CSIRO PUBLISHING
www.publish.csiro.au/journals/ajsr Australian Journal of Soil Research, 2007, 45, 512–523

The Brigalow Catchment Study: III.* Productivity changes on brigalow land cleared for long-term cropping and for grazing

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Abstract. Productivity of grain crops and grazed pastures inevitably declines without soil nutrient replacement and may eventually make these enterprises unprofitable. We monitored these declines in north-eastern Australia during 23 years after clearing 2 of 3 adjacent brigalow catchments, in order to define the productivity levels of developed brigalow land over time. One catchment (11.7 ha) was used for grain production and another (12.7 ha) for beef production from a sown buffel grass pasture. There was no upward or downward trend in annual rainfall amounts throughout the study period. In the cropped catchment, grain yield from 14 winter crops without added nutrients declined significantly in 20 years from 2.9 to 1.1 t/ha.year on the upper-slope clay soil (92 kg/ha.year) and from 2.4 to 0.6 t/ha.year on the Sodosol (88 kg/ha.year). Crop production per year declined by 20% between 2 successive 10-year periods. Wheat grain protein content also declined with time, falling below the critical value for adequate soil N supply (11.5%) 12 years after clearing on the Sodosol and 16 years after clearing on the clay soil. Such declines in grain quantity and quality without applied fertiliser reduce profitability. The initial pasture dry matter on offer of 8 t/ha had halved 3 years after clearing, and a decline in cattle liveweight gain of 4 kg/ha.year was observed over an 8-year period with constant stocking of 0.59 head/ha. Due to fluctuating stocking rate levels of 0.3–0.7 head/ha over the trial period, liveweight productivity trends are attributed to the multiple effects of stocking rate changes and fertility decline. The amount of nitrogen exported from the cleared catchments was 36.1 kg/ha.year in grain but only 1.6 kg/ha.year in cattle (as liveweight gain). Total soil N at 0–0.3 m declined by 84 kg/ha.year under cropping but there was no significant decline under grazing. The soil nutrients removed during grain and beef production need to be replaced in order to avert productivity decline post-clearing.

Additional keywords: beef cattle, brigalow, fertility decline, grain yield, grain protein, soil organic carbon, soil N.

Introduction

Dryland cropping and grazing generally result in declining productivity due to soil fertility decline, soil erosion, and soil structural degradation. Dalal *et al*. (1991) estimated the financial loss due to fertility decline in the Queensland wheat belt alone at AU$324 million. Removal of nutrients in harvested products is responsible for much of the decline in soil nutrients where continuous cropping is practised (Dalal and Mayer 1986). Soil nutrient elements are also removed from grazed pastures in the liveweight gains (LWG) of cattle.

In a natural ecosystem, nutrient cycling is essentially a closed system, with nutrients being taken up from the soil by plant roots and then being recycled back to the soil via leaf and litter fall (Moody 1998). Native brigalow (*Acacia harpophylla*) trees, being leguminous, also fix atmospheric N as part of the nutrient cycling process. Agricultural and pastoral systems disrupt this process by removing nutrients in harvested products, in overland runoff, in gaseous losses of N, and by leaching through the soil profile. These lost nutrients must be replaced using practices such as fertiliser application or the use of leguminous crop and pasture species.

A full description of the background of the Brigalow Catchment Study and the measurements taken is presented by Cowie *et al*. (2007, this series). The primary aim was to quantify hydrologic change in response to clearing (Thornton *et al*. 2007, this series). Our aim was to quantify any changes in the productivity of cleared brigalow land with time. We measured productivity under natural rainfall for 23 years in the 2 developed catchments, one for cropping (11.7 ha) and the other for beef production from a sown pasture (12.7 ha). Current best management practices were used but no fertiliser was applied so that fertility decline could be monitored. Productivity was measured using the grain yields and grain N contents in the cropped catchment and the pasture dry matter on offer and beef cattle LWGs in the grazed catchment. We also determined the amount of N removed in the harvested products in each catchment, and the changes in soil organic carbon and total soil N.

*Parts I and II, *Aust. J. Soil Res*. **45**(7), 479–495; 496–511.

 10.1071/SR07062 0004-9573/07/070512

Materials and methods

Site details

The Brigalow Catchment Study is located at 24.81°S, 149.80°E, using the Geocentric Datum of Australia 1994 (Australian Government—Geoscience Australia 2007), and lies at an altitude of 151 m. The Australian map grid reference is 782500 7252700 (Map 8848 Moura) (Lawrence and Sinclair 1989). Mean slope is 2.5%.

Rainfall is summer-dominant and highly variable, with an annual mean (for calendar years) of 720 mm (1965–2005), varying from 339 mm (1993) to 1098 mm (1983). Average annual evaporation is 2100 mm/year, and monthly evaporation exceeds monthly rainfall in all months of the year. The average maximum monthly temperature in summer is 33.1°C and the average minimum in winter is 6.5°C. A minimum temperature <2°C occurs on average 14.3 days/year.

Soil types in the catchments comprise associations of uniform fine-textured, dark cracking clays (Black and Grey Vertosols), some with gilgais, and non-cracking clays (Black and Grey Dermosols), with sub-dominant soils of thin-surfaced dark and brown, sodic, texture-contrast soils (Black and Brown Sodosols) (R. J. Tucker, pers. comm.; Isbell 1996). Clay soils (Vertosols and Dermosols) occupy 58–70% of the area of each catchment studied, and Sodosols occupy the remaining area. Cowie *et al.* (2007, this series) present a map showing the distribution of soil types within the catchments, details of several resource condition assessments and mapping exercises at the site, and a table of soil physical and chemical properties. The soils have a plant-available water capacity ranging from 160 to 200 mm in the surface 1.4 m. Clay contents at 0–0.1 m are 33, 32, and 21% in the upper-slope clay soil, lower-slope clay soil, and Sodosol, respectively; CEC values at 0–0.1 m are 33, 32, and 23 cmol/kg, respectively; and pH (1 : 5 water) values at 0–0.1 m are 6.8, 6.9, and 6.6, respectively.

The site originally supported 3 major vegetation communities, identified by their most common canopy species: brigalow, brigalow-belah (*Casuarina cristata*), and brigalow-Dawson gum (*Eucalyptus cambageana*). The understoreys of all major communities were characterised by *Geijera* sp., either exclusively, or in association with *Eremophila* sp. or *Myoporum* sp. (Johnson 2004).

Experimental design

Three contiguous catchments were identified by topographic survey. Catchment 1 (C1, brigalow scrub) is 16.8 ha in area, catchment 2 (C2, grain cropping) is 11.7 ha, and catchment 3 (C3, beef cattle grazing on improved pasture) is 12.7 ha. As the contour banks and waterway in C2 occupy 0.5 ha, the area under crop is 11.2 ha, of which 7.8 ha is clay soil and 3.4 ha Sodosol. C3 was fenced to contain 17.0 ha of grazing area, 4.3 ha of which was outside the catchment. Catchment productivities were compared using the total areas devoted to each enterprise, which for the crop production area included the contour banks and waterway, and for the grazing area included 1.0 ha of remnant brigalow scrub. There was no replication of the treatments in the 2 cleared catchments.

Treatments

The vegetation in C2 and C3 was pulled by bulldozer and chain in March 1982, and the fallen timber was burnt *in situ* on 25 October 1982. In this paper, time periods after 'clearing' were measured from 25 October 1982.

In C2, residual unburnt timber was raked to the contour, burnt, and then covered by narrow-based contour banks at 1.5 m vertical spacing. A grass waterway was later established. In September 1984, the first crop, grain sorghum (*Sorghum bicolor*), was planted (2.5 years after pulling and 1.9 years after burning). Wheat (*Triticum aestivum*) was then sown annually for 10 years (except for a drought year in 1993). During this period of wheat monoculture, weeds during fallow periods were controlled by conventional tillage (disc plough, chisel plough, and scarifier). A minimum tillage and opportunity cropping philosophy was introduced in the early 1990s and has continued (wheat, barley, or sorghum is sown whenever soil water content is considered adequate). For each crop, we used one planter on the same settings to sow all soil types.

In C3, unburnt timber was left and the catchment was sown to buffel grass (*Cenchrus ciliaris* cv. Biloela) in November 1982. Grazing commenced in December 1983 (1.8 years after pulling and 1.1 years after sowing the buffel grass). Stocking rates were adjusted periodically to maintain pasture dry matter level >1 t/ha and to maintain a level of ground cover in excess of 85%. The treatment reflected a continuous grazing system with stocking rates that varied between 0.29 and 0.71 head/ha (each animal typically 0.8 adult equivalent). There was no feed supplementation as the aim was to assess the impacts of soil and pasture condition on LWG. No fertiliser was applied in either catchment.

Monitoring plots

Three monitoring plots 20 by 20 m (on an upper-slope clay soil, lower-slope clay soil, and Sodosol) were set up in each catchment. Each plot contained 4 PVC access tubes for soil water measurements by neutron meter.

Measurements in cropped catchment

Plant counts (to determine plant density) were determined in 6 areas of 1 by 1 m in each monitoring plot after crop emergence. Grain yield was determined from 6 strips 20 by 1.8 m in or near each monitoring plot using a small-plot header. The moisture content of grain samples was recorded at harvest and grain yields expressed at 12% moisture content.

Soil water was measured by neutron meter (0.2 to parent material or 2 m in 0.2-m increments) in 4 positions in all 9 monitoring plots at crop sowing, anthesis, and maturity. Soil water from 0 to 0.2 m (in two 0.1-m increments) was determined gravimetrically in 4 positions in each plot.

Grain samples from each plot were analysed for nitrogen (N) content using the Kjeldahl method (Bradstreet 1965) with a flow injection automated colourimetric finish. Protein content of the wheat was determined from grain N content at 0% moisture content × 5.7 (Tkachuk 1969). Grain N yield was calculated from grain N content × grain yield. Grain N yield was used as a measure of the available N in the soil.

Since cropping is more frequent under an opportunity-cropping regime, productivity was compared on a per-year rather than per-crop basis. So we measured productivity on an annual basis during 2 successive '10-year study periods': 11 January 1985 to 21 September 1994 (9.7 years) and 21 September 1994 to 23 March 2005 (10.5 years). We also determined the water use efficiency (WUE) of the total rainfall retained in the catchment during each period, with an adjustment for the difference in soil water content at the beginning and end of each period.

Measurements in pasture catchment

Plant density counts were made in 125 permanently located quadrats (1 by 1 m) in the monitoring plots in January 1983. The frequency and density of buffel grass, native grasses, and herbaceous plants were recorded.

The total pasture dry matter on offer was measured at half-yearly intervals (in May/June and October/November) from 0.5 to 9.1 years after clearing, and at 20.6 and 21.7 years (both in June). Estimates were made from *c.* 240 quadrats (0.5 by 0.5 m) randomly located in the catchment using the double sampling method of Tothill *et al*. (1978). Botanical composition was also determined at each sampling time.

Twenty-one drafts of 5–12 Brahman-cross beef cattle (steers or females) with a mean initial weight of 311 kg (s.d. 67 kg) were grazed for periods of about 1 year, and each animal was weighed before and after grazing to determine LWG. Weighing was conducted after a 1-day fasting period, during which feed was withheld but water was provided. Cattle were placed in the catchment in the middle of the dry season (June–August) each year from 1984 to 1996. From 1997 to 2004, cattle were replaced between January and August each year. The LWG/ha.year was used as a measure of catchment productivity.

Enterprise comparisons

The annual rate of LWG from 25 October 1982 (clearing) to 15 February 2005 (a period of 22.3 years) and the annual rate of grain production during the same period were determined. Comparisons were also made between the amounts of each end product (grain and beef) obtained per mm of rainfall, the rates of N removal from the 2 catchments, and the gross output value of product removed.

Rainfall and runoff measurements

Rainfall at the site was measured from a 203-mm, brass-rimmed, tipping-bucket pluviograph at the head point of the catchments. The outlet of each catchment was instrumented with a 1.2-m (4 ft) steel HL flume with stilling well and a 3.9-m (12.8 ft) by 6.1-m (20 ft) concrete approach box (Brakenseik *et al*. 1979). Flow height through the flume was measured with float-driven recording equipment.

Soil organic carbon (SOC) and total soil nitrogen (TSN) measurements

Samples for SOC and TSN were taken in the 9 monitoring plots before clearing (9 December 1981), soon after burning (8 December 1982) and on 3 September 1983, 25 September 1984, 13 October 1985, 6 November 1986, 7 November 1987, 11 November 1990, 1 February 1994, 15 February 1997, 12 May 2000, and 3 November 2003.

Topsoil (0–0.1 m) samples

Each monitoring site was divided into 10 equal blocks, and from each block, 8 samples were taken (2 random samples from 4 stratified locations), bulked, thoroughly mixed, subsampled, and analysed. Sampling was more intensive for the initial sampling (9 December 1981) when 20 samples were taken from each block, bulked, and analysed. Average values for the 10 blocks are presented.

Profile (0–0.1, 0.1–0.2, and 0.2–0.3 m) samples

Each monitoring site was divided into 5 equal blocks, 1 core was taken from each block, and the samples were bulked, mixed, subsampled, and analysed. (Profile samples were not taken on 8 December 1982, 25 September 1984, or 6 November 1986.)

SOC was determined soon after sampling using the dichromate oxidation method (Walkley and Black 1934), followed by titration or (after 1997) a colourimetric procedure with sucrose standards (Sims and Haby 1971). A comparison of these 2 methods gave an R^2 value of 0.96 (Cowie *et al*. 2002). TSN was determined by macro-Kjeldahl digestion (Bremner 1965). Quantities of SOC and TSN were calculated using soil bulk density data determined from 42–45-mm-diameter cores obtained from push tubes. The same values were used for all sampling times, and were the means for a particular site and depth increment from 3–5 sampling occasions (9 December 1981, 7 November 1987, 1 February 1994, 15 February 1997, and 12 May 2000) in which corresponding values were not significantly different. No consistent changes in bulk density with time were detected. The change in quantity of SOC and TSN at 0–0.3 m after 21 years was determined from stored soil samples taken on 9 December 1981 and 3 November 2003. These stored samples were analysed together in order to eliminate differences due to analytical technique.

Results

Rainfall and soil water storage

The total annual rainfall at the site showed no consistent trend with time during the 23-year study period (Fig. 1). This indicates that variation in amounts of rainfall with time was not a factor affecting changes in productivity. Similarly, there was no consistent trend with time for the following variables in C2: in-crop rainfall, soil water at sowing, and soil water at sowing plus in-crop rainfall (data not shown). Fallow rainfall per crop tended to decline with time as fallow periods became shorter (when opportunity cropping was adopted) but soil water at sowing showed no such decline (perhaps because the earlier fallow periods were longer than necessary and the adoption of minimum tillage increased the efficiency of soil water storage).

Crop establishment

Wheat plant populations were generally satisfactory except for the low populations in the lower-slope clay and Sodosol in crop 1 (Fig. 2).

Sorghum plant populations exceeded the optimum range of 50 000 to 100 000 plants/ha (Thomas *et al*. 1981) in crop 2 and were below optimum in crops 4, 5, and 9 on the upper-slope clay soil and crop 5 on the lower-slope clay soil (Fig. 2). The effects of suboptimal and differing populations on grain yield vary with growing conditions. The excessive population in crop 2 used most of the plant-available water before grain filling and resulted in extremely low yields (<0.3 t/ha).

Crop productivity

Grain yield was generally higher on the brigalow clay soil than the Sodosol (see Fig. 3), although in 3 of 23 crops the Sodosol

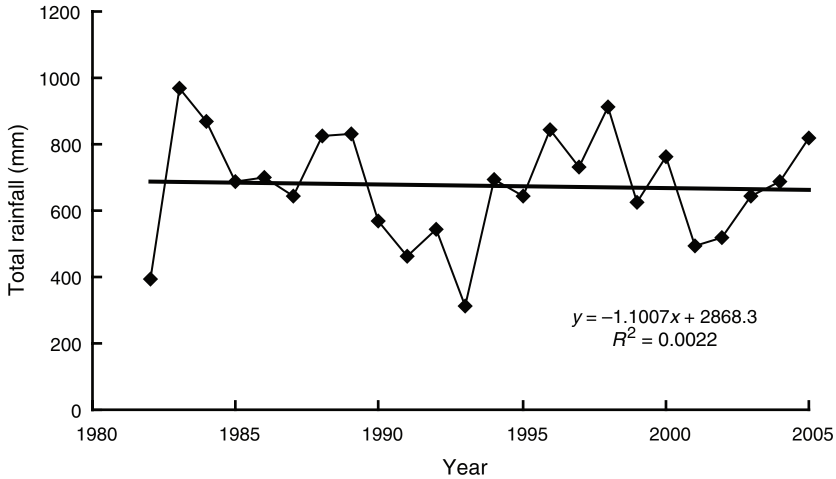

Fig. 1. Annual rainfall totals (for calendar years) at the site since clearing in 1982. $R^2 = 0.002$, not significant; $n = 24$.

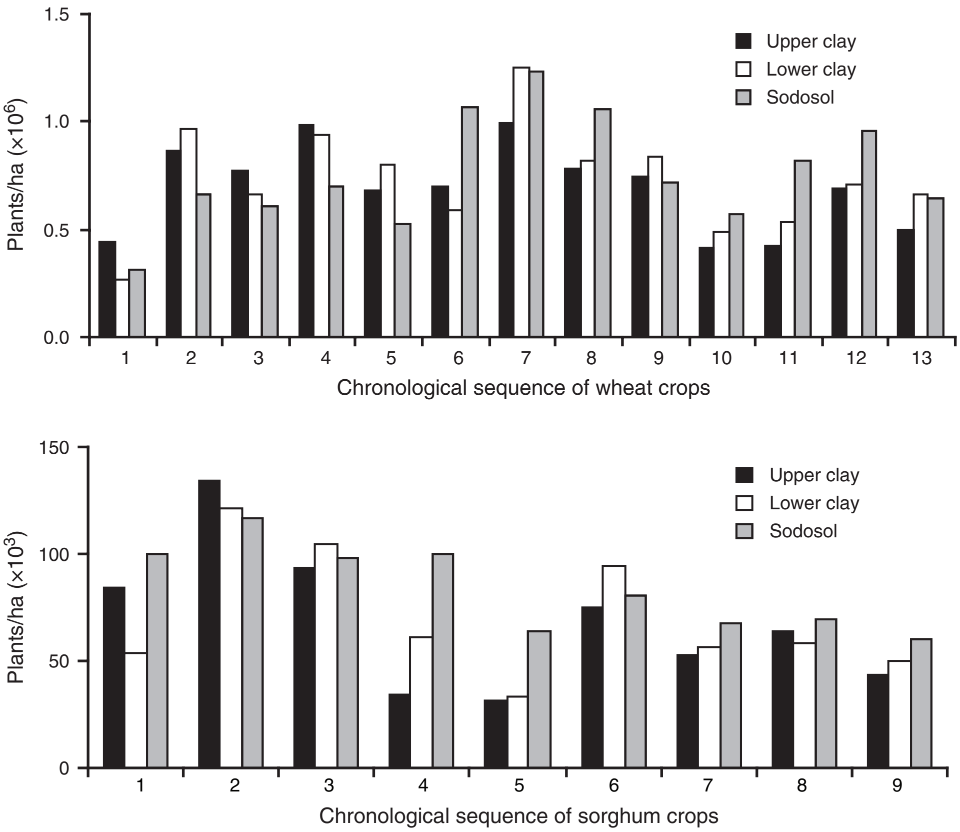

Fig. 2. Plant population densities of wheat and sorghum crops on the upper and lower-slope clay soils and the Sodosol.

outyielded the clay soils. Mean yield was 2.03 t/ha on the clay soil and 1.57 t/ha on the Sodosol.

Yield from all 23 crops harvested declined with time after clearing on both the upper-slope clay soil and the Sodosol, but the values of R^2 were not significant ($P > 0.05$) (Fig. 3*a*). When yields from only the 14 winter crops were tested, however, the values of R^2 for the regression of yield against time were significant ($P < 0.05$) (Fig. 3*b*). Winter crop production is largely dependent on stored soil water and is therefore less subject to the seasonal variability of in-crop rainfall. The yield of winter crops declined at a rate of 92 kg/ha.year on the upper-slope clay soil (2913 to 1073 kg/ha) and 88 kg/ha.year on the Sodosol (2395 to 634 kg/ha). The decline pattern on the lower-slope clay soil was similar to that on the upper-slope clay soil.

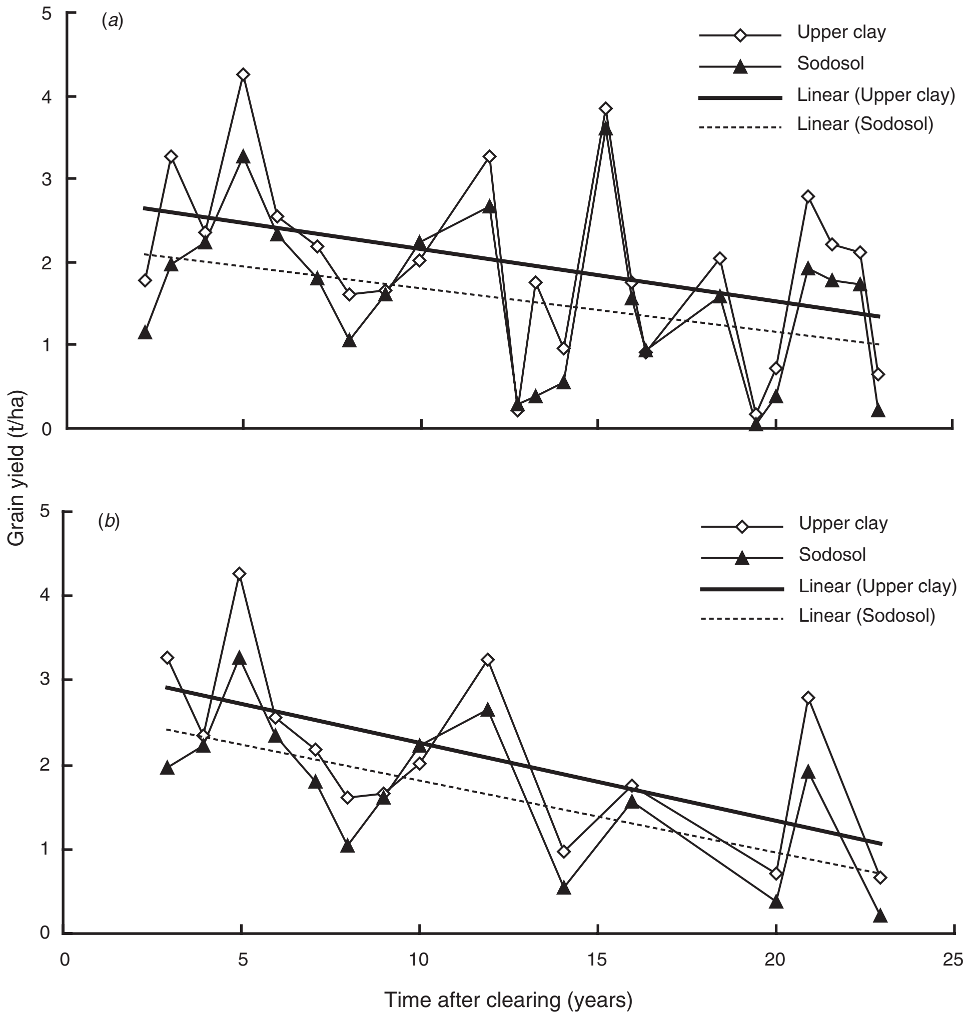

Fig. 3. Grain yields on the upper-slope clay soil and the Sodosol during 23 years since clearing. Linear trend lines are shown. (*a*) Grain yields of the chronological sequence of 23 crops (wheat, barley, and sorghum). $R^2 = 0.15$, n.s. for the upper-slope clay soil; $R^2 = 0.13$, n.s. for the Sodosol. (*b*) Grain yields of the chronological sequence of 14 winter crops (wheat and barley). $R^2 = 0.34$, $P < 0.05$ for the upper-slope clay soil; $R^2 = 0.40$, $P < 0.05$ for the Sodosol. $Y = 3.18 - 0.09T$ (upper-slope clay soil) and $Y = 2.65 - 0.09T$ (Sodosol) where Y is grain yield and T is time after clearing.

These yield trends with time since clearing were confounded, however, with the change from conventional tillage and wheat monoculture (CT/WM) in the first 12 years to minimum tillage and opportunity cropping (MT/OC) thereafter. Despite the adoption of these 2 improved management practices, yield per year had declined by 20%, and yield per crop by 36%, during 10 years of MT/OC compared with the preceding 10 years of CT/WM (Table 1). The WUE of the rainfall that remained in the catchment (rainfall minus runoff) declined by 27% in the second 10-year period (Table 1).

Wheat grain protein content and grain N yield

The grain protein content and grain N yield of the 13 wheat crops declined significantly ($P < 0.05$) on the upper-slope clay soil during the first 21 years after clearing (Fig. 4). This indicates that the supply of soil N was becoming more limiting. Wheat gain N yield declined at a rate of 3.5% per year on the upper-slope clay soil.

Pasture productivity

The initially established densities of buffel grass were 0.4 plants/m^2 on the upper-slope clay soil, 1.8/m^2 on the lower-slope clay soil, and 13.1/m^2 on the Sodosol.

Pasture dry matter levels measured in the wet (October–December) and dry (May–July) seasons were initially high (~8 t/ha) but declined rapidly during the first 3 years. Thereafter, dry matter continued to decline slightly but apparently stabilised at lower levels (~3–4 t/ha) 10–20 years after clearing (Fig. 5). There were no marked changes in botanical composition (data not shown).

Table 1. Measures of productivity during two successive periods of grain cropping in the cropping catchment after clearing

Measurement	Time periods after clearing	
	Period 1 (2.2–11.9 years)	Period 2 (11.9–22.4 years)
Measurement period (years)	9.69	10.50
Management regime	Conventional tillage/wheat monoculture	Minimum tillage/opportunity cropping
No. of tillage operations	35 (3.6 per year)	11 (1.0 per year)
No. of crops harvested	9 (all wheat)	12 (8 sorghum, 4 wheat)
Cropping frequency (number/year)	0.93	1.14
Total grain yield in C2 (t)	243.5	207.2 (85% of period 1)
Mean yield per crop (t/ha)	2.40 ± 0.78	1.53 ± 1.05 (64% of period 1)
Yield per year (t/ha.year)	2.23	1.74 (78% of period 1)
Total rainfall (mm)	5879	7327 (125% of period 1)
Total runoff (mm)	561	923 (164% of period 1)
Rainfall left in catchment (mm)	5318	6404 (120% of period 1)
Net soil water use during period (mm)	88	–90
Total water use (mm)	5406	6314 (117% of period 1)
WUE of rainfall remaining in catchments (kg/ha.mm)	4.02	2.93

Beef productivity

The beef production trends were confounded by the multiple effects of fertility decline and stocking rate changes. Stocking rates had to be adjusted to ensure dry matter availability exceeded 1 t/ha.year. Pasture yields were successfully maintained at levels >1 t/ha.year throughout the study period.

During the 22.3 years, stocking rates were generally reduced over time to maintain pasture dry matter and ground cover targets (Fig. 6*a*). Stocking rates fell into 2 broad categories; they were initially around 0.59–0.71 head/ha and were gradually reduced to 0.29–0.47 head/ha at the end of the trial.

Drawing on the cattle drafts that were replaced in the middle of the dry season over the first 14-year period, productivity trends in LWG/ha can be described by the interaction of stocking rate (S) and time after clearing (T) in the following multiple regression relationship:

$$\mathrm{LWG} = 40.38 + 133.92\mathrm{S} - 3.04\mathrm{T}\,(R^2 = 0.80,\ P < 0.01;\ n = 12) \quad (1)$$

This implies that a unit increase in stocking rate (head/ha) increased LWG by 134 kg/ha.year, and for each year post-clearing, site fertility factors reduced LWG by 3 kg/ha.year. Clearly, changes in stocking rate had a major and significant ($P < 0.01$) effect on productivity trends over this period, although time after clearing was a weakly significant variable ($P < 0.10$ with $P = 0.062$) and accounted for a proportion of the changes.

In order to further assess the impact of fertility decline on livestock productivity, data were analysed for the 7 drafts of steers at the same stocking rate (0.59 head/ha) between 2.8 and 10.7 years after clearing (Fig. 6*b*). Over this period of 7.9 years, LWG declined significantly ($P < 0.05$) by 4 kg/ha.year.

Comparison of grain production and beef production

In terms of the gross output value of commodities derived from the cropped and grazed catchments, the cropped catchment generated an annual value of AU$441/ha.year and the grazed catchment $121/ha.year (Table 2). These values are based on the product removed and 5-yearly average commodity prices for wheat and medium-weight steers, converted to 2005–06 dollars based on movements in the consumer price index. Over the trial period, this equates to about $10 000/ha from cropping and $2700/ha from grazing. No allowance was made for associated capital and operating costs used to generate the outputs which would have a major influence on the respective profitability of the 2 enterprises.

Soil organic carbon (SOC) and total soil N (TSN)

The concentrations of SOC and TSN at 0–0.1 m did not change in the brigalow scrub or pasture, but declined significantly ($P < 0.01$) under cropping (Fig. 7). After 21 years of production, SOC had declined by 38% and TSN by 56% in the 0–0.1 m layer.

Mean SOC in the 0–0.3 m layer of the cropping soil 21 years after clearing had declined by 21.1 t/ha or 33%, a rate of loss of 1004 kg/ha.year or 1.6% of the initial amount per year. Mean TSN in the 0–0.3 m layer after 21 years of cropping had declined by 1.76 t/ha or 40%, a rate of loss of 84 kg/ha.year or 1.9% of the initial amount per year.

Discussion

Productivity of both grain and beef declined during the first 20 years after clearing (Figs 3 and 6). A 20.7-year period of cropping without fertiliser application reduced grain yield (wheat, sorghum, and barley) to 51% (upper clay soil) and 47% (Sodosol) of its original level. In an adjoining catchment, an 8-year period of grazing on the sown buffel grass pasture with constant stocking at 0.59 head/ha reduced the annual LWG of cattle to 70% of its original level. We conclude that 20 years of cropping post-clearing halved grain production, while 8 years under pasture reduced LWG by 30% (beef production could be measured independently of stocking rate during only the first 8 years after clearing). These reductions in productivity were not associated with any decline in annual rainfall, in-crop rainfall, soil water at sowing, or soil water at sowing plus in-crop rainfall. Also the established plant populations of wheat and sorghum generally lay within the optimum range for maximum grain yield.

Compared with the first decade of production, crop yields in the second decade had declined by 36%, annual crop production (yield per year) by 21%, and WUE by 27% (Table 1).

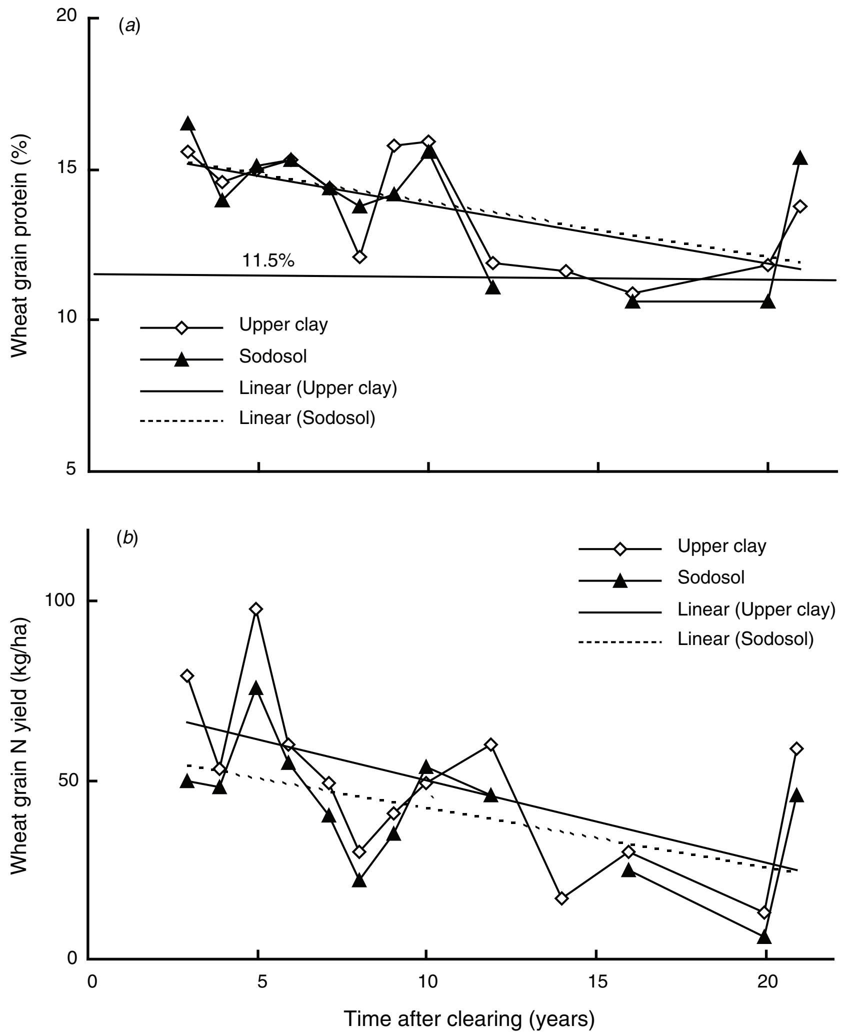

Fig. 4. Wheat grain protein contents and grain N yields for the upper-slope clay soil and the Sodosol during 23 years since clearing. Linear trend lines are shown. (*a*) Wheat grain protein contents. The horizontal line at 11.5% delineates sufficiency and deficiency of soil N supply. $R^2 = 0.38$, $P < 0.05$, $n = 13$ for the upper-slope clay soil; $R^2 = 0.31$, n.s., $n = 12$ for the Sodosol. $Y = 15.7 - 0.19T$ (upper-slope clay soil) where Y is grain protein content and T is time after clearing. (*b*) Wheat grain N yields. $R^2 = 0.32$, $P < 0.05$, $n = 13$ for the upper-slope clay soil; $R^2 = 0.31$, n.s., $n = 12$ for the Sodosol. $Y = 72.9 - 2.30T$ (upper-slope clay soil) where Y is grain N yield and T is time after clearing.

Productivity declined despite the following factors which may have masked it: (*1*) higher annual rainfall in the second study period (708 *v.* 611 mm); (*2*) increased water storage under minimum tillage (Radford *et al.* 1995); and (*3*) crop variety improvement (Williams *et al.* 1981). The following factors, however, may have exacerbated productivity decline: (*1*) the switch to minimum tillage, which reduces N mineralisation (Rovira and Greacen 1957), increases denitrification (Aulakh and Rennie 1985), increases nitrate leaching (Turpin *et al.* 1992), and increases N immobilisation (Cochran *et al.* 1980); and (*2*) the switch to more frequent (opportunity) cropping, which hastens the depletion of soil N.

Productivity decline under cropping is attributed largely to fertility decline, particularly soil N decline, but soil structure degradation, soil erosion, and a decline in the biological health of the soil may also have contributed (Truong and Diatloff 1998). The protein content of wheat grain and the grain N yield provide indices of soil N sufficiency for crop needs. Russell (1963) showed that the grain yield response of Gabo wheat to N fertiliser under a wide range of growing conditions was associated with grain N levels of <2.0% (i.e. 11.4% protein), while few significant yield increases occurred at 2.3% (13.1% protein). Goos *et al.* (1982) reported that grain protein content of dryland winter wheat was an effective post-harvest indicator of adequacy of N nutrition for grain production; the critical level between N deficiency and sufficiency was 11.5% protein. Strong and Holford (1997) concluded that a critical value of 11.5% was a reasonably robust and reliable wheat grain protein level

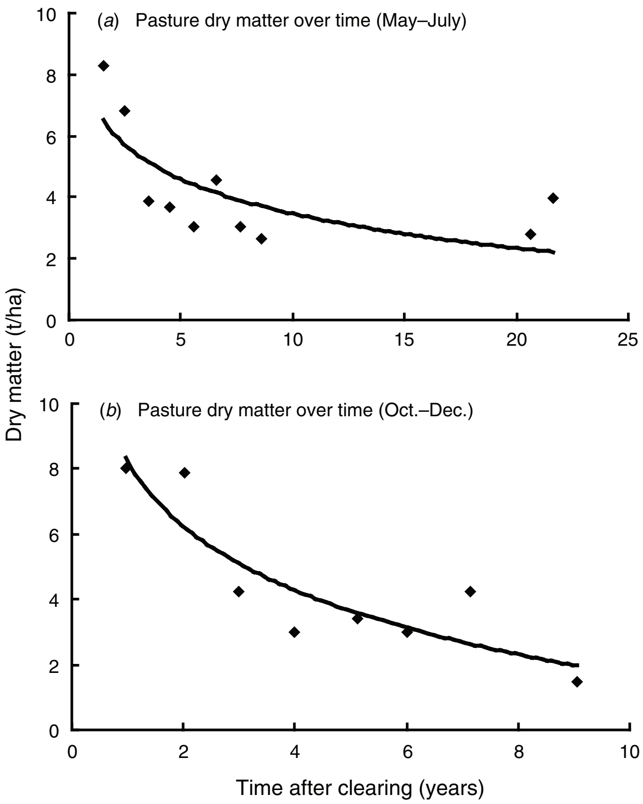

Fig. 5. Pasture dry matter on offer during 22 years since clearing. (*a*) Measurements taken in May–July (at the end of the growing season). $R^2 = 0.41$, $P < 0.05$, $n = 10$. $Y = 7.19 - 1.62 \ln(T)$ where Y is dry matter and T is time after clearing. (*b*) Measurements taken in October–December (at the start of the growing season). $R^2 = 0.71$, $P < 0.01$, $n = 8$. $Y = 8.21 - 2.83 \ln(T)$ where Y is dry matter and T is time after clearing.

indicating an adequate N supply to meet crop needs. Grain N yield is also a retrospective measure of available N that reflects the capacity of the soil to supply N during the fallow and growth periods combined; the best any soil test can offer is a measure of N supply made available during the fallow period only (Strong and Holford 1997). In the present study, wheat grain protein content and wheat grain N yield declined with time after clearing (Fig. 4). The first instance of N deficiency occurred in 1994 (12 years after clearing) when the Sodosol yielded 11.1% wheat grain protein (Fig. 4*a*). The first instance in the clay soil occurred in 1998 (16 years after clearing) when a wheat grain protein content of 10.9% was recorded after a long (18-month) fallow. In 2003, however, after 21 years of cropping, protein levels surprisingly exceeded 11.5% after a short (6-month) fallow.

Wheat protein concentrations of 13%, 11.5%, and 10.5% are the minimum requirements for Australian Prime Hard (APH), Australian Hard (AH), and Australian Premium White (APW) grades, respectively. Decline below these levels reduces the quality and hence the value of the grain produced. Protein content <13% was found only 8 years after clearing on the upper-slope clay soil. Protein content <11.5% was recorded 12 years after clearing on the Sodosol and 16 years after clearing on the upper-slope clay soil (Fig. 4*a*). So our results indicate that declining soil N availability quickly reduces wheat profitability after clearing by lowering both the quantity and the quality of the grain.

We conclude that pasture productivity declined into a run-down phase only 3 years after clearing. Myers *et al*. (1987) observed a similar rapid run-down of a green panic pasture within 2 years of establishment. The initially high production of sown pastures is a transient consequence of increased available N and water that accumulate after clearing and during fallow, and the run-down condition is the normal equilibrium (Myers and Robbins 1991). N deficiency is the major causal factor due to immobilisation of N and limited mineralisation of humic material (Myers and Robbins 1991). We found no measurable net loss of total soil N associated with pasture run-down. Graham *et al*. (1981) found the same. After 21 years, run-down has not yet been associated with any loss of desirable species or any replacement with more tolerant or less nutrient-demanding plants. In the brigalow environment these may include *Dichanthium*, *Astrebla*, *Bothriochloa*, and *Heteropogon*, although the major limitation to this occurring is seed availability (Burrows 2000). Provided that desirable species are retained, productivity of a run-down pasture is sustainable (Myers and Robbins 1991). Other studies have reported similar levels of pasture dry matter for a brigalow vegetation community 5–6 years after clearing, but suggest the stabilisation of pasture production after clearing may take up to or beyond 30 years (Kaur *et al*. 2005).

The pasture run-down was associated with a decline in animal production. This is shown in Fig. 6*b*, which provides a valid comparison over time by presenting LWG data obtained at the same stocking rate (0.59 head/ha). Robbins *et al*. (1987) also observed a decline in LWG with increasing age of pasture in central Queensland.

SOC and TSN levels declined significantly in the cropping land but not in the brigalow scrub or pasture land (Fig. 7). The mean rates of loss from the top 0.3 m of cropping soil during 21 years were 1004 kg/ha.year for SOC and 84 kg/ha.year for TSN. Dalal and Mayer (1986) found a similar rate of loss of TSN (67.1 kg/ha.year from the top 0.9 m) on a soil type (Langlands-Logie) similar to the clay soils in this study. The rate of loss in the top 0.3 m of cropping soil provides an indication of the rate of N replacement required to sustain the soil N fertility level. Of the 84 kg N/ha.year that was lost during cropping, 43% (36.1 kg N/ha.year) was exported in harvested grain. The amounts of N removed in runoff water during the 5 years after burning were 11.4 kg/ha.year from the cropping catchment and 3.4 kg/ha.year from the pasture catchment (Cowie 1993). If this loss rate remained constant for the 21 years, 14% of the N lost during cropping was exported in runoff water. Further N would have been removed from the cropping land by runoff water and deposited in the waterway. Losses would also have occurred through the processes of leaching and denitrification.

The amounts of phosphorus (P) removed in produce during the 5 years after burning were 7.0 kg/ha.year under cropping and 0.8 kg/ha.year under grazing (Cowie 1993). These amounts provide an indication of the replacement rates required for P on brigalow soils.

Grain farmers in central Queensland are reluctant to use fertilisers because of their cost and unreliable response (Lambert and Leighton 2002). Our results show, however, that brigalow

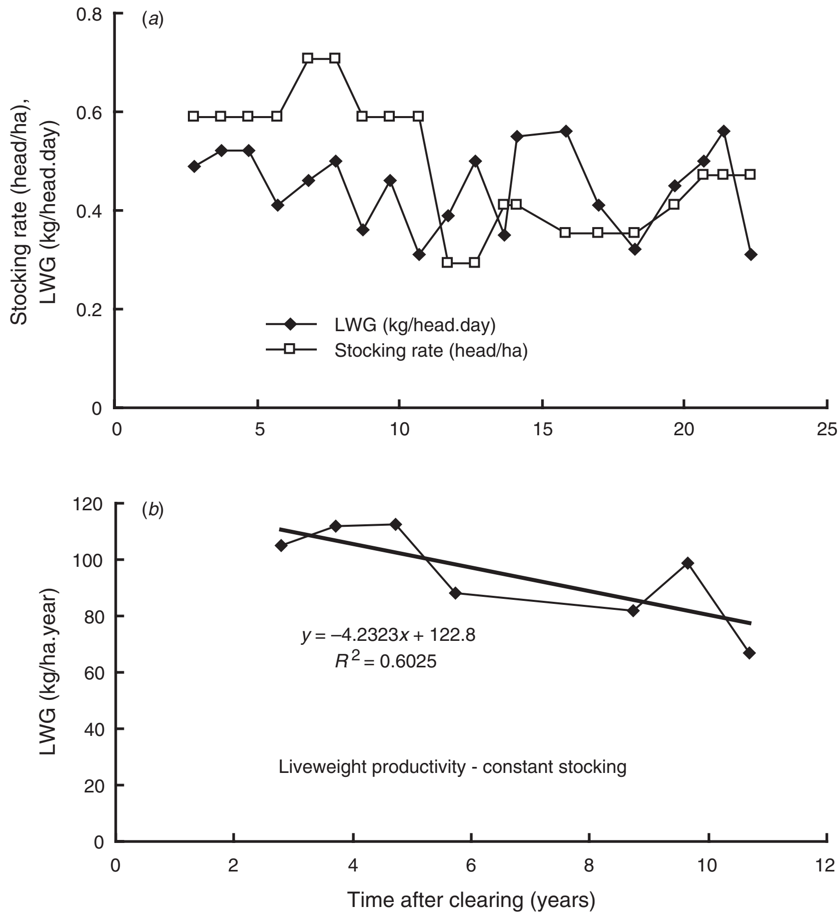

Fig. 6. Cattle liveweight data during 21 years since clearing. (*a*) Stocking rate and average daily LWG/head. (*b*) Annual LWG/ha at a constant stocking rate of 0.59 head/ha. $R^2 = 0.60$, $P < 0.05$, $n = 7$. $Y = 122.8 - 4.23T$ where Y is LWG and T is time after clearing.

Table 2. Comparison of the productivities of the cropped and grazed catchments in 22.3 years after clearing

Measurement	Cropped catchment (C2)	Grazed catchment (C3)
Product removed (kg/ha.year)	1778 (grain)	67 (cattle LW)
Dry matter removed (kg/ha.year)	1564 (grain)	28[A] (cattle LW)
Rainfall use efficiency for dry matter production (kg/ha.mm)	2.30	0.04
N removed (kg/ha.year)	36.1 (grain)	1.6[B] (cattle LW)
Gross output value of product removed ($/ha.year)	$440.94[C]	$120.60[D]

[A] Estimates of the water content in beef cattle vary from 40 to 75% (Bruns *et al*. 2004; Little and McLean 1981; Little and Morris 1972; Meissner *et al*. 1980). We used 57.5% (the midpoint of this range).
[B] Measurements of the N content in beef cattle have been reported as 2.1% (Bruns *et al*. 2004), 2.4% (Agricultural Research Council 1980), and 2.8% (Meissner *et al*. 1980). We used 2.4% (the mean of these values).
[C] Based on 2001–02 to 2005–06 average Australian price for wheat converted to real 2005–06 dollars at $248/t (ABARE 2006).
[D] Based on 2001–02 to 2005–06 average Queensland price for medium weight steers (C3 400–500 kg) converted to real 2005–06 dollars at $1.80/kg LWT (Meat and Livestock Australia 2007).

soils need nutrient inputs to avert productivity decline. Nutrients can be provided in fertilisers, or N can be added by including leguminous crop species or grass/legume ley pastures in the rotation. In the long-term, graziers will also need to replace the nutrients removed during beef production. The productivity decline in the pasture is attributed to reduced N availability; the initial high level of production in newly established pasture is largely due to a transient boost (‘run-up’) in available N and water in the soil during the fallow before seeding (Robbins *et al*. 1986). Invasion by woody weed species, which compete with grass

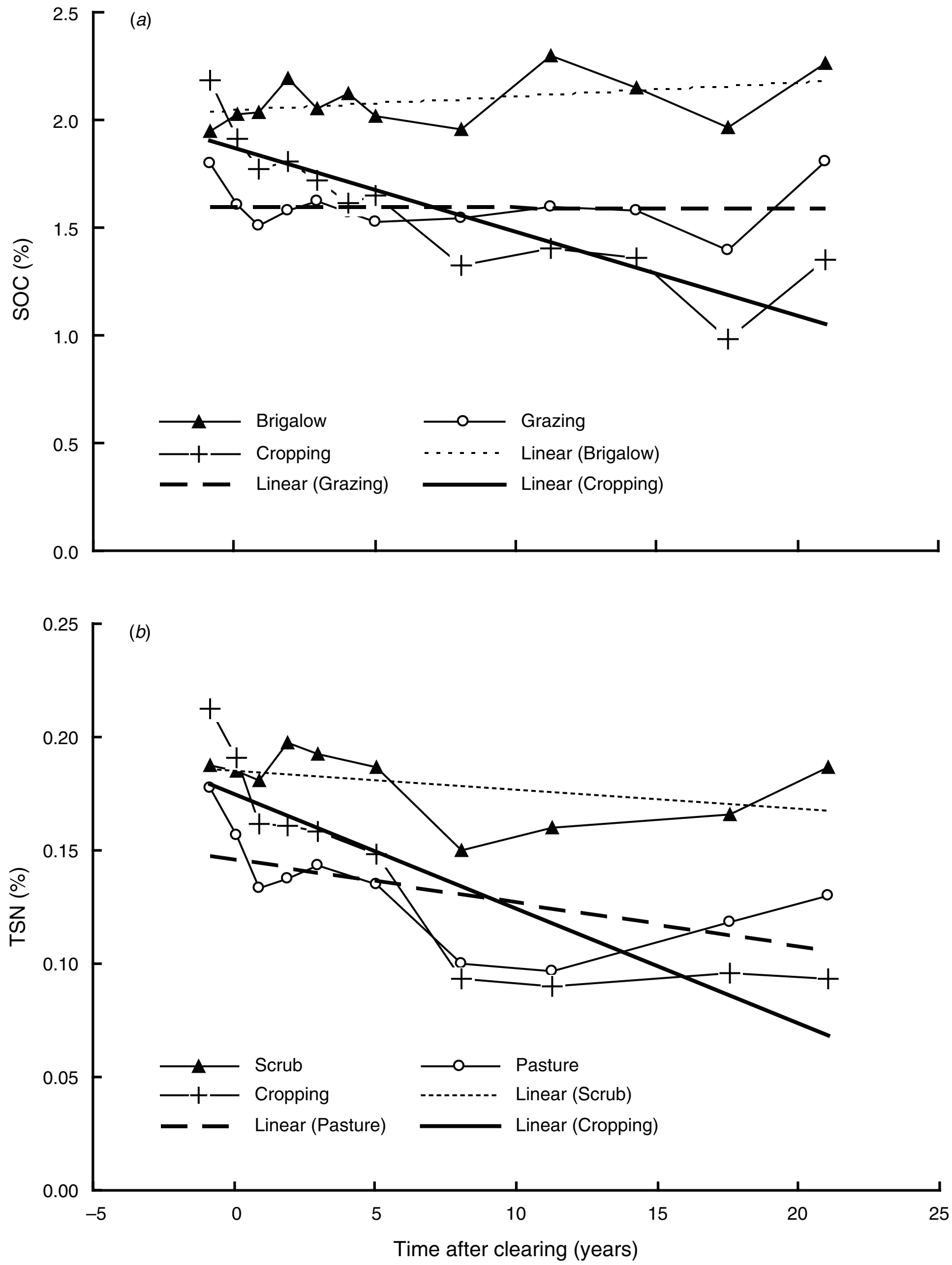

Fig. 7. Mean concentrations of soil organic carbon (SOC) and total soil nitrogen (TSN) at 0–0.1 m in the 3 catchments from pre-clearing to 21 years post-clearing. Bulk densities did not change significantly during this period. Linear trend lines are shown. (*a*) SOC. $R^2 = 0.16$, n.s. (scrub), 0.00 (pasture), and 0.75, $P < 0.01$ (cropping); $n = 10$. $Y = 1.87 - 0.04T$ (cropping) where Y is SOC and T is time after clearing. (*b*) TSN. $R^2 = 0.16$, n.s. (scrub), 0.34, n.s. (pasture), and 0.74, $P < 0.01$ (cropping); $n = 10$. $Y = 0.18 - 0.005T$ (cropping) where Y is TSN and T is time after clearing.

for light, water, and nutrients, also contributes to productivity decline. Pasture management using renovation techniques (to mobilise soil nutrients) or strategic burning (to control the woody weeds) may help but response is unreliable (Myers and Robbins 1991). It has been demonstrated elsewhere that nitrogen fertiliser treatments can avert long-term decline in cattle production for various stocking rate levels on brigalow pasture, but that the costs of such strategies relative to the partial gains may be uneconomic (Jones *et al*. 1995).

Fertility decline is not the only environmental impact resulting from clearing brigalow land for cropping or grazing. The initial clearing and burning reduces the amount of sequestered carbon in the trees and soil. Both cropping and grazing doubled annual runoff and changed its timing compared with the former brigalow landscape (Thornton *et al*. 2007, this series). Such changes could increase the risk of erosion and transport of nutrients and agricultural chemicals off site, could have biodiversity impacts on species and systems reliant on the native flow regime, and could increase groundwater recharge (Thornton *et al*. 2007, this series). The change from brigalow scrub to cropping or pasture also increased deep drainage and salt leaching (Thorburn *et al*. 1991).

Acknowledgments

We thank the managers and staff of Brigalow Research Station from 1965 to 2006 for providing the study area and assisting with the planting, tillage, spraying, and harvesting operations and for measuring the cattle weights. We thank the staff of the Chemistry Centre of the Department of Natural Resources and Water for the soil and grain analyses. A complete list of names of people who helped generate these results is given in paper I of this series (Cowie *et al*. 2007, this series).

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Manuscript received 21 May 2007, accepted 5 October 2007