Sustaining multiple production systems
2. Soil fertility decline and restoration of cropping lands in sub-tropical Queensland

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Abstract

Fertile soil is the basis of sustainable agriculture. Continuous cultivation and cereal cropping lead to the depletion of soil fertility, low crop yield and poor grain quality. It is estimated that 1.2M ha of the total cropping area of 1.5M ha in southern sub-tropical Queensland are affected by soil fertility decline, with a consequent reduction in crop yield and grain quality valued at an output loss of $324M/yr. There is an urgent need to adopt fertility restorative practices to maintain economically viable farming enterprises.

Legume based leys, grain legumes, fertiliser N and zero-tillage were compared for their effectiveness in restoring or maintaining soil fertility and for sustaining wheat yield and quality on a fertility-depleted brigalow soil at Warra on the western Darling Downs. Both annual N fertilizer application and zero tillage accompanied by N application maintained wheat yields although they are uncertain options for long-term fertility restoration. The grain legume, chickpea, provided a moderate level of N supply to the following wheat crop but it is also an uncertain option for fertility restoration. Pasture leys based on annual and perennial legumes, with or without grasses, provide a useful option for fertility restoration. One year medic and lucerne leys contributed to soil N to a moderate level although lucerne leys may have an adverse effect on the moisture available for following crops. Grass-legume mixed pastures increased soil fertility as measured by an increase in soil total N.

Of these options, pastures based on annual and perennial temperate legumes and tropical grasses have the potential to increase or maintain soil fertility. Legume leys and especially grass-legume pasture leys will play a key role in future ecologically and economically sustainable farming systems.

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Resumen

Un suelo fértil es la base para una agricultura sostenida. El continuo uso de la tierra y producción ininterrumpida de cereales conducen a una reducción de la fertilidad del suelo, a un bajo rendimiento y a una inferior calidad del grano. Se estima que de un total de 1.5 M ha destinada a la producción de cultivos en el sub-trópico al sur de Queensland, 1.2 M ha se encuentran afectadas por una reducción en la fertilidad del suelo, con la consiguiente reducción en el rendimiento de los cultivos y en la calidad del grano, lo cual constituye una perdida de $324 M/a. Se tiene una necesidad urgente de adoptar prácticas que restauren la fertilidad a fin de mantener económicamente viable las empresas agrícolas.

La rotación de cultivos basados en leguminosas, las leguminosas de grano, la fertilización con N y la no-labranza, fueron comparadas en su eficiencia para restaurar o mantener la fertilidad del suelo y sostener el rendimiento y la calidad del trigo en los suelos de brigalow con reducida fertilidad ubicados en Warra al oeste de Darling Downs. Tanto la aplicación anual de N como la combinación del N con la no- labranza mantuvieron los rendimientos del trigo pero son opciones inciertas para restaurar la fertilidad del suelo a largo plazo. La leguminosa de grano, chickpea, contribuyó con un nivel moderado de N al siguiente cultivo de trigo pero también es una opción incierta para restaurar la fertilidad del suelo. La rotación de cultivos con pasturas basadas en leguminosas anuales o perennes, con o sin gramíneas, proporciona una opción *útil par restaurar la fertilidad del suelo. Los rotación anual de cultivos con medic y alfalfa contribuyeron con un nivel moderado de N pero la rotación con alfalfa puede tener un efecto adverso en la disponibilidad de humedad para el cultivo siguiente. Las pasturas mixtas de leguminosas y gramíneas incrementaron la fertilidad medida a travês del incremento en el N total del suelo.*

De estas opciones, las pasturas basadas en leguminosas anuales o perennes y las gramíneas tropicales tienen el potencial para incrementar o mantener la fertilidad del suelo. La rotación de cultivos con leguminosas y especialmente la rotación de cultivos con pasturas de gramíneas-leguminosas pueden tener un papel clave en el futuro ecológico y económico de los sistemas de producción agrícola sostenida.

Introduction

A prerequisite for sustainable agriculture is the maintenance of soil fertility. In the long term, agriculture is required to produce food of good quality, for both human and livestock needs, without impairing the fertility of the soil. Continuous cultivation and cereal cropping have led to the depletion of soil fertility, deterioration in soil structure (So *et al.* 1988), lower beneficial biological activity (Haas *et al.* 1957; Dalal and Mayer 1986a), increased incidence of disease and pests, and frequently to increased soil erosion (Lal 1989).

The depletion in soil fertility results in reduced crop yields and quality, mainly because of reduced nutrient supply from soil organic matter. The organic matter content of a soil depends upon the relative rates at which organic materials (crop residues, animal manures, organic wastes and green manures) are added to the soil and lost from it through decomposition. Organic matter or any soil constituent derived from organic matter decreases when the rate of loss exceeds the rate of addition. The aim for sustainability of the soil resource is for the rate of loss to be less than the rate of addition.

The greatest single challenge to our arable agriculture in the long term is the maintenance, and preferably the improvement, of soil fertility. Management options for maintaining or increasing fertility include: application of annual dressings of N fertiliser (Strong 1988); use of zero tillage in order to reduce loss of organic matter through decomposition (Dalal 1989); use of grain legumes (Doughton 1989); and use of pasture legumes (Lloyd 1979; Holford 1980; Littler and Whitehouse 1987; Weston and Lloyd 1988).

There are currently 3M ha of crop land in Queensland. Inevitably all lands subjected to continuous cultivation and crop removal will deteriorate in soil fertility. This paper targets the cropping area (1.5M ha) of sub-tropical southern Queensland, about 80% of which is affected by soil fertility decline to various degrees. It reviews the rates, magnitude and consequences of soil fertility decline and emphasises the need for soil fertility restorative practices, especially legume leys and grass-legume pastures, in ecologically and economically sustainable farming systems. Many data referred to are based on a long term study of fertility restoration options being carried out on a brigalow clay soil at Warra (R.C. Dalal, W.M. Strong and E.J. Weston, unpublished data) in sub-tropical southern Queensland.

Soil fertility decline

Assessment

Continuous cultivation and cereal cropping of southern Queensland soils, previously supporting native vegetation, have resulted in reduced organic matter content, lower nutrient supplying capacity and increased bulk density (Dalal and Mayer 1986a). The lower the clay content, the greater was the rate of loss of organic matter under cultivation and larger the addition of organic materials needed to maintain organic matter levels at steady-state (Table 1).

Soil organic N declines with cultivation and cereal cropping (Figure 1), at the mean rate of 31-51 kg/ha N per year in a number of soils (Dalal and Mayer 1986b). As a consequence cereal yield and protein content also decline with cultivation.

The marked loss of organic matter following cultivation and cereal cropping is accompanied by soil structural degradation, such as an increase in bulk density (Dalal and Mayer 1986a) and decrease in soil aggregation (R.C. Dalal, unpublished data) (Figure 2). In a red earth, soil aggregation declined about five times faster than in a grey clay brigalow soil. Therefore, there is an urgent need to initiate structural restorative practices on red earths under cultivation.

Magnitude and consequences

The current cropping area in sub-tropical southern Queensland is about 1.5M ha. Of this, 0.3M ha has been cultivated for more than 50

Table 1. Rates of additions of organic materials required to maintain organic matter levels at equilibrium or steadystate[1]

Soil series[2]	Great soil group	Clay content	Soil texture	Rate of addition
				(t/ha/yr)
Waco	black earth	72	clayey	1.4
Thallon	grey, brown and red clays	59	clayey	0.8
Langlands-Logie	grey, brown and red clays	49	clayey	1.6
Cecilvale	grey, brown and red clays	40	clayey	4.6
Billa Billa	grey, brown and red clays	34	loamy clay	5.4
Riverview	red earth	18	sandy loam	29.2

[1] From Dalal and Mayer (1986b) and assuming organic materials contain 40% C.
[2] Dominant natural vegetation: *Dichanthium sericeum*, *Eucalyptus microtheca*, *Acacia harpophylla*, *Eucalyptus populnea*, *Casuarina cristata* and *Eucalyptus melanophloia*, respectively.

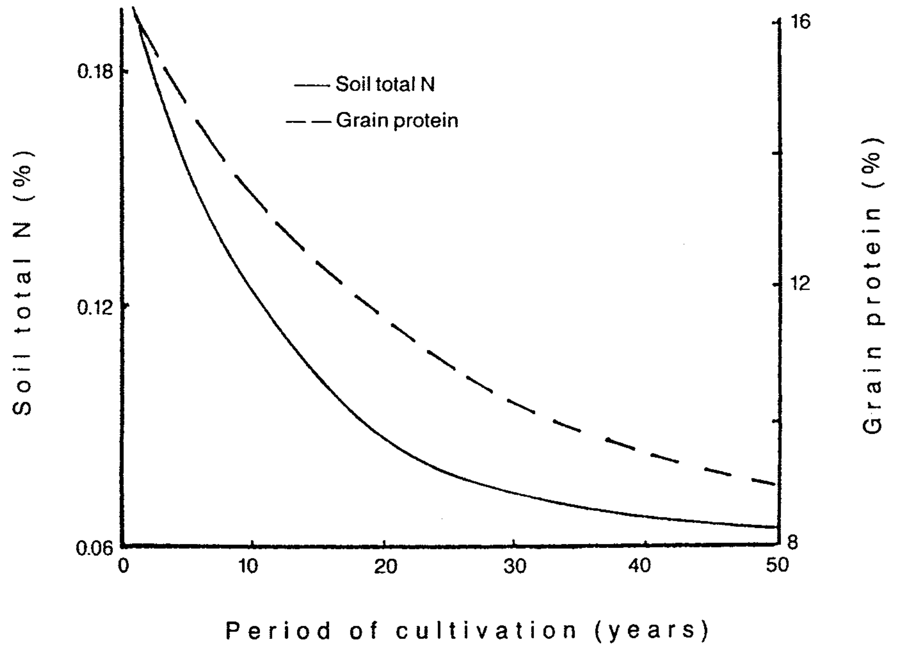

Figure 1. Decline in soil nitrogen and wheat grain protein with increasing period of cultivation.
Soil total N(%) = 0.068 + (0.201 − 0.068) exp (−0.086 yr)
Grain protein (%) = 8.0 + (16.4 − 8.0) exp (−0.0433 yr)

years, and a further 0.9M ha have been cultivated for at least 20 years (Figure 3). If these soils were still at their initial fertility status, then the likely additional annual output of wheat at current market prices would be valued at $324M/year (Table 2). The sheer size of this estimated loss implies that some effort in exploring alternatives to exploitive cropping practices is warranted. Currently, 0.19M ha of the cereal cropping area are fertilised (Australian Bureau of Statistics 1990), and this at the rate of only 32 kg/ha N per year (13.7×10^3 t of fertiliser costing $4.2M).

Consequently the opportunity for a significant increase in sown pasture area in the sub-tropics is 0.6M ha (at a crop-pasture ratio of 1:1) and this is twice the average annual sowing of pasture state-wide (Walker and Weston 1990). For the future, the potential for cropping in sub-tropical southern Queensland is estimated at 6.6M ha (Weston *et al.* 1981), and nearly one-half of this area would require restorative practices to maintain soil structure or soil fertility.

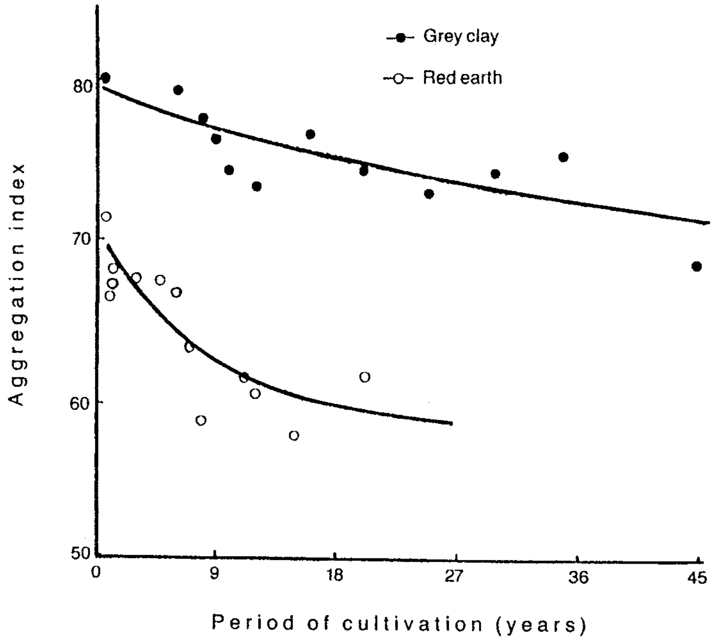

Figure 2. Decline in soil aggregation index (AI) with increasing period of cultivation in Langlands-Logie (grey clay) and Riverview (red earth) soils.
Red earth: AI (%) = 58.3 + 11.6 exp (−0.117 yr), R^2 = 0.67
Grey clay: AI (%) = 67.2 + 12.2 exp (−0.025 yr), R^2 = 0.54

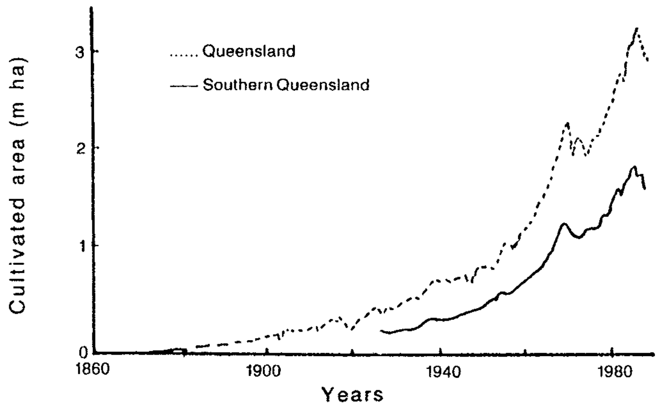

Figure 3. Trends in total cultivated area from 1860 to 1990 in Queensland.

Table 2. Estimated decline in value of crop loss with age of cultivation (based on wheat)

Cropping period	Pre-plant nitrate-N[1]	Grain yield	Grain protein	Cultivated area[2]	Value of crop loss[3]
	(kg/ha)	(t/ha)	(%)	(M ha)	($M)
1	120	4.5	15.2	—	—
20	53	2.6	11.5	0.9	229
50	35	2.2	9.0	0.3	95
Total					324

[1] Calculated from Dalal and Mayer (1986c) as 60% of potentially mineralisable N during the fallow period in a grey clay brigalow soil (Langlands-Logie).
[2] Estimated from Figure 3 (southern Queensland).
[3] Assumed net $90/t grain at 11.5% protein and premium or discount of $5 for each 1% difference in protein concentration.

Restoration of fertility depleted cropping lands

In a sustainable system of soil management the nutrient status of the soil is maintained, all factors directly harmful to plant growth (high acidity, high alkalinity, or poor drainage) are absent, the land grows the crops desired and weeds are kept under control, and both water and wind erosion are absent (Russell 1973). Restorative practices must ensure that (i) the rate of nutrient input or addition exceeds the rate of loss or removal from the soil system, (ii) there is minimum aggregate disruption, and (iii) optimum aeration and soil-water relations are achieved to reduce leaching, runoff and erosion and to promote optimum plant biomass production.

Management options

Management options for restoring or maintaining soil fertility, especially in terms of N status, include:

- fertiliser application
- minimum or zero tillage
- rotations containing grain legumes
- rotations containing legume and grass-legume pastures
- a combination of one or more of the above options.

Of these, legume-based pastures, especially legume-grass pastures, primarily meet the three criteria stated above for a restorative practice to be effective. However, non-pasture options are described briefly to evaluate their comparative performance.

Fertiliser application: N fertiliser application provides a realistic option for maintaining crop yield and quality (Table 4) where there has been no significant structural degradation and where rainfall is reliable. Since fertiliser residues generally remain in the soil or are returned to the soil in crop residues after harvest a potential exists for fertiliser N applications to maintain soil fertility (Strong 1988). However while applied fertiliser can supply the needs of the immediate crop, it is less likely to restore fertility levels than some other options. In lower rainfall areas and those with unreliable rainfall, economic returns from fertiliser applications are uncertain.

Minimum or zero tillage: Through a reduction in cultivation, these practices reduce the rate of organic matter decomposition. However, the maximum beneficial effects are likely to be obtained when crop residues are retained and fertiliser nitrogen is applied (Dalal 1989).

Grain legumes: The contribution of grain legumes to fertility restoration or maintenance in the long-term will depend upon their N fixing capacity and their net contribution to the N balance of the soil-plant system after nitrogen is removed in the grain crop (Doughton 1988). Although grain legumes may provide a significant N supply to subsequent cereal crops (Strong *et al.* 1986), their fertility restorative values over extended periods need to be confirmed. Provided other factors are not limiting, legumes fix maximum N where pre-plant nitrate-N is kept to a minimum (Doughton 1988) by using practices such as zero-tillage, intensive cereal cropping, addition of cereal crop residues and short fallows (Peoples and Herridge 1990).

Pasture leys: The alternative practices of fertiliser application, minimum or zero-tillage and grain legumes do not necessarily lead to fertility restoration in some soils, even though reasonable crop yields are obtained. Pastures containing legume and grass may restore fertility through increased return of organic materials, by reduction in cultivation, leaching, runoff and soil erosion and through N fixation. In sub-tropical Queensland, the pasture ley options will be needed to restore soil fertility on medium to coarse-textured soils, which require inputs of larger amounts of organic materials than fine textured soils (Table 1). They will also be appropriate for areas of uncertain and variable rainfall on all soils, since the production of leys will better synchronise with available water and thus optimise crop growth.

A wide diversity of ley pasture systems have been used in southern Queensland (Weston and Lloyd 1988; Russell 1988). They have been commonly applied as pure legume swards grown for one to four years, and grass-legume pastures grown for four or more years.

Since annual medics are self-regenerating legumes they can be used in short-term pasture leys when cropping cycles do not normally exceed three to four years. They are well adapted to the arable soils in the southern sub-tropics. They deplete soil moisture less than lucerne, and are less likely to create water stress in the following crop. The major limitations to adoption of annual medics in crop-pasture rotations currently are their sensitivity to the majority of herbicides (thus not compatible with zero-till), the potential to be weeds in some winter cereal crops, and bloat.

Lucerne is also well adapted to the cropping soils in the sub-tropics. As a perennial with aphid tolerance and adapted to low temperatures, it is capable of growing throughout the year. It can also be undersown in a cereal crop. The major limitations for lucerne in rotations are the risk of bloat to animals (Weston and Lloyd 1988) and a severe depletion of subsoil moisture which increases the likelihood of water stress in the following cereal crops. Also, lucerne is sensitive to waterlogging, and heavy losses of plant stands may occur in wetter years.

Both of these legumes are used in conjunction with tropical grasses in longer term grass-legume pasture leys. While they are not as flexible in rotations as pure legume swards, they have the advantage of a more even distribution of dry matter production throughout the year. Poor establishment of small seeded grasses was a major limitation to adoption of grass-legume pastures in the past (Russell 1988), but grass species with improved reliability of establishment are now available (Walker and Weston 1990). Annual dry matter yields of grass-legume leys at Warra were generally higher than those from pure legume swards (Table 3).

Table 3. Annual dry matter yields of pastures at Warra in the last three seasons

	Dry matter yield		
	1987-88	1988-89	1989-90
		(t/ha/yr)	
Medic ley	6.32	5.36	3.55
Lucerne ley	5.79	3.57	2.82
Grass-legume ley[1]	7.26[2]	6.39[3]	7.40[4]

[1] All pastures compared at the same age.
[2] Mean dry matter yield of pastures sown in 1986.
[3] Mean dry matter yield of pastures sown in 1987.
[4] Mean dry matter yield of pastures sown in 1988.

Duration of ley pastures

The duration of leys required to meet the needs of the cereal in rotation can be estimated from equation (1) derived as follows (Greenland 1971):

$$(dN/dt)\ t_p = -k_pN_e + A_p$$

and

$$(dN/dt)\ t_c = -k_cN_e + A_c$$

since at equilibrium,

$$(dN/dt) = 0,$$

$$(-k_cN_e + A_c)\ t_c + (-k_pN_e + A_p)\ t_p = 0$$

and

$$t_c/t_p = (A_p - k_pN_e)/(k_cN_e - A_c) \quad (1)$$

where t_c and t_p are the durations of crop and pasture required to maintain equilibrium soil N (N_e) estimated after long periods of cereal cropping, k_c and k_p are the rates of loss of N and A_c and A_p are the rates of addition of N during cropping and pasture phases, respectively.

For a brigalow soil at Warra, k_c value for N is 0.1/yr (Dalal and Mayer 1987), k_p value is 0.025/yr (k_c - net k_p, 0.1 - 0.075), N_e value is 800 mg/kg N (0-0.1 m), and estimated values of A_p and A_c are 80 and 20 kg/ha N per year for pasture and crop respectively (R.C. Dalal, W.M. Strong and E.J. Weston, unpublished data). Thus the soil fertility is maintained if cereal crop:legume ley of 1:1 is practised (Eq. 1). If the N accretion rate by legume is 140 kg/ha per year, then soil fertility will be maintained with cereal crop:legume ley of 2:1, and if it is 50 kg/ha per year, then cereal crop:legume ley needs to be 1:2.

No allowance has been made for soil N losses other than in crop removal. Losses such as leaching, denitrification, and volatilisation could modify the lengths of crop and pasture phases. Moreover, both k_c and k_p and N_e can only be obtained from long-term experiments.

The extent of benefits of N accretion during the pasture phase to the following cereal crop varies widely (Holford 1980; Littler and Whitehouse 1987; Clarkson 1988), and, therefore, the lengths of crop and pasture phases would vary accordingly. At the Warra site, either medic or lucerne leys of one season or one year growth after wheat, appear to provide an adequate N supply for the following wheat crop. A medic ley was able to provide from 60 to 80 kg/ha additional mineral N as compared with the continuous wheat crop. The corresponding values following a lucerne ley were from 80 to 105 kg/ha. Conversely, the amount of N removed as forage during the ley phase was greater for medic (70 to 60 kg/ha) than for lucerne (58 to 36 kg/ha) (R.C. Dalal, W.M. Strong and E.J. Weston, unpublished data). Therefore, it appears that N accretion by annual medics and perennial lucerne is essentially similar (130 to 140 kg/ha per year). Similar trends were observed for a longer duration (4 years) grass-legume pasture.

Comparison of management options

Wheat yields and quality: Substantial improvements in cereal yield and quality have been observed following fertiliser N application (Strong *et al.* 1986), grain legumes (Doughton 1988; Strong *et al.* 1986) and pasture legumes (Holford 1980; Littler and Whitehouse 1987; Clarkson 1988). A comparison of the four management options, made at Warra in two contrasting

Table 4. Effect of tillage, fertiliser nitrogen, previous grain legume and legume based pasture on wheat yield and protein in 1988 (wet season) and 1989 (dry season) at Warra in the sub-tropical brigalow (R.C. Dalal, W.M. Strong and E.J. Weston, unpublished data)

Treatment	Grain yield		Protein	
	1988	1989	1988	1989
	(t/ha)		(%)	
CT-wheat[1]	3.08	2.08	8.2	7.7
CT-wheat and 75 kg/ha/yr N	4.65	2.32	13.0	14.2
ZT-wheat	2.56	2.09	7.7	7.8
ZT-wheat and 75 kg/ha/yr/N	4.78	2.47	10.4	13.2
		(2.83)[2]		
Previous chickpea	4.62	2.89	9.3	9.8
Previous annual medic (1 yr)	—	2.83	—	12.9
Previous lucerne (1 yr)	—	1.86	—	15.4
LSD (P=0.05)	0.63	0.27	1.0	0.9

[1] CT = conventional till, ZT = zero till.
[2] ZT-wheat with 25 kg/ha/yr N.

seasons (1988 wet season, 1989 dry season) (Table 4), showed that (a) wheat yields were essentially similar in both zero-tilled and conventionally tilled treatments, (b) fertiliser N application significantly increased wheat yields although protein levels were lower in zero-tilled than conventionally tilled treatments, (c) wheat yields following chickpea or medic were 35 to 50% higher than those from conventionally tilled continuous wheat and protein levels increased by 13 to 67%, and (d) in one situation, although wheat grain protein levels doubled following lucerne, wheat grain yields were as low as unfertilised conventionally tilled treatments apparently due to a soil water stress effect.

Economic impact: Comparative steady-state budgets were used to estimate the relative profits from soil fertility management options based on fertiliser N, chickpea, annual medic, lucerne, and mixed grass-legume pasture, theoretically adopted on a fertility-depleted farm in the brigalow lands of sub-tropical southern Queensland (Table 5). The favourable effect of chickpea and pasture ley systems on farm economics is due to an increase in wheat yields achieved with less than 50% reduction in the wheat growing area, decrease in less valuable crops (oats and sorghum) and, with pasture leys, improved quality feeds.

The major limitations of such an assessment are the assumptions that steady-state in fertility

Table 5. Relative profit of soil fertility management options on a typical farm in the brigalow lands of sub-tropical southern Queensland

Cultural practice[1]	Management options				
	Fertiliser N[2]	Chickpea	Medic	Lucerne	Grass-legume
			Area distribution (ha)		
Wheat	480	320	333	300	320
Sorghum	80	80	67	50	
Oats	160	80	0	100	80
Fallow	80	80	67	50	
Chickpea		240			
Medic			333		80
Lucerne				300	
Grass-legume					320
			Animal distribution (no.)		
Beef cows	160	150	215	330	300
Fat 24 months	69		92		129
Store 18 months		64		142	
			Relative profit ($)[3]		
	16 000	27 000	31 000	26 000	31 000

[1] Also 1200 ha of native pasture.
[2] Fertiliser at 50 kg/ha/yr N.
[3] Extra benefit above unfertilised conventional tilled system with yield and price at the gate — wheat, 1.75 t/ha, $110/t; sorghum, 2 t/ha, $100/t; and chickpea, 1.25 t/ha, $225/t.

maintenance is achieved rapidly, that the areas, yields, prices, and costs remain unchanged and that average seasonal conditions prevail. By accepting these limitations, it can be inferred that the economics of soil fertility restoration practices compare favourably with current exploitive cultural practices.

Conclusions

The concern for the non-sustainability of current cropping practices is widespread. Continuous exploitive cereal cropping has resulted in severe depletion in soil fertility, notably in N, on black earths, grey, brown and red clays and red earths in sub-tropical southern Queensland. In reliable rainfall regions, application of nitrogenous fertilisers may alleviate the N deficiency problem. In areas of lower and less reliable rainfall, where economic returns from fertilisers are uncertain, other fertility restorative measures may be economically viable. Grain legumes, such as chickpea, and short-term legume leys (1 yr) based on annual medic and lucerne, appear to be attractive options in cereal crop-legume rotations although optimum durations of each of these systems need to be further investigated in marginal rainfall areas. Grass-legume pastures provide a useful option for fertility restoration and generally optimise soil-water relations, thus reducing leaching, runoff and soil erosion. From current studies it is concluded that pasture leys would play a key role in ecologically and economically sustainable farming systems.

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