Promoting soil health in dryland agriculture by increasing cropping intensity

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Abstract

Extended fallow periods are implemented in dryland cropping systems to allow recharge of soil moisture for the subsequent crop. Over time, fallow periods deplete soil carbon (C), a foundation of soil health that affects soil microbial activity and the long-term capacity of soils to store moisture. Reducing fallow periods by increasing cropping intensity (e.g. cover or double cropping) can promote soil health and thereby contribute to the long-term sustainability of dryland cropping systems. However, the agronomic feasibility of increasing cropping intensity in dryland systems is unknown. Using a cropping systems experiment in southeast Queensland, we investigated the impacts of cover and double cropping on indicators of soil health and sorghum grain yields in comparison to conventional fallow-based cereal production systems. Both cover and double cropping systems increased concentrations of soil C compared with the conventional systems. In the cover crop system, this was associated with greater soil microbial activity and improved surface soil moisture storage at crop establishment. Additionally, sorghum grain yield in the cover crop system did not differ significantly from those in the conventional systems. In contrast, the double crop system depleted soil moisture reserves leading to dramatic yield loss as well as reduced nitrogen- and water-use efficiency. Our results demonstrate that reducing fallow periods via cover cropping is a potentially feasible method for promoting soil health in subtropical dryland cropping systems. Longer-term research is required to determine the trade-offs and tipping points associated with the use of cover crops in drylands.

Key Words

Fallow, cover crop, double crop, soil carbon, soil water, soil microbial activity

Introduction

Dryland cropping systems implement extended fallow periods to recharge soil moisture for the subsequent crop. However, while offering short-term benefits for soil moisture storage, fallow periods lead to depletion of soil organic matter (SOM). Depletion of SOM is problematic because SOM is a foundation of soil health, affecting soil microbial activity and soil fertility, and is a critical determinant of soil structure and capacity to capture rainfall efficiently. Thus, in the long-term, repeated implementation of extended fallow periods undermines soil fertility and the capacity of soils to store moisture. Consequently, identifying agronomically feasible methods of reducing the extent of fallow periods and halting SOM decline is fundamental for the long-term sustainability of dryland cropping systems.

One approach to reducing the extent of fallow periods is to maintain more continuous living plant cover. The presence of living plants ensures greater continuity of inputs of fresh organic matter (OM). Fresh OM inputs provide nutriment to soil microbial communities; this can prevent SOM depletion while generating stabilised SOM that builds soil fertility and soil water holding capacity (Tiemann et al. 2015). Maintaining more continuous living plant cover can be achieved by increasing cropping intensity, such as by cover cropping or double cropping. Cover cropping is the growing of plants not intended for harvest between cash crops to protect and enrich the soil. Double cropping is the harvesting of two crops grown sequentially on the same unit of land in the same season. However, cover or double cropping in dryland environments carries the short-term risk of exhausting soil moisture reserves, which can compromise yields of the main cash crop.

We utilised a multi-year farming systems experiment in southeast Queensland to investigate the capacity of cover and double cropping systems to promote soil health relative to conventional subtropical dryland cropping systems. Soil health was quantified in terms of soil building (i.e. soil C and moisture storage) and active turnover (i.e. soil microbial activity and nutrient availability) processes. Further, we assessed the impacts of the different cropping systems on key agronomic indicators, namely sorghum grain nitrogen-use efficiency (NUE), water-use efficiency (WUE) and yield.

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Methods

In summer 2017/18, soil samples (0-30 cm depth, then 20 cm increments down to 120 cm depth) were collected from selected systems within the Northern Farming Systems experiment at Pampas, southeast Queensland (Table 1). The experiment, established in summer 2014/15, implements a range of cropping systems (Bell et al. 2017). Amongst these we compared two conventional summer-based dryland systems against a system incorporating cover crops and a system utilising regular double crops. In addition, a grass-legume ley and a long-term fallow were sampled to provide opposite ends of the fallow spectrum (Table 1).

Topsoil samples (0-30 cm depth) were analysed for indicators of soil building and active turnover processes. Analysis of these processes were limited to the topsoil because it is where the majority of plant roots are located, and it is where the most rapid changes in soil properties in response to management can be expected. For soil building processes, gravimetric water content (GWC), total C (TC) and total nitrogen (TN) were assessed at the start of the summer 2017/18 sorghum crop. GWC was quantified by oven-drying soils at 105°C; TC and TN were determined by combustion on a LECO analyser. Additional sub-samples were dried at 65°C and dispersed overnight before wet-sieving to isolate particulate C (PC; >53 µm) and humus C (HC; <53 µm). The PC fraction represents a labile C pool with short soil residence times (months to years); the HC fraction represents a stabilised C pool with long residence times (decades to centuries). Soil samples were collected near planting (14/11/17, which was two-weeks after planting in the conventional and cover crop systems, and three-weeks before planting in the double crop system [planting was delayed in the double crop system to allow harvest of preceding chickpea crop]). For active turnover processes, soil mineral nitrogen (minN) and microbial respiration (MR) were assessed at three time points: at planting (14/11/17), at sorghum panicle emergence (03/01/18 for the conventional and cover crop systems, and 31/01/18 for the double crop system); and post-harvest (09/04/18). MinN was determined by extraction with 2 M KCl; MR was assessed by CO_2 evolution after a seven-day incubation at 22°C (mg CO_2/kg soil/day). Grain was harvested with a plot harvester with yield data expressed at 12% grain moisture.

MinN data at planting and post-harvest was used to estimate crop extraction of soil nitrogen (N). This was combined with grain yield data to estimate grain N-use efficiency (NUE; kg/ha/kg N). Additionally, soil moisture across the soil profile (0-120 cm depth) before planting and post-harvest was assessed in conjunction with pre-crop rainfall and in-crop rainfall to estimate crop water use. This was combined with grain yield data to estimate grain water-use efficiency (WUE; kg/ha/mm).

Table 1. Details of the crop sequences implemented at the Northern Farming Systems experiment from summer 2014/15 to summer 2017/18.

System	Code	Crop sequence[a]	Above-ground biomass inputs[b] (t/ha)
Conventional cereal	Conv.Cr	x[c]-wheat-x-x-maize-x-sorghum	6.7
Conventional cereal plus cotton	Conv.Ct	x-wheat-x-x-cotton-x-sorghum	7.0
Cover crop	Covr.Cp	x-chickpea-x-oat CC[d]-sorghum-oat/vetch CC-sorghum	8.3
Double crop	Dble.Cp	x-wheat-mungbean-x-sorghum-chickpea-sorghum	7.0
Grass-legume ley	Past.Ley	Bambatsi/Rhodes grass and Burgundy bean/snail medic mixture	7.0
Long-term fallow	Perm.Fal	x-x-x-x-x-x-x	0

[a]Sequences are shown as summer 2014/15-winter 2015-summer 2015/16-winter 2016-summer 2016/17-winter 2017-summer 2017/18; [b]Mean annual crop residue returned to soil; [c]x – Fallow; [d]CC – Cover crop

Results and Discussion

The grass-legume ley and long-term fallow showed wide disparity in terms of indicators of soil building and active turnover processes, confirming the positive impact of continuous living plant cover versus no plant cover on soil health (Table 2). Between these two ends of the fallow spectrum, the cover and double crop systems showed significant improvement in soil building processes relative to the conventional systems (Table 2). Both conventional systems had levels of TC that did not differ significantly from the long-term fallow. In contrast, TC in the cover and double crop systems was equivalent to that of the grass-legume pasture, which was significantly greater than TC in the long-term fallow and conventional cereal system. Interestingly, changes in TC were primarily driven by changes to the HC fraction (data not shown), demonstrating that cover and double cropping can generate rapid increases in the stabilised soil C pool (i.e. within four years). This result is consistent with those found in temperate humid climates, where reductions in fallow periods by increasing cropping intensity have promoted increases in TC and the HC fraction (e.g. Romaniuk et al. 2018). Our results show that similar soil responses occur within subtropical drylands.

Table 2. Indicators of soil building and active turnover processes at 0-30 cm depth in each system in summer 2017/18. Subscript letters within columns indicate significant differences.

	Indicators of soil building processes					Indicators of active turnover processes		
System	TC[a] (g/kg)	TN[b] (g/kg)	GWC[c] T1 (%)	GWC T2 (%)	GWC T3 (%)	MR[d] T1[e] (mg/kg/day)	MR T2[f] (mg/kg/day)	MR T3[g] (mg/kg/day)
Conv.Cr	15.4_{a}	1.0_{a}	23.7_{ab}	30.3_{a}	23.1_{ab}	5.2_{a}	24.8_{a}	9.7_{a}
Conv.Ct	15.9_{ab}	1.0_{a}	24.1_{b}	29.0_{a}	22.4_{b}	5.7_{a}	23.1_{a}	5.3_{b}
Covr.Cp	16.9_{b}	1.0_{a}	30.4_{c}	33.2_{b}	24.0_{a}	16.9_{b}	44.2_{b}	19.5_{c}
Dble.Cp	16.7_{b}	1.1_{a}	26.6_{b}	17.5_{c}	18.6_{c}	18.2_{b}	39.3_{b}	38.9_{c}
Past.Ley	16.7_{b}	1.2_{b}	27.9_{bc}	34.4_{b}	26.0_{a}	13.2_{b}	39.2_{b}	29.3_{c}
Perm.Fal	14.7_{a}	1.0_{a}	21.9_{a}	26.2_{d}	24.7_{a}	3.2_{a}	16.2_{c}	2.8_{b}

[a]Total C; [b]Total N; [c]Gravimetric water content; [d]Microbial respiration
[e]T1 – Planting; [f]T2 – Panicle emergence; [g]T3 – Post-harvest

The cover crop system was able to maintain higher levels of topsoil GWC (0-30 cm depth) over the course of the summer compared to both the conventional systems and the double crop system (Table 2). This indicates the potential of cover cropping to improve soil seedbed conditions for germination and seedling development compared with conventional systems by maintaining more stable water availability. In addition, by maintaining greater GWC in the topsoil during panicle emergence, the cover crop system may be able to maintain more stable nutrient availability to crops in synchrony with crop physiological demand, including access to immobile nutrients concentrated in the surface soil, e.g., phosphorus and zinc. Greater residue cover on the soil surface combined with greater TC is likely to have driven the observed increase in soil moisture retention in the cover crop system. In contrast, the double crop system had significantly lower topsoil GWC compared with the conventional and cover crop systems, which persisted from panicle emergence to post-harvest (Table 2).

In terms of active turnover processes, the grass-legume ley, cover and double crop systems showed higher levels of soil microbial respiration compared with the conventional systems (Table 2). This is likely generated by higher levels of TC providing substrate to support greater microbial biomass and activity. Soil microbial activity drives mineralisation processes and is thus a key determinant of nutrient supply to crops. By enhancing soil microbial activity, the cover crop system offers opportunity for more efficient nutrient cycling. This is deserving of greater research. Additionally, enhanced soil microbial activity may generate positive feedbacks with TC; current theory and evidence indicate that by-products from soil microbial activity are rapidly preserved and constitute a major component of the stabilised soil C pool, i.e. the HC fraction (Throckmorton et al. 2015).

Sorghum grain yields across the conventional and cover crop systems did not differ significantly (Table 3). However, yield was 11% lower on average in the cover crop system compared to the conventional systems. In contrast, yield in the double crop system was 79% lower than in the conventional systems (Table 3). Lower grain yield in the double crop system was closely related to lower soil water availability (Table 2) and crop water use (Table 3). This is unsurprising, given that the significant reduction in soil moisture coincided with flowering, during which moisture stress can cause poor head-fill (GRDC 2017). Reduced grain yield in the double crop system was also linked with lower soil N availability (data not shown) and soil N extraction (Table 3). This suggests water stress likely began even before our time of sampling, e.g. from as early as the five-leaf stage, as yield potential is set during this time and is strongly impacted by limitations in water and nutrient availability (GRDC 2017).

Grain NUE was similar across the conventional and cover crop systems, but was significantly lower in the double crop system (Table 3). Preliminary grain N data (data not shown) indicate elevated grain N concentrations in the double crop system compared with the conventional and cover crop systems. Elevated grain N concentrations typically indicate lower NUE (Muchow 1998). Water stress during this time would have limited crop photosynthetic capacity and subsequently constrained yield set and grain-fill. This is further evidenced by the observed reductions in soil N extraction and crop water use within the double crop system (Table 3).

Table 3. Sorghum grain yields (12% moisture), nitrogen- (NUE) and water-use efficiency (WUE) in summer 2017/18. Subscript letters within columns indicate significant differences.

System	Grain yields (t/ha)	Soil N extracted (kg/ha)	Grain NUE (kg/kg)	Crop water use (mm)	Grain WUE (kg/mm)
Conv.Cr	4.44_{a}	90_{a}	54_{a}	521_{a}	8.5_{a}
Conv.Ct	4.04_{a}	82_{a}	52_{a}	516_{a}	7.9_{a}
Covr.Cp	3.76_{a}	60_{ab}	65_{a}	436_{b}	8.6_{a}
Dble.Cp	0.90_{b}	37_{b}	23_{b}	309_{c}	2.7_{b}

Likewise, grain WUE was similar in the conventional and cover crop systems, but greatly reduced in the double crop system (Table 3). The double-cropped sorghum had significantly lower water use compared with the other systems and had drastically lower yields. This indicates the crop had insufficient moisture available to effectively fill grain and hence did not efficiently convert biomass into grain yield, resulting in lower yield and WUE.

Conclusions

Our results demonstrate that increasing cropping intensity with cover crops is a potentially feasible method of promoting soil health in dryland agricultural systems. The use of cover crops led to improvement in indicators of both soil building and active turnover processes while maintaining crop productivity at levels equivalent to conventional cereal production systems. In contrast, while double cropping was found to improve some indicators of soil health (e.g. TC), it involved higher risk for crop yield. Lower risk systems require an extended fallow to recharge soil moisture reserves, but as shown here have negative consequences for soil C and microbial activity. The flexibility offered by cover crops allows them to be managed more effectively within the constraints of soil moisture availability than double crops. That said, while the soil health variables measured have in-part accrued over the four years since implementation of the experiment, our yield data was only for the summer crop of 2017/18. The true feasibility of including cover crops within a dryland rotation will only be determined through longer experimentation, and it remains unlikely that it will be feasible to plant cover crops in every fallow period. Consequently, while our results demonstrate the promise of cover crops to enhance soil health in dryland agricultural systems, further research is required to determine the trade-offs and tipping points associated with their use.

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