Rotations - maintaining our soil quality and profitability

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Abstract. In agricultural systems, soil quality is thought of in terms of productive land that can maintain or increases farm profitability, as well as conserving soil resources so that future farming generations can make a living. Management practices which can modify soil quality include tillage systems and crop rotations. A large proportion of cotton grown in Australia has been grown with various rotation crops (mainly cereals) with corn and vetch increasing in recent years. Wheat rotation crops can improve soil quality indicators such as subsoil structure, salinity and sodicity under irrigated and dryland conditions, while leguminous crops can increase available nitrogen. Generally, soil organic carbon is unaffected by rotations crops and it is uncertain whether rotation crops change cotton water use efficiency. Profitability of cotton-rotation crop sequences varies with the relative price of cotton to wheat. Cotton-rotation crop sequences may be more resilient to price increases in fuel and fertiliser due to lower overall input costs.

Introduction

Sustainability in any farming system is dependent upon a number of interacting factors which include climate, soil quality, plant nutrition, management, weed and disease incidence, and economic factors. Cooper (2), in a survey of cotton cropping systems conducted in New South Wales during 1992, noted that many cotton growers assume that a "sustainable" system is represented by a cotton-rotation crop sequence as it is thought to improve soil quality, minimise disease incidence, increase cotton yield and maintain profitability. In contrast, back-to-back cotton was thought to degrade the soil and increase disease incidence, although it could increase short-term profits more than a cotton-rotation crop sequence. This paper reviews the research conducted during the past 25 years on the effects of sowing rotation crops after cotton on soil quality and profitability.

Australian Cotton Cropping Systems

Cropping systems under which cotton is grown can be broadly classified into three groups: back-to-back cotton, where cotton is sown in the same field every year indefinitely; long-fallow cotton, where cotton alternates with a bare fallow; and cotton-rotation crop sequences where cotton alternates with either summer or winter rotation crops (2). Fixed crop rotations are more common in irrigated cotton production systems, whereas opportunity cropping is the norm in dryland systems. The first reported use of rotation crops in NSW cotton production systems was during the period 1965-1972 when wheat was sown after cotton for the first time by several cotton growers in the lower Namoi valley (3). Following this (1972-1977) other crops such as sorghum, soybean and sunflowers were also sown as rotation crops. Similar information is not available for the Queensland cotton industry. However, given the long history of cotton growing in Queensland, a similar pattern is likely to have occurred with summer rotation crops such as corn dominating in the summer-dominant rainfall zones.

A survey conducted during December 1992 (2) indicated that 53% and 80% of cotton growers surveyed in the central-west and north-west, respectively, of New South Wales sowed rotation crops after cotton on a regular basis. A follow-up survey in 1998 indicated that the proportions of growers practicing rotation cropping were similar in both regions. Wheat was the favoured rotation crop with 71% of cotton growers who sowed rotation crops in the central-west and 74% in the north-west of New South Wales sowing it in either a 1:1 or 2:1 cotton:wheat rotation (2,10). The 1992 survey indicated that legumes such as field pea and soybean were preferred as rotation crops by 13% of cotton growers in the central-west, whereas 6% in the north-west, increasing to about 10% by 1998, preferred legumes such as soybean, field pea, faba bean , chickpea, and dolichos (2,10). Other crops sown in rotation with cotton include corn and sorghum, and more recently, woolly pod vetch (2,10,43). Anecdotal evidence suggests that both corn and woolly pod vetch have gained in popularity during the past 5 years.

Soil quality

Soil quality is defined as "the degree of fitness of a soil for a specific use—its ability or capacity to function for a specific purpose" (5,7). In agricultural systems, soil quality is thought of in terms of productive land that can maintain or increases farm profitability, as well as conserving soil resources so that future farming generations can make a living (7). Indicators of soil quality include soil structural indices (aggregate stability, porosity) and related measures such as available water holding capacity, strength, drainage and leaching potential; labile, microbial and total soil organic carbon; exchangeable cations and cation exchange capacity; pH; soil nitrates and phosphates; salinity; sodicity; and accumulated toxins such as herbicides and pesticides (4,5,7,30). In addition, the presence or absence of soil fauna such as ants and earthworms can be used as indicators of "good" or "poor" soil quality (47). Management systems whereby soil quality can be modified and managed include tillage and stubble management systems, and by sowing crop rotations (30).

Soil quality and crop rotations

Research into the effects of cotton-rotation crops systems on soil quality commenced during the late 1970's and was focussed mainly on indices such as soil structure and N balance (1,9,11). Early work in the lower Namoi valley indicated that soil structural amelioration was better after safflower than after wheat (11) although later research in the Macquarie valley suggested that major differences were not detectible between the two crops (12). Safflower however, does, have three main disadvantages: firstly, it is extremely thorny and can cause some discomfort during harvesting; secondly, harvest usually occurs during January when frequent summer storms can result in wet harvests which may reduce harvestable yield and grain quality; and thirdly, available safflower varieties have low yield potential (T. Farrell, pers. comm..). Hearn (9) reported that without applied N, cotton yield was greatest after wheat or fallow and least after cotton or sorghum with soybeans intermediate. Response to N was greatest after cotton or sorghum, least after wheat or fallow with soybeans again intermediate. These effects were associated with structural degradation of the subsoil, with wheat rotation crops improving structure the most. Constable *et al.* (1) also reported that in comparison with back-to-back cotton, cotton sown after a wheat rotation crop produced more lint of a better quality. This was again, thought to be due to amelioration of subsoil structure and better re-cycling of soil N by the wheat.

More recent research has also demonstrated that wheat rotation crops can improve overall soil quality under irrigated and dryland conditions and in a range of climates where cotton is grown. In several long-term on-farm and on-station field experiments Hulugalle *et al*. (22,23,25,27,28,29) reported that better soil structure resulted by sowing wheat after cotton than by sowing legumes such as dolichos, chickpea, faba bean, and field pea. In addition, greater profitability, recycling of leached N, and a lower incidence of black root rot are more likely with wheat than with legumes (15,25,27,29,35). Excess soluble salts and exchangeable sodium in the soil profile were also leached faster with cotton-wheat rotations than with either cotton-dolichos rotations or with back-to-back cotton (21,49).

Leguminous rotation crops can improve soil aggregate stability and N by fixing atmospheric nitrogen, by reducing N volatilisation and leaching losses, and by decreasing exchangeable sodium content through a process of chemical exchange rather than leaching (16,20,29,25,28,41,43). However, these changes, particularly in sodic soils, are restricted to the surface regions. Among legumes, faba bean and Namoi woolly pod vetch increase soil N more than field pea, chickpea, or dolichos (41,42,43). Two studies: a field study by Rochester *et al*. (42) and a laboratory study by Pillai and McGarry (40) have also suggested that aggregate stability, subsoil strength and compaction were reduced more by leguminous than by cereal rotation crops. Both these studies, however, were conducted in good quality soil which did not have any major subsoil chemical constraints such as high sodicity or salinity, whereas most of the other research (25,29,27) was conducted in on-farm locations where subsoil sodicity was present. At the same time, soil maps and surveys of Australia suggest that the surface, sub-surface or both in a majority of cotton-growing regions in eastern Australia can be described as "sodic" (34,39). Commonly-grown row-crop legume varieties are also more sensitive to salinity and sodicity than cereal crops such as wheat or sorghum (31). It is not surprising, therefore, that under most on-farm conditions, where subsoil sodicity commonly occurs, cereal crops perform better than leguminous crops in maintaining soil physical and chemical quality. Legumes in the rotation may, however, reduce cotton yield because: (a) herbicides commonly used with legumes are incompatible with cotton; (b) they can be alternative hosts of seedling disease-causing organisms of cotton such as such as *Thielaviopsis basicola* which is the causal agent of black root rot, *Fusarium*, *Rhizoctonia* and *Pythium*; and (c) their seed material can be allelopathic to cotton (24,25,27,35). Namoi woolly pod vetch is an exception in that it is not an alternative host of black root rot of cotton, although it can be a host to other disease-causing organisms of cotton such as *Fusarium*, *Rhizoctonia* and *Pythium* (35).

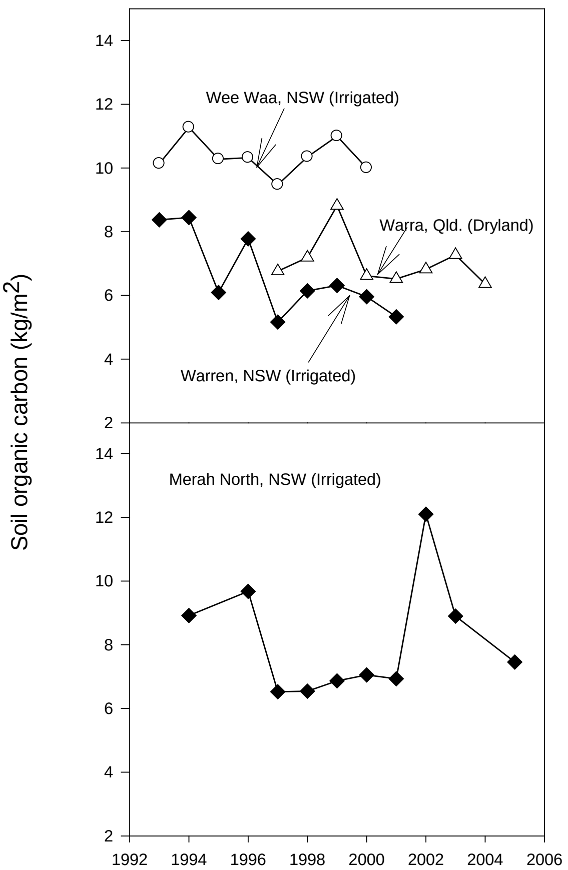

Figure 1. Variation of soil organic carbon in the 0-0.6m depth with time in some irrigated and dryland cotton farms in NSW and Qld.

Can soil organic carbon content be increased by sowing rotation crops?

In many cotton farms, soil organic carbon (SOC), a key indicator of soil quality and fertility, is either declining or has remained unchanged at a low level in spite of sowing rotation crops (Fig. 1).

The three major causes for this are insufficient amounts of crop residues, management practices and climatic extremes. In the case of insufficient amounts of crop residues being returned to the soil, approximately 20 to 30 t/ha of dry matter needs to be returned to the soil to maintain or increase SOC (23). Figure 1 shows that a sharp increase occurred in SOC between 2001 and 2002 at Merah

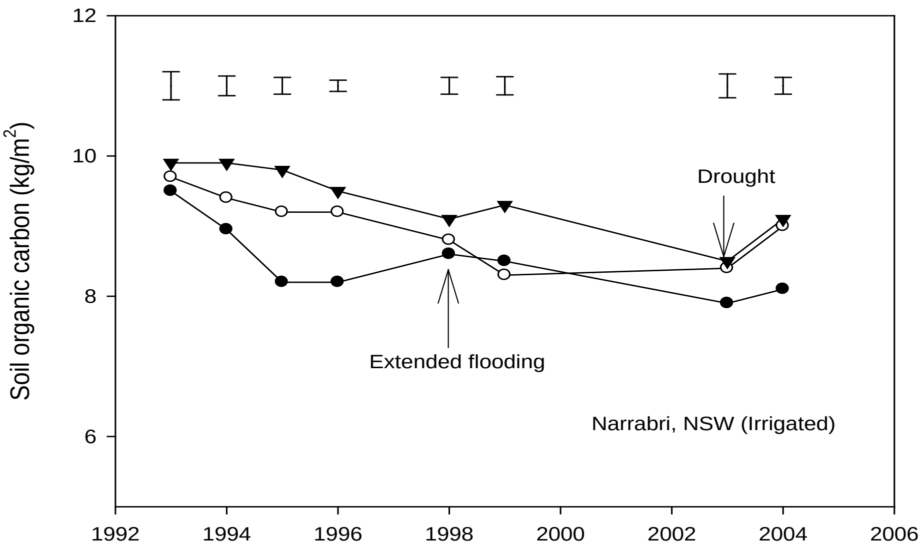

Figure 2. Effect of tillage system and wheat rotation crop on soil organic carbon the 0-0.6 m depth, Narrabri, NSW. ● – Back to-back cotton/ conventional tillage; ○ – Back to back cotton/permanent beds; ▼ – Cotton-wheat/permanent beds. Vertical bars are standard errors of the means.

North when a well-watered and fertilised crop of wheat was followed by irrigated sorghum. The above-ground dry matter returned to the soil by the two crops was of the order of 25 t/ha. The

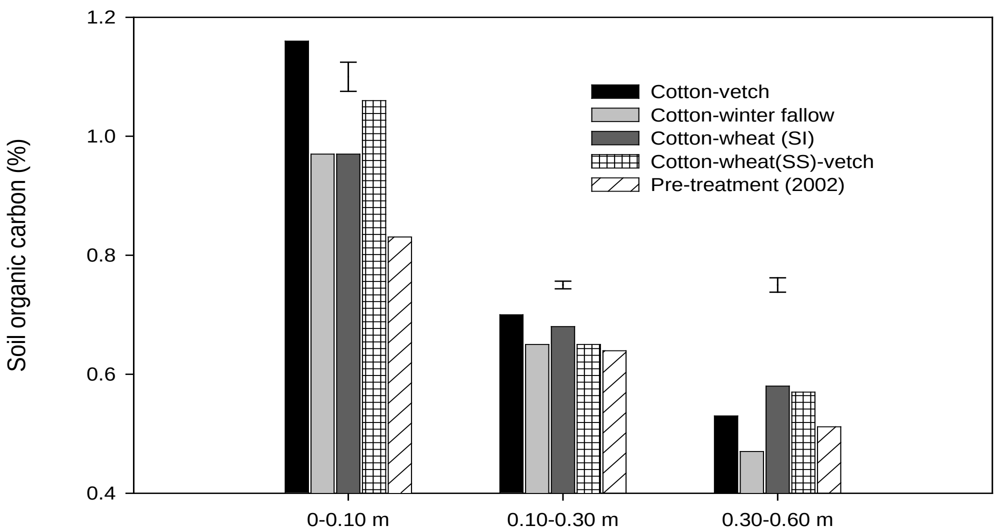

Figure 3. Effect of wheat and vetch rotation crops on soil organic carbon in the 0-0.6 m depth, October 2005. All cotton stubble was slashed, root-cut and mulched, followed by incorporating into the beds with go-devils. Vetch stubble was retained as a surface mulch into which cotton was sown. SI, wheat stubble incorporated; SS, standing wheat stubble. Vertical bars are standard errors of the means.

subsequent return to a cotton-wheat-summer fallow sequence resulted in SOC decreasing. In the case of management practices and climate, it is intensive tillage operations, excessively high N application rates and climatic conditions (warm, wet summer conditions and floods) which facilitate SOC mineralisation. In some locations, SOC has remained stable at a relatively high level (Fig. 1, Wee Waa). This is probably due to the clay mineralogy in these soils. In many dryland farms, SOC has remained relatively constant at a low level, mainly due to drought, except during wet seasons when a sharp increase occurs (Fig. 1, Warra).

In the short-term, exceptions do occur to the general observation that merely sowing rotation crops do not increase SOC. One example is the previously mentioned wheat-sorghum sequence which returned a very large amount of crop residues to the soil (Fig. 1). Other examples are cotton-corn, and minimum-tilled cotton-vetch and cotton-wheat-vetch (Fig. 3). Sowing a wheat rotation crop alone however, can slow the rate of SOC decrease, particularly if the wheat stubble is not incorporated but is retained as standing stubble (Fig. 2).

Rotation crops and cotton water use efficiency

Sowing rotation crops may or may not change cotton water use efficiency (WUE). In a seven year study average WUE of back-to-back cotton (2.3 kg lint/mm.ha) was similar to cotton sown after wheat (2.4 kg lint/mm.ha), although in some years the latter's WUE was far greater (46). These values are similar to the industry average of 2.5 kg lint/mm.ha. In an on-going trial at ACRI, however, rotation crops and stubble management significantly improved WUE of cotton, with treatments which included a wheat rotation crop outperforming the cotton-winter fallow sequence in all years, and cotton-vetch in some years (Fig. 4).

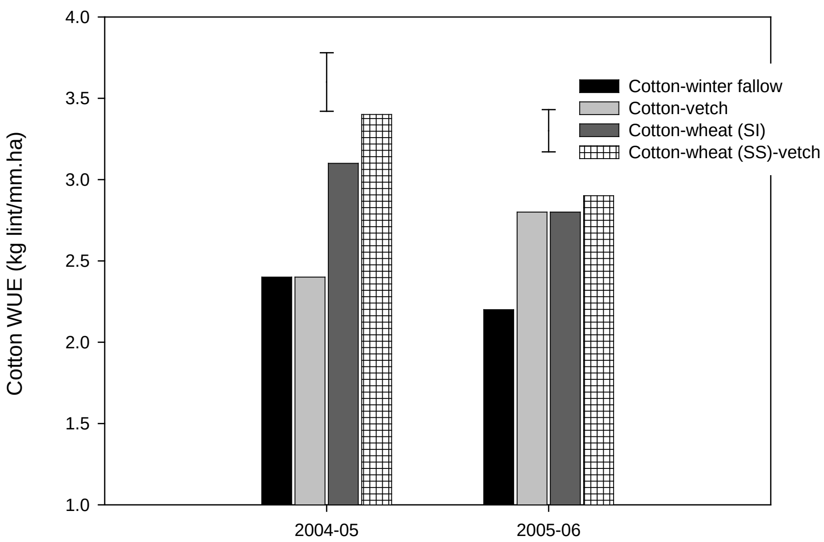

Figure 4. Effect of rotation crop and stubble management on cotton WUE. All cotton stubble was incorporated. Vetch stubble was retained as a surface mulch. SI, stubble incorporated; SS, standing stubble. Vertical bars are standard errors of the means.

Rotation crops, biodiversity and soil quality

Published reports on the effects of rotation crops in cotton production systems on soil biodiversity are few. The little research that has been conducted is limited to soil invertebrates and microflora such as VAM (vescicular arbuscular mycorrhiza). With respect to soil invertebrates, Hulugalle *et al*. (18) observed that compared with a cotton monoculture, ants and springtail numbers were highest when a cotton-wheat rotation was sown on permanent beds. The ants are able to change soil quality in cotton fields, particularly in areas near and adjacent to ant hills and foraging paths, by increasing soil organic matter, nitrates and phosphates; by reducing clay and silts contents, and sodicity; and by improving soil structure and deep drainage (13,37). N'Kem *et al*. (37) also noted that pH of soil in foraging paths were lower than that of bulk soil. This difference may result in improving uptake of Ca, Mg, K and phosphates in foraging paths by increasing the solubility of their respective carbonates and sulphates. In a comparison of N-fertilised and unfertilised wheat rotation crops, N'kem *et al*. (38) observed that numbers of ants and other insects were higher in the latter due to higher winter soil temperatures caused by less ground cover.

In addition to insects, other invertebrates such as earthworms can also be found in cotton production systems (19). The effects of rotation crops on earthworm populations have not been studied, although lucerne strips in cotton fields can increase their numbers. Native earthworms (Myall worms) can modify soil structure through their burrows, which in turn results in higher drainage and salt leaching rates (19).

VAM is known to improve P and Zn nutrition in cotton (36). Nehl *et al*. (36) report that reductions in VAM numbers were not detected after sowing cereals, legumes and canola as rotation crops, and after long fallow. They also found that in some locations, faba bean and dolichos rotation crops increased VAM numbers but not in others.

Cotton nutrition and rotation crops

As previously discussed, sowing leguminous rotation crops can result in significant benefits to the N nutrition of cotton through a combination of N fixation (depending on stubble management, crop harvest index, type and health this can range between 50 and 300 kg N/ha) and minimising N losses by volatilisation and leaching (41,42,43). Consequently reductions of 30-100% are possible with respect to N fertiliser rates for cotton. Wheat rotation crops, on the other hand can recover N leached with deep drainage during the cotton season (15). Applying N fertiliser to the wheat, in addition to increasing wheat grain yield and protein content, can further improve recovery due by increasing the depth and density of the wheat root system. Over a 6 year period in an on-farm trial near Wee Waa, NSW, average N recovery from the subsoil (>0.6 m depth) by N-fertilised wheat was 110 kg N/ha per cotton-wheat cycle and by unfertilised wheat 76 kg N/ha (15). Assuming that the cost of anhydrous ammonia is $900/t, then the value of N recovered by the fertilised wheat was $99/ha/cycle and by unfertilised wheat $68/ha/cycle. The recovered N, when released into the soil by decomposing wheat stubble, can be used by the following cotton crop. Similar observations were also made at the Cotton CRC's Farming systems experiment at Warren.

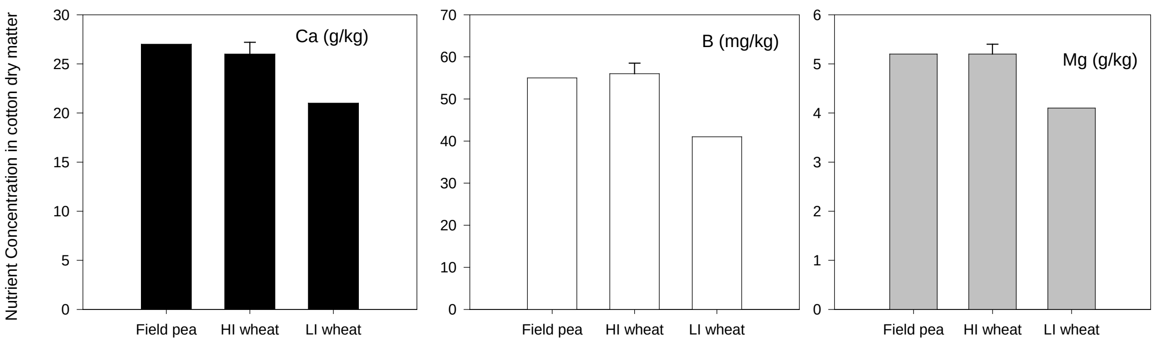

Figure 5. Effect of rotation crop on concentrations of Ca, Mg and B in cotton (vegetative material), Warren, early March 1997

Research in Australia on the effect of rotation crops on uptake of nutrients other than N by cotton is limited. The little research that has been done suggests strong interactions can occur among nutrients. For example, during early March 1997, Ca, Mg and B uptake was higher in cotton sown after rotation crops which were able to increase N supply; *viz*. field pea and high input (N-fertilised, irrigated) than in cotton which was sown after low input wheat (no N-fertiliser, dryland) (29) (Fig 5). A similar interaction between N and K nutrition, and cotton-corn rotations have been reported by researchers from the southern United States (6).

Many dryland soils are low in potassium due to export in crop harvests over time and either the absence of or historically low rates of K fertiliser application (8,32). This has resulted in significant depletion of available and non-available K in the soil. (32). Consequently, in potassium-depleted soils, cotton crops, particularly those which have high levels of boll retention, could suffer from physiological symptoms of potassium stress such as premature senescence. Anecdotal evidence and research from overseas suggests that application of organic sources of K such as cattle manure and compost, which release nutrients slowly, may have long-term benefits (45,48). Research into the K and carbon cycling associated with adding organic amendments to cotton-based farming systems in Australia is on-going.

Similar pathways of potassium depletion do not appear to be present in irrigated soils, as significant amounts of K are brought in with irrigation water. Typical seasonal values range from 8 to 18 kg K/ha for river water, 15 to 28 kg K/ha for bore water and 45 to 70 kg K/ha/season for treated sewage effluent (14,26). Potassium stress in irrigated soils is more likely to occur due to uptake of sodium at the expense of potassium in sodic or saline soils (14). Phosphorus uptake is also low in sodic soils. While some researchers have claimed a direct link between increasing exchangeable Na in the soil and reduced P uptake (I.J. Rochester, Unpublished data), indirect effects are more likely to be its cause. Increasing sodicity in grey clays is usually associated with increased alkalinity and waterlogging, and inhibited root growth and activity (33). Under such conditions and where Ca availability is high, P in soil precipitates out as calcium phosphate, thereby reducing P availability to crops (33). Uptake of immobile nutrients such as P, which are closely related to root activity, are also inhibited in waterlogged, sodic soils, further reducing P uptake.

Rotation crops and profitability

Analysis of results (44) from a series of cotton-rotation system trials run at Warren, Merah North and Wee Waa from 1993 to 2001 (10,25,29,27) showed that highest gross margins/ha (over the period of the study) were with back-to-back cotton. This was because there were more cotton crops sown with back-to-back cotton than with cotton-rotation crop sequences. Average cotton yield/ha/crop, however, was lowest with back-to-back cotton. Across the three trials, gross margins/ha were in the order of back-to-back cotton > cotton-fertilised wheat > cotton-unfertilised wheat > long-fallow cotton > cotton-legumes. The cotton-wheat systems generally returned higher gross margins/ML of irrigation water than back-to-back cotton across the trials. This indicates that where irrigation water, rather than land, is the limiting resource, cotton-wheat systems would be a more profitable option (10,25,29,27,44).

More recent results (2000-2006) from two trials at ACRI were similar to those from the previously-mentioned on-farm trials. The first, established in 1985 but in which economic analyses were conducted only since 2000, compares either conventional tillage or permanent beds under back-to-back cotton (6 cotton crops since 2000), and permanent beds under cotton-wheat (3 cotton and 3 wheat crops since 2000). Using a cotton price of $450/bale, the back-to-back cotton on permanent beds returned the highest average gross margin ($1533 ha) (Fig. 6). This was 8% higher than the conventionally-tilled back-to-back cotton (6 cotton crops) ($1424/ha) and 27% higher than the cotton-wheat on permanent beds ($1211/ha). In the case of gross margin/ML of irrigation water, cotton-wheat on permanent beds gave a 27% higher return ($363/ML) than conventionally-tilled back-to-back cotton ($285/ML). Back-to-back cotton on permanent beds was 8% higher ($307/ML) than conventionally-tilled. When cotton prices fall to $350/bale, the relative ranking of average gross margins in the order of back-to-back cotton on permanent beds ($776/ha) > cotton-wheat on permanent beds ($742/ha) > conventionally-tilled back-to-back cotton ($692/ha).

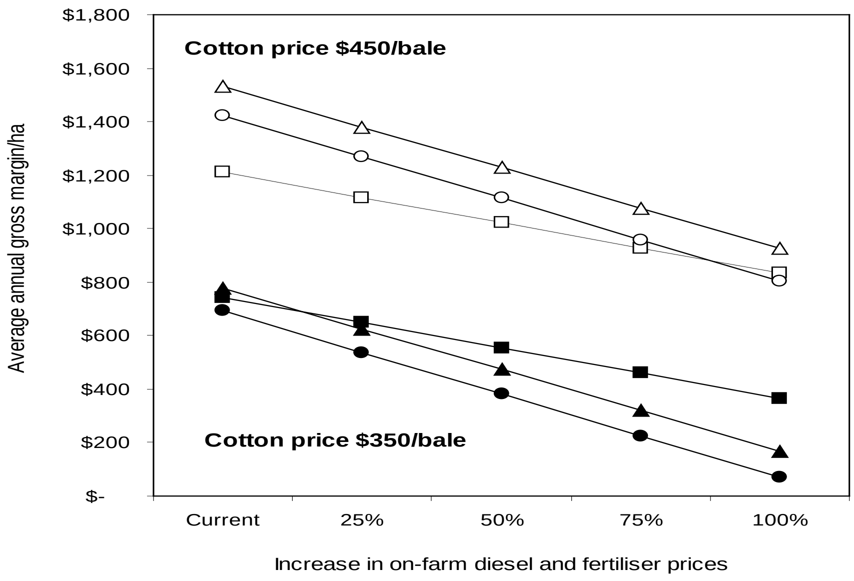

Figure 6. Effect of tillage system and crop rotation on gross margins under different cotton, fuel and fertiliser prices. Squares, cotton-wheat/permanent beds; Triangles, cotton-cotton/permanent beds; Circles, cotton-cotton/conventional tillage

In addition to the static results, an issue of current importance is increasing fuel and fertiliser prices due to recent world oil price increases. The profitability of different rotations is affected by different cotton prices relative to wheat, but rotations can also differ in terms of their resilience to changing input prices. Generally, rotations with lower overall fuel costs will be less impacted by rising fuel prices. Figure 6 illustrates this exercise, using cotton lint prices of $450 and $350/bale, a cotton seed price of $175/ton, and by increasing on-farm diesel and fertiliser prices by 25, 50, 75 and 100%. Since contract costs are a large part of cotton operations, it was assumed that there would be a 0.5% increase in contract charges for every 1% increase in the price of fuel. Even though in practice some contract rates are quoted “plus fuel” (i.e. the grower pays a base rate/ha and pays for fuel on top of that), for ease of calculation, contract rates used were calculated to include the cost of fuel. The relative rate increases were estimated by calculating the estimated contract rates for a sample tractor (using variable costs, including fuel and oil, and overhead costs per hectare plus a 20% profit margin). The average increase in estimated contract rates was in the order of 50% when fuel prices increased by 100%. Using this assumption, for example, an aerial spraying charge of baseline $14/ha would increase to $21/ha if fuel prices rose by 100%. The base diesel price used was $1.52/liter at the bowser (which is equivalent to $1.00/litre on-farm, ex-GST and the off-road diesel rebate), bowser fuel prices used were $1.90 ($1.35 on-farm), $2.28 ($1.69 on-farm), $2.66 ($2.04 on-farm) and $3.04 ($2.38 on-farm). The base price of the major fertiliser used, anhydrous ammonia, was $900/tonne. All other input costs were kept equal. Rising world

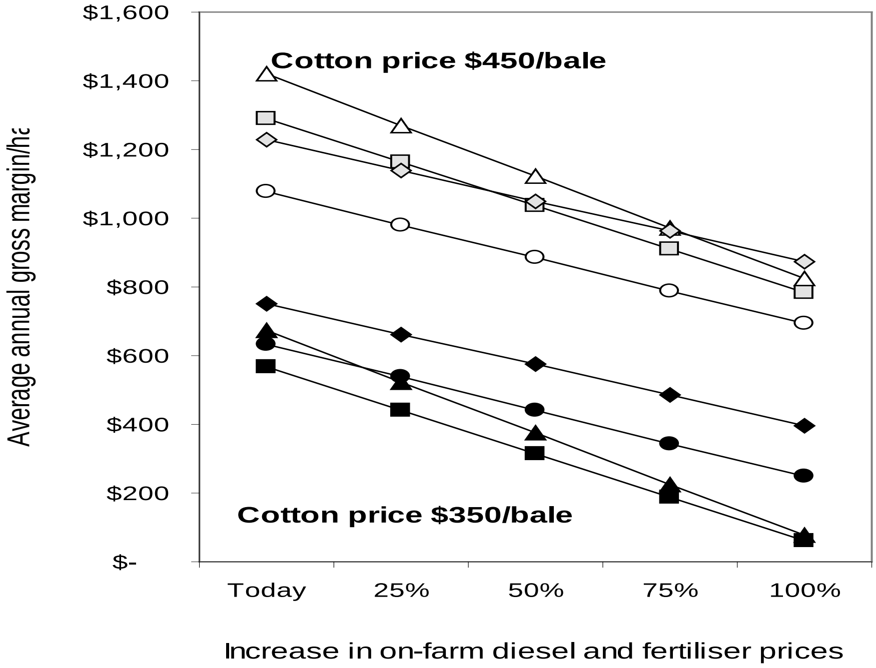

Figure 7. Effect of crop rotation on gross margin under different cotton, fuel and fertiliser prices. Squares, cotton-vetch; Triangles, cotton-cotton; Circles, cotton-wheat; Diamonds, cotton-wheat-vetch.

fuel prices may also affect other inputs such as chemicals, but the magnitude of this will differ between chemicals. As shown in Figure 6, the cotton-wheat rotation on permanent beds was less affected by the increase in diesel and fertiliser costs and so appears to be more resilient to such increases, especially at low cotton prices. This is due to a lower frequency of cotton crops and hence, lower overall input costs. The relative profitability of the rotations also changes as cotton price increases, due to the increase in the price of cotton relative to wheat.

The second ACRI trial, which commenced in 2002, compares back-to-back cotton, cotton-vetch-cotton, cotton-wheat with wheat stubble incorporated and cotton-wheat-vetch where vetch is sown into standing wheat stubble. All rotations are sown on permanent beds with supplementary irrigation, and economic analyses commenced in 2003. At a cotton price of $450/bale, average annual gross margins have been in the order of back-to-back cotton ($1419/ha) > cotton-vetch ($1288/ha) >cotton-wheat-vetch ($1227/ha) > cotton-wheat ($1077). In terms of gross margin/ML of irrigation water, profitability has been in the order of cotton-wheat-vetch ($368/ML) > cotton-wheat ($359/ML) > back-to-back cotton ($304/ML) > cotton-vetch ($227/ML). This trial has only returned 3 years of data so it is difficult to draw any conclusions about the long-term differences between the rotations. However, on the basis of the results so far, in a back-to-back cotton situation, the inclusion of vetch between cotton crops has not been profitable. This is because cotton yield in the cotton-vetch rotation was lower than that in back-to-back cotton during the first two years of the trial. This contrasts with Williams *et al*. (50) who reported that cotton-vetch was more profitable than back-to-back cotton. However, the addition of vetch to a cotton-wheat rotation has been profitable in this trial, similar to that reported by Williams *et al.* (50).

When the fuel and fertiliser price changes mentioned previously are applied, the relative profitability of the rotations changes (Fig. 7) similarly. The rotations with a higher frequency of cotton crops (back-to-back cotton, cotton-vetch) give better returns with a higher cotton price, but with a lower cotton price relative to wheat, the cotton-wheat and cotton-wheat-vetch become more profitable per hectare. The cotton-wheat and cotton-wheat-vetch rotations are also less sensitive to falling cotton prices due to lower overall costs.

Conclusions

Wheat rotation crops can improve soil quality indices such as structure and water-holding capacity, particularly where sodicity and salinity is present in the subsoil, recycle N leached below cotton's root zone and facilitate leaching of excess salts. Legumes improve soil N balance and surface structural stability. Legumes may reduce growth and yield of the following cotton crop, primarily because they are alternative hosts to seedling diseases of cotton and their seed residues can be allelopathic. Good management (fertiliser, irrigation, weed control) of rotation crops can benefit the following cotton crop in terms of crop nutrition.

Soil organic carbon in most locations has not been increased merely by sowing any rotation crop, but by sowing crops which return about 25 t/ha/crop cycle of residues to the soil, minimising tillage and optimising N inputs. The effect of rotation crops on cotton water use efficiency is variable and appears to be site and season specific.

Profitability analyses of on-station and on-farm trials indicate that highest gross margins/ha and lowest average lint yields were with back-to-back cotton. This was because there were more cotton crops sown with back-to-back cotton than with cotton-rotation crop sequences. In general, gross margins were in the order of back-to-back cotton > cotton-fertilised wheat > cotton-unfertilised wheat > long-fallow cotton > cotton-legumes. The cotton-wheat systems generally return higher gross margins/ML of irrigation water than back-to-back cotton. Cotton-rotation crop sequences may be more resilient to falls in the price of cotton lint, and price increases in fuel and fertiliser.

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