not appreciably expand on those already identified. For organic agriculture, it appears that the potential benefits far outweigh the risks but that there will be considerable ‘head scratching’ to implementation. The main risk seems to be that polyculture production might reduce risk! Much like conversion from conventional production to organic, the typical practitioner can’t see how it can be done at first, struggles during the transition, and then wonders why it wasn’t always done this way.

However, it is useful to reiterate some risk categories to shed light on what will be needed to extend the ideas of polyculture production further.

**Information/Research Gaps**
- Below ground interactions
- Systems suited to dryer areas
- Weed and disease interactions
- Insufficiency of industrial, mechanised examples
- Lack of farmer-friendly information
- Lack of management knowledge, options.

**Research Orientation**
- Research results often not generalisable
- Need for site, species and farmer specific models
- Need to more closely link ecologists and land use planners
- Lack of researcher acceptance of qualitative R & D
- Need to integrate social & natural science
- Need for changes in the way science is conducted.

**Plants and Cropping Systems**
- Poor predictability of new polycultures
- Progress takes time, competition dominates early, complementarity later
- Lack of suitable cultivars
- Inherent plasticity of components
- Loss of traditional knowledge
- Little information on mechanised polycultures.

**People**
- Lack of appropriate knowledge, skills
- Need for new models of R, D & E
- More complex management required that is iterative & adaptive
- Lack of information on economic returns and appropriate ESD compatible measures (externalities accounted for or triple bottom line)
- Polyculture as a mix of public & private benefits/values.
11.2 Specific outcomes and implications of the research

Specific Outcomes

- A body of knowledge was assembled for the first time (>250 item literature search)
- A firm grounding in science for polyculture production was established
- The principles and benefits of polyculture practices were clearly articulated
- Constraints to the wider use of polyculture practices were identified
- The proposition that organic producers in Australia are substantively innovating in polyculture production was not substantively supported.
- Polyculture was identified as an exemplary integrating theme across native and man-made land uses and between ecologists and agronomists.

Implications of the research for Australian land use

1. Expanded knowledge base now available, previously under utilised in Australia, but with a sound scientific and cultural base
2. Provides an integrating theme to bridge management of human/native systems and build communication between ecologists and agronomists
3. Establishes future importance of polyculture approaches
4. Requires new paradigms of scientific research
5. Requires a new socioeconomic framework.
12. Recommendations

1. **Further Development of Polyculture Production Options**
   Research is required to act on this body of knowledge, both in the ecologic and agronomic understanding. The first ‘best bet’ is to conduct further research to identify currently used, mechanised polyculture production elsewhere in the world and trial implementation in Australia. This will entail investigating biophysical conditions, crop component suitability, management requirements, and economic viability under a range of future economic scenarios. There is a need to translate traditional knowledge into current farming systems, to relearn sustainable land use from those who have sustained land use. The ecological basis of polyculture requires substantial support of ecologists.

2. **Disseminate the Knowledge Base**
   In addition to prompt publication and extensive distribution of this report by RIRDC, there is a critical need to extend the principles, practices, benefits and constraints offered by the polyculture approach. Specific environments/climates or commodity groups could be useful initial targets for extension. Only when individual land use enterprises are aware of the opportunities for redesign, can they come to meet the challenge of higher management capabilities required for a successful polyculture. Simple informational booklets, video demonstration of successful overseas examples, and retraining workshops for conventional agriculture and forestry extension staff would be most useful. Developing R & D partnerships among and with commodity based RDCs, state resource managers, and industry bodies (organic and conventional) is indicated. Farmer-friendly condensations of this report as small booklets would be necessary to extend on-ground trial and adoption.

3. **Exploit Polyculture Commercially**
   Based in on-farm participatory approaches that generate commitment and ownership, develop cropping system/environment specific polyculture demonstration projects. Adaptive planning and iterative cycling between design and component characteristics determination should generate commercially viable options in a short time. This should be explored with organic farming groups, commodity groups, farm organisations and commodity based RDC’s. These systems should be evaluated holistically, not according to economic rationalist optimisations of crop components only.

4. **Change the ‘Monoculture of the Minds’**
   Accept that holistic, system-wide and process based research and development will be most likely to succeed. Question market driven economic rationalism and accept the coming age of the environmental management system including the further developments toward the ‘triple bottom line’ which expects an enterprise to fully document the economic, social and environmental impacts of conducting business. New paradigms will need to be developed to implement these new realities, in resource science, agronomy, rural sociology, land use planning and certification of resource-based production. Thus the way that science is practiced, how research and extension is conducted and how normative ‘prescriptions’ are translated into specific site/species and land-holder solutions will have to change and adapt.

5. **Investigate Barriers and Risks**
   On an ongoing basis, research and resolve identified barriers to further adoption of polyculture production. Action at crop/farming system, R & D agency operations and further investigation of why and how the identified polyculturalists adopted in spite of constraints would be warranted.

6. **R & D for Organic/Conversion Agriculture**
   Most polyculturalists are organic. Organic farmers are most needful of polyculture principles and practices. Polyculture approaches should pervade future R & D in organic/conversion research as an overriding and integrating theme. Indeed, it can extend to agroforestry, forestry and other land use research planning.
13. References

Altieri, M. A. 1987, Agroecology: The scientific basis for alternative agriculture, Westview Press, Boulder CO.


Callahan, P. S. 1975, Tuning into Nature, Devin Adair, Old Greenwich.


Chapman, B., Penman, D. & Hicks, P. 1986, Natural Pest Control, Nelson Publishers, Melbourne.


Drolsom, P. N. & Smith, D. 1976, ‘Adapting species for forage mixtures’, in Multiple Cropping, R. I. Papendick (ed), (pp. 223-234), ASA Special Publication #27, American Society of Agronomy, Madison WI.
Erbach, D. C. & Loveley, G. 1976, ‘Machinery adaptations for forage mixtures’, in Multiple Cropping, R. I. Papendick (ed), (pp. 337-346), ASA Special Publication #27, American Society of Agronomy, Madison WI.
Gause, G. F. 1934, The Struggle for Existence, Williams & Williams, Baltimore.
Gomez, A. A. & Gomez, K. A. 1983, Multiple Cropping in the Humid Tropics of Asia, IDRC 176E, IDRC, Ottawa.
Gomm, F. B., Sneva, F. A. & Lorenz, R. J. 1976, ‘Multiple cropping in the western United States’, in Multiple Cropping, R. I. Papendick (ed), (pp. 103-116), ASA Special Publication #27, American Society of Agronomy, Madison WI.
Hart, R. D. 1986, ‘Ecological framework for multiple cropping research’ in Multiple Cropping Systems, C. A. Francis (ed), (pp. 40-56), Macmillan, New York
Harwood, R.R. & Price, E. C. 1976, ‘Multiple cropping in tropical Asia’, in Multiple Cropping, R. I. Papendick (ed), (pp. 11-40), ASA Special Publication #27, American Society of Agronomy, Madison WI.


Jackson, W. 1980, *New Roots for Agriculture*, University of Nebraska Press, Lincoln.


Lewis, W. M. & Phillips, J. A. 1976, ‘Double cropping in the eastern United States’, in Multiple Cropping, R. I. Papendick (ed), (pp. 41-50), ASA Special Publication #27, American Society of Agronomy, Madison WI.


Mollison, B. 1996, Travels in Dreams, Tagari Publications, Tyalgum NSW.


Nasr, H. G. 1976, ‘Multiple cropping in some countries of the Middle East’, in Multiple Cropping, R. I. Papendick (ed), (pp. 117-128), ASA Special Publication #27, American Society of Agronomy, Madison WI.


Okigbo, B. N. & Greenland, D. J. 1976, ‘Intercropping systems in tropical Africa’, in Multiple Cropping, R. I. Papendick (ed), (pp. 63-102), ASA Special Publication #27, American Society of Agronomy, Madison WI.


Passioura, J. B. 1999, ‘Can we bring about a perennially peopled and productive countryside?’, *Agroforestry Systems*, vol. 43, pp. 411-421.


‘Polyculture on six levels and growing’, 1999e, *Acres Australia*, vol. 7, no. 8, pp. 36-40.


Sanchez, P. A. 1996, ‘Multiple cropping: An appraisal of present knowledge and future needs’, in Multiple Cropping, R. J. Papendick (ed), (pp. 373-379), ASA Special Publication #27, American Society of Agronomy, Madison WI.


Snaydon, R. W. & Harris, P. M. 1981, ‘Interactions below ground- The use of nutrients and water’, in Proceedings of the International Workshop on Intercropping, R. Willey (ed), (pp. 188-201), ICRISAT, Patancheru India


Trenbath, B. R. 1976a, ‘Diversity or be damned?’ in *Multiple Cropping*, R. I. Papendick, P. A. Sanchez & G. B. Triplett (eds), (pp. 129-170), ASA Special Publication #27, American Society of Agronomy, Madison WI.


14. Appendix A- Sample Questionnaire

Larry Geno, The Polyculture Project
Reply Paid 66796, Ilkley Qld 4554

ARE YOU POLYCULTURAL?

Taking a few minutes to fill out this survey will help you and others become better producers. By understanding innovative multiple cropping methods, we can encourage the transition to more sustainable land uses. We think some of the best innovation comes from producers. We need your input and suggest it is also in your interest to participate in the survey. If you are part of a farmers’ group, feel free to copy and distribute this survey or accompanying article or phone us for more information.

The Polyculture Project Who are we?

As long time organic tree crop farmers and researchers, we have both academic and real life experience and commitment to building sustainable land use opportunities. This project is funded through the Rural Industries Research and Development Corporation (RIRDC) in its organic produce program under advice from the Organic Industry Advisory Committee. As agricultural consultants we know the value of participatory approaches as we conduct the three (3) parts of this project: a literature search of the field, a survey of producers and follow-up on-farm interviews. We can help you if you help us, but we also respect your privacy or confidentiality needs. You can contact us directly to discuss your potential involvement:

Dr Barbara and Mr. Larry Geno
Ph/Fx 07 5478 8815 before 4 pm, early mornings OK.

Please fold the questionnaire with the panel below visible and staple or tape to MAIL.
This questionnaire should take about 10-15 minutes to complete.  
Your response is very much appreciated. A reasonable estimate is preferred to no answer.

**SECTION 1: ABOUT YOUR CURRENT FARM BUSINESS**

1. **WHAT IS YOUR GEOGRAPHICAL REGION** (e.g. Darling Downs; Southern Tablelands NSW; Sunraysia)?

2. **HOW WOULD YOU DESCRIBE THE DOMINANT CROPPING SYSTEM(S) IN YOUR AREA?**

<table>
<thead>
<tr>
<th>Options</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broadacre Crops</td>
<td>☐</td>
</tr>
<tr>
<td>Dairy</td>
<td>☐</td>
</tr>
<tr>
<td>Timber</td>
<td>☐</td>
</tr>
<tr>
<td>Broadacre Crops/Grazing</td>
<td>☐</td>
</tr>
<tr>
<td>Fruits or nuts</td>
<td>☐</td>
</tr>
<tr>
<td>Small crops</td>
<td>☐</td>
</tr>
<tr>
<td>Sugarcane</td>
<td>☐</td>
</tr>
<tr>
<td>Small acreage mixed</td>
<td>☐</td>
</tr>
<tr>
<td>Other</td>
<td>☐</td>
</tr>
</tbody>
</table>

3. **HOW WOULD YOU DESCRIBE YOUR FARM NOW? (TICK ONE ONLY)**

<table>
<thead>
<tr>
<th>Options</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Just being established</td>
<td>☐</td>
</tr>
<tr>
<td>At an early stage of development</td>
<td>☐</td>
</tr>
<tr>
<td>At a late stage of development</td>
<td>☐</td>
</tr>
<tr>
<td>Developed to peak production</td>
<td>☐</td>
</tr>
<tr>
<td>Declining in productivity</td>
<td>☐</td>
</tr>
<tr>
<td>Run down</td>
<td>☐</td>
</tr>
</tbody>
</table>

4. **HOW LONG HAVE YOU BEEN FARMING?**

5. **HOW LONG HAVE YOU OPERATED YOUR PRESENT FARM?**

6. **SIZE OF FARM** ............ acres or ............ hectares

7. **TYPES OF FARMING OPERATION** (If you have more than one, please number in the order of importance):

<table>
<thead>
<tr>
<th>Options</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broadacre Crops</td>
<td>☐</td>
</tr>
<tr>
<td>Dairy</td>
<td>☐</td>
</tr>
<tr>
<td>Timber</td>
<td>☐</td>
</tr>
<tr>
<td>Broadacre Crops/Grazing</td>
<td>☐</td>
</tr>
<tr>
<td>Fruits or nuts</td>
<td>☐</td>
</tr>
<tr>
<td>Small crops</td>
<td>☐</td>
</tr>
<tr>
<td>Sugarcane</td>
<td>☐</td>
</tr>
<tr>
<td>Small acreage mixed</td>
<td>☐</td>
</tr>
<tr>
<td>Other</td>
<td>☐</td>
</tr>
</tbody>
</table>

8. **HOW MANY DIFFERENT CROPS DO YOU PRODUCE COMMERCIALY?**

(Please note, if you are growing a variety of small crops in one area (market garden), please count this as ONE crop).

Please list these crops in the order of economic importance to you.

________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

9. **HOW WOULD YOU CHARACTERISE YOUR FARMING STYLE?**

<table>
<thead>
<tr>
<th>Options</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Certified organic</td>
<td>☐</td>
</tr>
<tr>
<td>Uncertified organic</td>
<td>☐</td>
</tr>
<tr>
<td>Organic by neglect</td>
<td>☐</td>
</tr>
<tr>
<td>Certified biodynamic</td>
<td>☐</td>
</tr>
<tr>
<td>Uncertified biodynamic</td>
<td>☐</td>
</tr>
<tr>
<td>Transition to organic</td>
<td>☐</td>
</tr>
<tr>
<td>Not organic but sustainable</td>
<td>☐</td>
</tr>
<tr>
<td>Conventional</td>
<td>☐</td>
</tr>
<tr>
<td>Other</td>
<td>☐</td>
</tr>
</tbody>
</table>

10. **YOUR MAJOR MARKETS ARE** (Number in order of importance):

<table>
<thead>
<tr>
<th>Options</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commodity buyers</td>
<td>☐</td>
</tr>
<tr>
<td>Export</td>
<td>☐</td>
</tr>
<tr>
<td>Direct to retailer</td>
<td>☐</td>
</tr>
<tr>
<td>Capital city wholesalers (non-export)</td>
<td>☐</td>
</tr>
<tr>
<td>Food processors</td>
<td>☐</td>
</tr>
<tr>
<td>Direct to consumer</td>
<td>☐</td>
</tr>
<tr>
<td>Local and bioregional markets</td>
<td>☐</td>
</tr>
<tr>
<td>Other producers</td>
<td>☐</td>
</tr>
<tr>
<td>Other</td>
<td>☐</td>
</tr>
</tbody>
</table>
**Section 2: Defining Polyculture and Your Cropping Pattern(s)**
We’d like to know if you practice any of these methods. Polyculture encompasses a wide variety of cropping patterns, defined as:

**Sequential cropping**- growing 2 or more crops in sequence on the same land per year or cropping period longer than a year. E.g. double or triple cropping; ratoon cropping.

**Intercropping**- growing 2 or more crops simultaneously in the same area where there is significant interaction between the crops and more than one crop is managed at the same time.

**Mixed intercropping**- intercropping with no row arrangement, e.g. broadcast/ratoon; multi-species planted pastures.

**Row intercropping**- intercropping with 1 or more crops in rows; **Strip intercropping**- intercropping with width for independent cultivation, but close enough for the crops to interact; **Relay intercropping**- cropping pattern where the time of interaction is limited but with some overlap in life cycles.

**Multilines/mixtures**- growing multiple varieties of a single crop species e.g. different wheat strains of different genetics planted together.

**Silvopastoral**- growing timber and animals in the same area; **Agrisilviculture**- growing trees and annual crops in the same area; **Agri-silvopastoral**- growing timber, annual crops and animals in the same area; **Agroforestry**- growing wood crops with annuals or animals at the same time in the same space.

Using the definitions above, could you please briefly describe your cropping pattern(s), using only crops that are sold commercially.

Example: Cropping Pattern 1  **Agroforestry**- market garden under apple orchard.
Cropping Pattern 2  **Row intercropping**- peas and canola.
Cropping Pattern 3  **Silvopastoral**- beef on improved pasture under wide spaced pine trees.

<table>
<thead>
<tr>
<th>Cropping Pattern 1</th>
<th>Agroforestry- market garden under apple orchard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cropping Pattern 2</td>
<td>Row intercropping- peas and canola</td>
</tr>
<tr>
<td>Cropping Pattern 3</td>
<td>Silvopastoral- beef on improved pasture under wide spaced pine trees</td>
</tr>
</tbody>
</table>

Add more on another page if necessary.
Section 3: Benefits and Risks of Multiple Cropping/Polyculture
We want to know why you practice multiple cropping, or polyculture. For each of your cropping patterns, you will have observed some results, some impacts of that cropping pattern in any number of important agricultural objectives. Where your crops interact in time or space, what categories of impacts do you believe offer benefits to you and your farm? Please tick the 5 (five) most important cropping objectives where you believe BENEFITS occur.

Example benefits you see in the use of multiple cropping or polyculture

<table>
<thead>
<tr>
<th>Agricultural Objective</th>
<th>Cropping Pattern 1</th>
<th>Cropping Pattern 2</th>
<th>Cropping Pattern 3</th>
<th>Cropping Pattern 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased yield/productivity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increased yield stability</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decreased weed problems</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decreased disease problems</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decrease in purchased inputs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increased wild lands diversity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increased crop diversity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decreased pest problems</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decreased economic risk</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increased social sustainability (family &amp; community vitality)</td>
<td></td>
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<td>Higher labour efficiency</td>
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<td>Higher capital efficiency</td>
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<td>More efficient use of space</td>
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<td>More efficient use of time</td>
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<tr>
<td>Benefits beyond the farm</td>
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<tr>
<td>Increase in soil health</td>
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<tr>
<td>Minimise climatic risk</td>
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<tr>
<td>Improved profits</td>
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<td>Other (please specify)</td>
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Are there any other comments you’d like to add?

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**Risks you see in the use of multiple cropping or polyculture**
For each of your cropping pattern(s) where your multiple crops interact in time or space, what categories of farming objectives do you believe experience **INCREASED RISK** to you and your farm? Please tick the 5 (five) most important risks you perceive.

<table>
<thead>
<tr>
<th>Agricultural Objective</th>
<th>Cropping Pattern 1</th>
<th>Cropping Pattern 2</th>
<th>Cropping Pattern 3</th>
<th>Cropping Pattern 4</th>
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<tbody>
<tr>
<td>Decreased yield/productivity</td>
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<tr>
<td>Decreased yield stability</td>
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<tr>
<td>Increased weed problems</td>
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<tr>
<td>Increased disease problems</td>
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<td>Increase in purchased inputs</td>
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<td>Decreased wild land diversity</td>
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<td>Decreased crop diversity</td>
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<td>Increased pest problems</td>
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<td>Increased economic risk</td>
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<td>Decreased social sustainability (family &amp; community vitality)</td>
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<td>Less labour efficiency</td>
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<td>Lower capital efficiency</td>
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<td>Fewer benefits beyond the farm</td>
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<td>Decrease in soil health</td>
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<td>Increased climatic risk</td>
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Are there any other comments you’d like to add?
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Section 4: Monitoring Benefits and Risks

For each of the agricultural objectives used in the previous two charts, determination of actual, real results often depends on physical monitoring, data, tonnes, dollars, number of employees, etc. We want to know how you know you are seeing benefits or risks. For each category where you are able to monitor the performance, please tell us how you determine real benefit or risk.

Example:

Cropping Pattern 1
Row intercrop of peas & canola
1. Increased soil health
2. Better weed control
3. Higher total yield

1. Faster tillage speed
2. Less cultivation needed
3. More income

1. Not enough soil moisture
2. Machinery constraints
3. More income

1. Poorer growth & yield
2. Jobs done poorly

Please fill out the chart below.

<table>
<thead>
<tr>
<th>Benefit</th>
<th>Indicator</th>
<th>Risk</th>
<th>Indicator</th>
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<tbody>
<tr>
<td>Cropping Pattern 1</td>
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<td>Cropping Pattern 3</td>
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<td>Cropping Pattern 4</td>
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Please list any general guidelines or principles you follow in designing your cropping patterns?

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We would like to contact a selected number of farmers who use multiple cropping/polyculture for longer interviews. If you give us contact details, we may arrange an interview in person in order to investigate your farm’s cropping patterns in more detail. We will also send survey results to you if you supply us with your contact details below.

☐ YES, consider me for an interview        ☐ YES, Please send me survey results

Name______________________________ Telephone contact________________________AH
Address____________________________ ________________________BH

Town___________State_________Postcode________ When the best time to ring you?  _______Time _______Day

WE THANK YOU FOR YOUR PARTICIPATION IN THIS SURVEY.
PLEASE FOLD IT WITH THE REPLY PAID ADDRESS VISIBLE AND SEND IT TO US.

All questionnaires must be received by JULY 15