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Being realistic about no-tillage, legume ley farming for the Australian semi-arid tropics

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Summary. There is a long tradition of expectation that, in time, land use in the better-endowed areas of Australia's semi-arid tropics would intensify from beef production on grassy woodlands to broadacre production of dryland crops. However, successive development attempts have yet to result in a substantial field crop industry.

This paper reflects on a recent 20-year research and development episode in which ley farming, so successful in the wheat–sheep zone of southern Australia, was adapted and trialed in the tropical north. The system tested in the tropics was one which featured (i) coarse grain crops in rotation with legume leys and (ii) cattle grazing native pasture in the crop growing season and ley and crop residues in the dry season. It can be concluded that this system is technically successful. But compared with the ley system in southern Australia, the benefits of pasture legumes are less efficiently captured, both in the animal and the crop production enterprises. In addition, in this climate and on these soils, pastures with the high legume composition needed to substantially substitute for nitrogen fertiliser in the crop phase pose a serious threat of soil acidification.

In contrast to legume leys, the advantage of no-tillage, mulch farming practices over conventional cultivation is much greater in this semi-arid tropical region than in temperate or Mediterranean areas: by slowing evaporation, mulch is often crucial in reducing high temperature injury or impedance to emerging seedlings as well as reducing the deleterious effects of intensive summer rainfall. But even with this improvement the climatic risks in dryland grain cropping remain a strong deterrent to crop industry development.

Today, the findings from past experimentation, accrued farming experience, and new information products combine to provide what seem to be more realistic expectations for agriculture in this region. Even with the 'best' technology, this region suffers comparative disadvantage with respect to dryland field crop production and marketing. However, the region enjoys comparative advantages in the production of several other types of commodities, and a more realistic approach to 'Research and Development' includes a shift of resources toward activities with production and marketing advantages.

Introduction

Pioneering effort is aided by audacity and abiding optimism. In northern Australia successive cohorts of farmers, politicians and researchers have not lacked either quality in their successive efforts to develop the better-endowed areas of natural grazing lands in Australia's semi-arid tropics for dryland cropping. But, as yet, the costs, risks, or returns have never matched those expected (or hoped for) well enough for a significant cropping industry to eventuate (Bauer 1977; Chapman *et al.* 1996). Each failed development effort, however, seems to have been followed by a period of research that organised its efforts more in line with economic and ecological realities as revealed by the recent experience. The uncertainties that have given agriculture in this region a 'frontier' status have been progressively reduced.

Following the failure of the cropping schemes in the 1960s and early 1970s, research on intensification of land use in the Northern Territory shifted to improved pastures. Emphasis was on legumes oversown into native pasture, accompanied by superphosphate fertilisation (Chapman *et al.* 1996). But by the late 1970s several important events had occurred which swung attention back toward cropping. Removal of the subsidy on superphosphate made fertilisation of pasture prohibitively costly; the benefits and feasibility of no-tillage, mulch farming in the tropics was demonstrated (e.g. Lal *et al.* 1978), and pasture legumes (e.g. Verano stylo) which were superior to those previously used at Katherine (e.g. Townsville stylo) became available. Together, these formed the basis for a new approach to farming for the region which capitalised on synergies of integration of cropping and grazing, featuring rotations of grain crops and leguminous pastures (McCown *et al.* 1985).

A research program was undertaken to test a 'hypothetical' no-tillage, ley farming system with 4 features:

(i) self-regenerating legume ley pastures grown in rotation with maize or sorghum;

(ii) cattle graze native grass pastures during the green season and legume pastures and crop residues in the dry season;
(iii) crops are planted directly into pasture residues following killing of pasture at, or shortly before, sowing by non-residual herbicide; and
(iv) the pasture legume sward which volunteers from hard seed, is allowed to form an under-story in the main crop.

No claim for originality can be made for any of these components nor is any claim made for first recognition of potential appropriateness of ley pastures for the Top End (see Wetselaar and Norman 1960; Fisher and Phillips 1970). The contribution of this research since 1977 has been to systematically research the technical 'feasibility' of a system comprised of these components and to do this by building as much as possible on existing knowledge. What ensued was a substantial body of research that included more than a decade of active experimental work at Katherine and Douglas–Daly and an overlapping period, which continues to the present, of testing and development at Douglas–Daly and Katherine, aided by applications of simulation models progressively developed during this period.

This paper first maps developments within this Research and Development episode that improved understanding of this agricultural environment, the special requirements for managing crops and croplands, and the advances in techniques that better meet these requirements. It additionally maps the development of a capability for 'simulating' cropping systems which can assist future efforts in reducing and managing the inherent difficulties of broadacre farming here.

No-tillage ley farming moved beyond the research arena to become, for a while, the basis of a commercial production system (Price *et al.* 1996). The apparent success and its apparent brevity make it pertinent to raise some searching questions about future prospects. Do cropping practices which combine legume leys and mulch farming make dryland cropping industries feasible in this region? Can further substantial alleviation of constraints to dryland production realistically be expected? Are other forms of agriculture better Research and Development investments than dryland cropping?

Problem diagnosis

It was not feasible to conduct experiments on all important facets of the hypothetical system. In 2 key areas we made assumptions that seemed rational and were well-founded in general experience elsewhere. The first was that the economic feasibility of cropping here was increased by integration with beef cattle grazing (Fig. 1, Flow Path 1). In the light of the importance of socioeconomic factors in earlier failures in the semi-arid North (Bauer 1977; Chapman *et al.* 1996) and the experience of mainstream dryland farming in southern Australia, it made sense to view cropping as an ecological and economic enhancement of the well-established extensive grazing system which provided much of the infrastructure which would be needed for a mixed enterprise. Within this, the specific synergy that served to link crop and grazing research activities was seen to be that concerning soil nitrogen (N) and phophorus (P) fertility (McCown *et al.* 1985).

A leguminous pasture could in principle reduce shortages of N for crop as well as for animal growth. But P is also very deficient in the sesquioxidic soils (Kandosols; Isbell 1996) which make up most of the potentially arable areas in the Australian semi-arid tropics. Although P fertiliser greatly increases legume production and N fixation, in permanent pastures containing legumes oversown into native grasses there are economic efficiencies in feeding most of the P directly to the animals rather than spreading it on the pastures (Winter 1989). However, in a more intensive system which includes production of crops and higher livestock carrying capacity, efficiency requires amelioration of P deficiencies in the soil. Thus in this hypothetical system for integrating crop and pasture production, the cost-effectiveness of P fertilisation increases—both directly by reducing P fertiliser requirements during the crop phase and indirectly via N fertiliser savings following legume pastures whose yields and N fixation are high because of P inputs.

The second assumption (Fig. 1, Flow Path 5) was that reduced tillage and retention of mulch was necessary for cost-effective soil conservation in the semi-arid tropics. The cover provided was needed to augment soil conservation structures in reducing runoff and soil loss and possibly to reduce their cost by increasing contour bank spacing. Experimentation to test these assumptions was not possible at Katherine, but they were soundly based on much work elsewhere and were soon to be tested elsewhere in the region (Dilshad *et al.* 1996).

Although problems of yield variability due to variability in the water climate (Fig. 1, Flow Path 4) were recognised as a disincentive to investment in a cropping industry in the Top End, there was also the realisation that in no area of semi-arid tropical Australia is growing season rainfall more reliable than along the transect from Katherine to Douglas–Daly (McCown 1982). From the outset, crop models were seen as essential for adequately evaluating innovations in terms of climatic risks, but investment in these tools was deferred until the technical feasibility of key agronomic innovations was demonstrated. Crop models were also seen as the key to linking research in the Northern Territory with research in northern Queensland (e.g. Carberry *et al.* 1993*a*). The main body of experimental research concerned feasibility of combining pasture legumes and coarse grain crops to reduce fertiliser costs (Fig. 1, Flow Path 2) and of alleviating problems of crop establishment by ameliorating soil surface conditions (Fig. 1, Flow Path 3).

Analysis of poor emergence and design of alleviating technology

Poor emergence of crop seedlings is a serious problem at Katherine, as it is in other regions of this climatic zone on similar soils (e.g. Peacock *et al.* 1993). The nature of crusting on the Tippera soil of the Katherine Research Station was comprehensively researched by Arndt (1965). The combination of tillage resulting in small aggregates, slaking by rainfall and rapid drying of the soil surface is especially effective in impeding seedling emergence. While Arndt's work made a major contribution to theoretical aspects of crusting and impedance, alleviation of the crop establishment problem had to await 2 subsequent practical developments. One was an affordable, effective, non-residual chemical which makes no-tillage farming technology feasible. A second development began with the discovery that high soil temperature is often a greater threat to good seedling stands in this climate than is soil crusting. By the time crop establishment research at the Katherine Research Station resumed, over 20 years later, understanding of the seedbed environment in the semi-arid tropics included high soil temperature and the efficacy of surface mulch in alleviating it (Lal 1978; Harrison-Murray and Lal 1979) and mechanised no-tillage technology was already well-developed in temperate regions. Early findings at Katherine indicated that the potential for no-tillage + mulch farming in the Australian tropics was high (McCown *et al.* 1985).

The first step in this module of the program (Fig. 1, Flow Path 3) was documentation of rates of drying, temperature rise, and strength development between sowing and emergence (or in the case of non-emergence, 5–7 days beyond expected emergence). Even with so-called no-tillage technology, a seedbed is created in the row zone. Within this zone, the processes of tillage, sowing, replacement of soil, and pressing over the row is very much like good conventional technology. Using make-shift equipment, it was confirmed that no-tillage sowing was technically feasible and beneficial to crops as long as there was adequate surface mulch cover. A major task was to identify the ideal sowing slot and the means to create it. One approach to this was to compare a wide range of existing planters and ground tools, and to analyse their effects on the seedbed and the seedling (Gould *et al.* 1996). A second was to create by hand, on small areas of contrasting soils, various slot/mulch configurations and combinations with crop species, seed depth, soil cover, pressure, etc. (Bristow and Abrecht 1989; Abrecht and Bristow 1990).

From this work, it became clear that the superior planter configuration had a plain coulter that cut residues

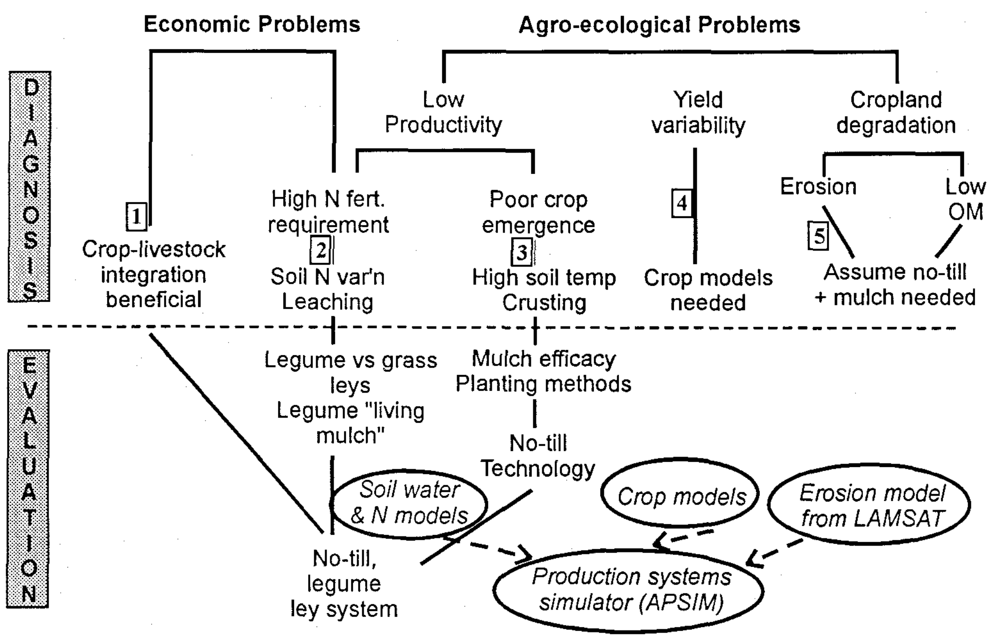

Figure 1. The organisation of research at Katherine from 1977 to 1990. (The LAMSAT project was conducted at Douglas–Daly, Northern Territory.)

followed by a narrow tine and a similarly-narrow, in-slot press wheel. Sowing 50–70 mm below the land surface and covering with about 20 mm of soil resulted in soil around the seed remaining wetter, cooler and penetrable longer, resulting in higher emergence rates with lower incidence of high temperature injury (Abrecht 1996).

Although focus of the research was on seedbed stress factors, sowing technology, and mulch efficacy, it is now clear that the most important aspect of successful no-tillage crop production in the semi-arid tropics is mulch management, i.e. managing the system to provide the right amount of mulch in the right place at the right time. The importance of mulch in no-tillage technology in this climatic zone is so pivotal that substitution of 'mulch tillage' or 'mulch farming' as more descriptive terms is warranted.

Mulch farming reduces important climatic risks, but a strategy that depends on growing and chemically-killing vegetation to create mulch brings new climatic risks. In this environment, cost-effective mulch provision cannot be taken for granted, and management of supply and retention is very demanding (Yeates *et al.* 1996). Problems can be due to inadequate growth of the vegetation that becomes the mulch when killed, problems in killing the vegetation (Sommervaille *et al.* 1996*a*), or rapid decomposition of mulch and cover decline (Dimes 1996).

In the semi-arid tropics, most crop or pasture residues remaining after the main growing season decompose by the time the next crop is sown. The most important source of mulch for a crop in the following season is new pasture growth or weeds, grown on water from storm rains early in the wet season and killed just before sowing. In mulch farming, the most important part of good management is getting a favourable outcome from this precrop growing period. Cover and yield of volunteer vegetation varies greatly in response to variation in: (i) amount of seed, (ii) presence of old residual mulch to aid establishment and growth of what will be the bulk of mulch for the crop, (iii) duration from germinating rains to time of crop sowing, and (iv) continuity of growing conditions in this period. In the main, if adequate rainfall occurs, problems are minimal, but rainfall is often scarce and always erratic in this period. Even when ample production of volunteer vegetation occurs, there are uncertainties in achieving timely, effective and efficient kill that again relate mainly to rainfall occurrence. Efficacy of glyphosate is reduced by water stress of target vegetation, and rain in the first few hours after spraying washes the chemical off before absorption (Yeates *et al.* 1996). Some mulch materials, especially legume residues, decompose very quickly, and may not be there when needed, especially if re-sowing is necessitated following a failed sowing (Dimes *et al.* 1996; Yeates *et al.* 1996). Reversion to cultivation results in better crops than no-tillage sowing when mulch cover is low (Dalgliesh and McCown 1996; Thiagalingam *et al.* 1996).

Evaluation of legume leys as a source of soil nitrogen for crops

Key questions in this research program were: (i) how much N do leys of the several well-adapted legume species supply to a maize or sorghum crop in this climate, and (ii) how is this influenced by soil type, length of ley, and how the ley is managed? At the time that this work was conducted, the 3 legumes considered to be the most suitable for ley pastures at Katherine were *Stylosanthes hamata* cv. Verano, *Centrosema pascuorum*, and *Alysicarpus vaginalis*. Nitrogen uptake by unfertilised maize crops following 1-year swards of each of these differed little (Cameron 1996, Table 4). The most comprehensive study of the effects of management was conducted using Verano stylo, and the results from the heavy soil component are reported by Jones *et al.* (1996). Although the scale of this study did not allow grazing of leys, 2 treatments in this provide logical limits for the degree of N return or removal under grazing, i.e. incorporation as a green manure and removal as hay. By the assay methods of Jones *et al.* (1996) which used N uptake by 2 successive maize crops, one can infer that N contributions by a 1-year ley under grazing would have been between 25 and 45 kg/ha. For 3-year leys this increased to 35 and 75 kg/ha. (The average additional contribution in years 2 and 3 of the long ley was only 3–15 kg/ha per year.)

Large losses of nitrate occur under dryland cropping systems in this environment (Wetselaar 1962; Day 1977). This is due in part to the fact that large pulses of through-drainage are unavoidable in a monsoonal climate on freely-draining soils. This is exacerbated by difficulties in synchronising demand by vegetation for water and N with supply of water and N. The major pulses of nitrate mineralisation occur following storm rains at the end of a long dry season. Under perennial pasture, most of this nitrate is intercepted, and the uptake of nitrate together with high radiation and temperature results in rapid growth until soil water is depleted (Dimes *et al.* 1996). Such pulses of production are triggered by each storm rain in the period of erratic rainfall between September and December. Under annual cropping with conventional cultivation, early storms allow soil to be cultivated and soil is managed as bare fallow until December when sowing can be carried out without large risks of crop failure due to subsequent lapses in rainfall. This means that often by the time crop roots are in position to effectively intercept nitrate much of the nitrate is well down the profile and effectively lost.

One of the important benefits of a no-tillage ley pasture system is the presence of the pasture (which is subsequently killed just before sowing the crop) as a buffer against nitrate leaching during this period of high vulnerability to such loss. Dalgliesh and McCown (1996) showed that under annual pasture vegetation it took a long time for soil to wet to depth because of the water extraction between rains. Under clean cultivation, however, soil rapidly wet to depth and provided the wet conditions for subsequent infiltrated rain to drain and leach.

Even a leguminous pasture acts as a buffer of nitrate during the presowing period of storm rains. But grasses, especially perennials, are more effective in preventing leaching losses. Due to their high C:N ratio, tropical grasses also have a high capacity for immobilising N, and subsequent crops have suppressed yields and N uptake (Jones *et al.* 1996). This conflict involving legumes *v.* grass and chemical *v.* physical consequences is exacerbated by the fact that legume mulch decomposes much more rapidly than grass and the greater longevity of grass mulch is often beneficial to seed bed physical conditions (Dimes 1996).

The fourth feature of the hypothetical system is the volunteer pasture legume sward which is allowed to form an understorey in the main crop. In a tight rotation with legumes having a large hard seed fraction, this occurs naturally unless action is taken to prevent it. Early experiments showed that a legume understorey can in some seasons provide impressive quantities of high quality forage for the dry season without serious consequences for maize yield (Chamberlin *et al.* 1986). But in many seasons, the quantity and distribution of rainfall often results in the legumes acting as competitive weeds. A useful picture of the relative frequencies of seasons with net benefits and net costs can be provided by simulating this system using historical weather records (e.g. Carberry *et al.* 1992, 1993).

Development and application of simulation models

Variability and uncertainty of rainfall presents the central challenge for management of agricultural production systems in this region. At the time this research program was getting underway, a simulation modelling approach using historical weather records was being used to analyse variation in beef cattle production (McCown 1982). We recognised from the beginning that in testing the hypothetical cropping system, the potential number of permutations and combinations of treatments, soils and seasons differing importantly in rainfall amounts and distribution severely limited the relevance of a purely experimental approach, and that simulation modelling was needed. Although we could not invest in simulation modelling for the first 8 years, appropriate data were collected to enable the early experiments to be simulated later. When the simulation modelling component was eventually undertaken, the strategy was to begin with the best available modelling software and to test, modify, and further develop as required. In Figure 1, ellipses indicate where models have been important in the research.

The simulation work began in 1986 with the CERES-Maize model (Jones and Kiniry 1986). This software was chosen because it was the most mature model of maize growth and development and, importantly, because it contained a soil nitrogen model. Experiments were conducted specifically to rigorously test CERES-Maize (Carberry *et al.* 1989). While performing adequately in many respects, it did not contain algorithms for certain crop and soil processes which are important in a semi-arid tropical environment, e.g. the effect of soil water deficit on phenological development and seedling mortality and of high soil temperatures on crop establishment. Carberry and Abrecht (1991) modified CERES-Maize to address each of these issues as well as improving basic routines for the simulation of leaf area development and water uptake. Crop models of sorghum (Birch *et al.* 1990; Carberry and Abrecht 1991) and kenaf (Carberry and Muchow 1992) were developed for the semi-arid tropics using the modified CERES-Maize as a template.

The limitations of crop models in research on cropping systems became progressively evident. Instead of a crop model with water and N submodels, a different type of model was needed in which the focus shifts to the soil resources and how they are affected by weather and management. With this structure, crops can come and go, responding to soil conditions and changing them over time. This structure enables crop sequences and crop mixtures to be simulated by connecting and disconnecting crop routines according to schedules or conditional rules (McCown and Williams 1989; McCown *et al.* 1996). APSIM (McCown *et al.* 1996) is a flexible software environment for simulating crop production systems and can now be used in conjunction with experiments conducted in this research program in the Australian semi-arid tropics (Carberry *et al.* 1996*b*; Jones *et al.* 1996).

The original CERES soil N model performed reasonably well in terms of simulating daily supply of mineral N to crops with fertiliser as the main source (Dimes 1996). The next main challenge was to adapt the model to provide N to crops when a preceding pasture was the main source and when residues were left on the surface rather than ploughed in. A substantial body of research (Fig. 1, Flow Path 2) provided the grounds for further development of the original model which can now simulate the N supply from a wide range of paddock histories, type and amount of residues, and soil types (Dimes *et al.* 1996). This made a major contribution to the SoilN module in APSIM (Probert *et al.* 1996), which in turn can now be used to add value to other experiments, e.g. that of Jones *et al.* (1996).

The simulation capability developed in this program of research has contributed to quantification of yield variability in notional dryland cropping enterprises and comparison of prospects of management strategies. For maize, sorghum and kenaf, these studies include the simulation of yields and assessment of risks to cropping at different locations, for different genotypes, for a range of sowing times, for alternative N fertiliser rates and for different tillage strategies (Carberry and Abrecht 1991; Muchow and Carberry 1991; Cogle *et al.* 1990; Carberry *et al.* 1991, 1996*b*; Muchow *et al.* 1991).

The LAMSAT project (Fig. 1) used the experimental site of the Conservation Commission of the Northern Territory at Douglas–Daly to study the effects of different cropping–tillage systems on runoff and soil loss (Dilshad *et al.* 1996), and to specify existing erosion models for such systems. This experimental facility, which serves as the only source of such information on cropping areas in the Australian semi-arid tropics, provided values for key hydrology and erosion parameters. This has enabled APSIM to be configured to enable soil loss consequences to be a component of management scenario analysis (M. Silburn pers. comm.)

Evaluation of the hypothetical system (and similar systems) in terms of economic viability and ecological sustainability would be greatly aided by realistic simulation of its performance. Good progress has been made in developing the capability for simulating such system phenomena as soil fertility dynamics in crop rotations (Jones *et al.* 1996; Carberry *et al.* 1996*a*, Turpin *et al.* 1996*a*, 1996*b*) and competition between mixtures (Carberry *et al.* 1996*b*). Although simulation of animal production in this system has yet to be attempted, development of the required simulation tools has begun. APSIM and GRAZPLAN have been linked to enable simulation of Mediterranean crop–pasture rotations (McCown *et al.* 1993), and a new project concerning live cattle exports sets out to test this simulator for tropical locations, including Katherine. In addition, the development of new software which realises full cross-compatibility of soil, crop, grazing, and animal production modules in GRAZPLAN and APSIM has begun.

Prospects for dryland cropping based on no-tillage, legume ley technology

No-tillage + mulch farming technology has undoubtedly lowered some of the environmental barriers to consistently good crop establishment in northern Australia. The research has resulted in a good understanding of what is the potentially best practice, as well as an appreciation of the risks faced by managers, even with the 'best' technology. An important contribution to this has been made by farmers and advisers in adapting the concepts and technology in practice (Price *et al.* 1996). The apparent economic benefits of this practice (Kirby *et al.* 1996) and the trend in the farming community toward greater adoption indicate that mulch farming will be an important component of any future dryland cropping industry in this region.

Legume ley farming concepts are attractive. Soil N increases under periods of grazed legume-based pasture. During crop phases, soil N is mined, with savings in purchased fertiliser. Weed populations which build up during a pasture phase are diminished by chemical control that is routine in the cropping phase (Martin 1996). The grazing enterprise provides an important economic buffer to the high sensitivity of crops to rainfall failure.

It is not clear, however, whether legume ley farming appeals to farmers in tropical Australia more than it has to farmers elsewhere in the tropics. It has become clear that despite the attractive concepts and major research and development efforts which include provision of well-adapted legumes, farmers in the tropics and in the Mediterranean region have shown by their overwhelming non-adoption of this system that ley farming does not adequately meet their needs and/or circumstances (McCown 1993). While agricultural professionals tend to see the legume pasture phase as an alternative to expensive fertiliser as a way of lifting crop returns, history shows that ley pastures are sown by farmers only when the expected returns from the animal enterprise make this option attractive (McCown *et al.* 1987; Nordblum *et al.* 1994). This seems rarely to be the case in the smallholder situation in Africa or the Middle East, where labour intensive options are more attractive because labour availability per hectare is relatively high (Nordblum *et al.* 1994). Ruthenberg (1980, p. 108) observed that, generally, before the barriers preventing smallholder intensification to a ley system are overcome, increase in population pressure requires intensification to go beyond that of ley farming to continuous cropping.

In the case of ley farming in the semi-arid tropics of northern Australia, incentives for intensification that lead from pastoralism to cropping relate mainly to individual responses to markets (and occasionally to governments with ambitious development plans) rather than to population pressure. In the 1980s, the Northern Territory government encouraged cropping by funding production 'Research and Development', infrastructure development, and providing financial incentives to producers. Following the demise of this scheme based on intensive cropping using conventional cultivation (Chapman *et al.* 1996), farms were bought by graziers. Subsequent development initially took the form of a ley farming system based on the legume, *Centrosema pascuorum* (Price *et al.* 1996). McCown (1993) claimed (rashly, in hindsight) that this was a rare case of adoption by farmers of ley farming technology. But by 1995 it was apparent that few grain crops were being produced, and most cropland was under permanent pasture or hay crops (Price *et al.* 1996).

We now know much more about the ecological limitations of ley farming in the semi-arid tropics. From research conducted in northern Australia, it is clear that in spite of legume pastures fixing quantities of N (Cameron 1996) comparable with many temperate and Mediterranean situations, rates of sequestering N and C in the soil are lower, and the potential saving in N fertiliser in the cropping phase is relatively low (Jones *et al.* 1996). In addition to inefficient capture of biological N being an important production cost, an important ecological consequence of losses through leaching has been overlooked until recently.

In southern Australia, serious soil acidification has occurred due to nitrate leaching under leguminous pasture (Helyar and Porter 1989). Risk of such loss in the semi-arid tropics is high due to the combination of rapid rates of mineralisation and a high frequency of rainfall events large enough to cause substantial pulses of drainage through the profile. Nitrate leaching has been well documented (Wetselaar 1962; Day 1977). It can be inferred that, on the poorly buffered sequioxidic soils that make up the arable and potentially arable areas of Australia's semi-arid tropics, normal nitrate leaching under legume pasture can be expected to be effective in acidifying soil, and this is beginning to be documented (A. Noble pers. comm.). That acidification has not yet been a major problem in the tropics of Australia can be attributed to the fact that there have not been substantial areas under legume pastures for long periods. But on first principles alone, the acidification risk can now be recognised as a major defect in the hypothetical system based on legume leys. A sobering new realisation of threat stems from: (i) acidification being an inevitable consequence of large nitrate losses, (ii) large nitrate losses being unavoidable in this climate if high legume yields are achieved, (iii) the prevalence of arable soils with low cation exchange capacity, and (iv) the high cost of application of lime in this region.

Past research strategies have been based on the principle, 'the more legume, the better the animal and crop production' (e.g. Norman 1970, McCown *et al.* 1985). The perceived threat to success has been grass invasion of leguminous pastures. Now, however, it is clear that success in preventing grass invasion contributes to the hazard of nitrate leaching and soil acidification, and, conversely, the price for lowering the N leaching risk with grassy pastures is greater immobilisation of mineral N and corresponding input of fertiliser in the short term.

Farmers tend to view ley farming very differently than do most researchers. Where ley farming has existed as a system for sustained periods, the main appeal to farmers has been flexibility in responding to diverse market opportunities. What agriculturalists term ley farming systems resulted largely from farmers responding in adaptive ways to shifts in crop and animal commodity markets rather than the implementation of any particular technology or strategy as such, although the availability of a well-adapted pasture legume was a necessary condition. In southern Australia, legume ley farming evolved from a wheat–bare fallow production system. Major change took place during periods of high wool prices, when large areas of legume pasture leys were sown in place of fallows; alternatively, in periods of high wheat prices, investment in pastures and animals waned (McCown *et al.* 1987).

As regards the implications for the prospects for dryland farming in the Australian tropics, we can conclude that although a no-tillage, legume ley system substantially reduces comparative disadvantages for dryland grain production, this system is more complex and requires higher levels of management expertise than conventional cropping and is more risky than the alternative of grazing animals on permanent pastures. Under conditions when incomes are sufficiently high from cattle there is little incentive for many farmers to grow crops with inescapably higher risks, and croplands are sown to permanent grass–legume pastures (farmers Bill and Eileen Doyle pers. comm.).

The realities of dryland cropping development in relation to other options

In hindsight, it is clear that an agronomic research program which sets out to find the best way to produce field crops in a region, even if it has the tools and expertise to do this well, runs a high risk of the error of 'sub-optimisation'. We may identify the 'best' way to grow crops under these conditions, but overlook the possibility that alternative forms of agricultural production may be a better Research and Development investment. Such assessments involve comparisons with other regions in which crops are grown and with other types of land use in this region.

Figure 2 provides an aid to thinking about land use options along a spectrum of changing land use intensity, with inputs increasing from left to right. Extensive cattle grazing on natural pastures has been and will, for the foreseeable future, continue to be the prevalent land use because of strong physical resource constraints to any other form of land use. Oversowing pasture legumes is the first increment of intensification, but this has not happened on a large scale because the returns from increased supply to a manufacturing beef market are insufficient to support it.

Clearing timber from areas of the most suitable soil is the next major cost increment in land use intensification.

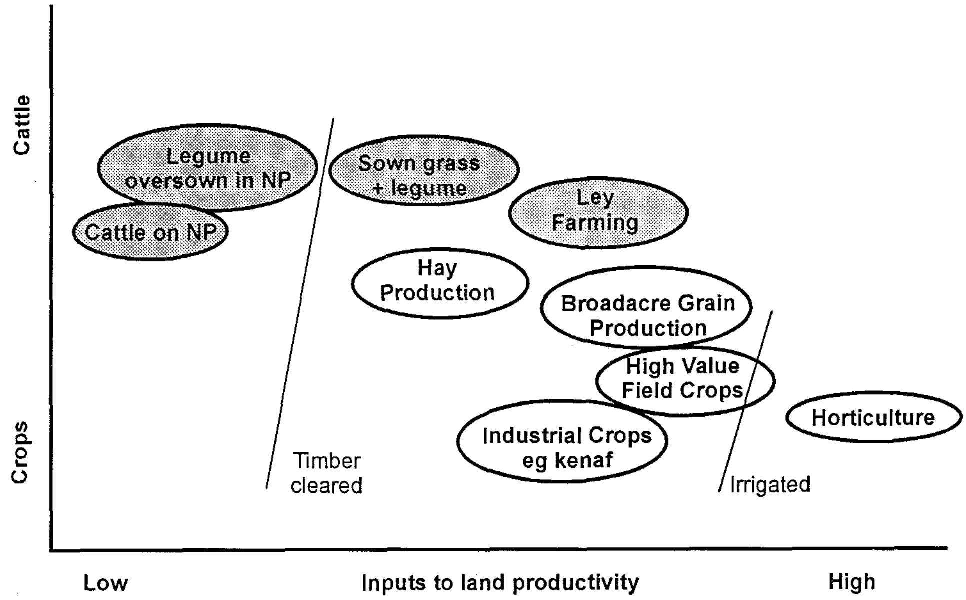

Figure 2. A conceptualization of relativities among production systems in the Top End of the Northern Territory in relation to capital and variable inputs to land productivity.

Most cleared land was originally sown to broadacre grain crops. Schemes such as that of the Northern Territory's former Agricultural Development and Marketing Authority at Douglas–Daly invested heavily in land resource assessment and property planning to ensure that soil and climatic resources can support profitable and sustainable dryland cropping. In zones where annual rainfall exceeds about 800 mm, certain soils have been shown to be able to produce high yields under good management in seasons of good rainfall, which occur relatively frequently. Often the best land has already been cleared and the 'sunk' costs of clearing and development are not fully reflected in current land prices. In spite of considerable production potential and clearing paid for largely by predecessors, the problems outlined in Figure 1 have prevented adequate profitability and/or sustainability.

The ley farming option (with implicit mulch farming) (Fig. 2) relieves several of the problems of continuous broadacre crop production, providing greater enterprise diversification, reduced N fertiliser inputs for cropping, improved mulch supply for reducing risks in cropping, and improved dry season nutrition of cattle. But, as recent experience has shown, the costs and risks in producing crops are still so high that producers are reluctant to persist with grain cropping when returns from cattle are high.

Periodically, the possibility of production of a special high value or industrial crop is considered. Carberry *et al.* (1993*b*) report the results of a simulation study for the government of the Northern Territory of the feasibility of a kenaf industry as it depends on stability of production. For each new crop considered, the agro-ecological problems of dryland cropping must be faced. But the higher the value of the product, the longer is the list of technological options which have a chance of being economically feasible.

The next step in intensification of production in Figure 2 is supplementary irrigation. Where water is available, development in the horticultural industry in recent years demonstrates that this region has clear comparative advantages for production of tropical fruit for southern markets and for production of vegetables asynchronous with production in southern Australia and in Asia (Kirby *et al.* 1996).

Of the production systems in the spectrum of Figure 2, only 3 are presently economically viable in this region. They are: (i) production of beef on natural pastures for an export manufacturing meat market, (ii) production of live cattle on sown tropical pastures for export to Asia, and (iii) intensive production of tropical fruits and out-of-season temperate vegetables using supplementary irrigation. Dryland grain crops, on the other hand, are at present grown at comparative disadvantage, and are competitive only due to local subsidies equivalent to costs of transport of grain from southern Australia and for a volume that meets the needs of the local pig and poultry industry.

Conclusions

Most of the land in the semi-arid tropics of northern Australia is suitable only for grazing. This episode of Research and Development activity has added considerably to our ability to be realistic about the future of agriculture in the modest areas that are suitable for cropping. Much of the research shows that a system such as the hypothetical system can, under favourable economic circumstances, provide substantial benefits. But it also shows that doing so means getting a lot of things right in a necessarily more complex system. Major risks can be reduced, but the technology brings new weather-related risks and demands on management. Efficiencies are achieved, but they are less than in other climatic regions. There is a certain perversity about requirements for sustainable dryland farming in the semi-arid tropics. Compared with most other climatic regions where dryland crops are produced, farming in the semi-arid tropics is more demanding of managers and offers lower average returns with higher risks. On the other hand, *vis a vis* Australia's more southern cropping areas, land is cheap, and good farmers can be attracted by the challenge of the problems and a sense of opportunity (see Price *et al.* 1996).

More realistic thinking by agricultural professionals will probably entail their seeing ley farming less as a technology with under-realised benefits (and risks) and more as a very flexible system that allows adaptation to changing market circumstances and production technology, while sustaining soil productivity. So perceived, we can expect that the farming system may at any time be anything from purely grazing to purely cropping as long as machinery for crop production, infrastructure for livestock husbandry (fencing, yards, water points etc.), and management expertise for both are retained.

Such a change in concept of ley farming appears to be occurring in southern Australia. Ley farming from the 1950s into the 1980s came to be characterised by legume pastures in rotations as close as 1 year pasture : 1 year crop, but more commonly about 3 years of pasture followed by several successive years of crop (Reeves and Ewing 1993). Price shifts then led to extended periods of continuous cropping (Carter *et al.* 1982; McCown *et al.* 1987). The resulting system when land is periodically returned to pastures, has been termed 'phase farming' (Reeves and Ewing 1993).

Perhaps the most important change in thinking at a policy level is the greater tendency for flexible use of arable land to respond to market opportunities. Distance from the main Australian population centres remains a supply and marketing liability, but proximity to Asia is a marketing asset. The tropical climate is a liability in producing field crops that can be grown better or more cheaply in southern Australia, but it is an important asset when used to supply horticultural crops which are exotic in southern Australia or for production of temperate vegetable crops asynchronous to production there.

After a history of being on the technological frontier, dryland farmers in the semi-arid tropics are now in a situation similar to farmers in other parts of Australia where technologies are mature. Much of the progress that will be made in agricultural development is likely to come about more through good use of existing technology than by the development of replacement technologies. This requires making good assessments of the economic and ecological ramifications of different strategies. One of the deficiencies of this research program was the paucity of input by professional economists. (Throughout the period, the researchers recognised this deficiency but largely failed in their attempts to overcome it.) If/when the economic/political circumstances in this region warrant another episode of field crop Research, Development and Evaluation, the stage is set in an unprecedented way for a good balance of *ex ante* economic analysis and adaptive on-farm, action-focused collaboration among farmers, advisers and researchers. Because of the achievements in this episode of Research and Development, it can be expected that research emphasis in the future will be less on developing better agronomy and more a collaboration by economists and agronomists on evaluating the economic and ecological consequences of alternative management actions and strategies, aided by simulations of scenarios made possible by an existing, locally tested simulator.

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