J. Crop Sci. Biotech. 2018 (March) 21 (1) : 13 ~ 22
DOI No. 10.1007/s12892-017-0044-0

RESEARCH ARTICLE

The Influence of Tillage Frequency on Crop Productivity in Sub-Tropical to Semi-Arid Climates

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Received: April 25, 2017 / Revised: September 24, 2017 / Accepted: October 18, 2017

Abstract

Strategic tillage (ST), an occasional tillage in a continuous no-till (NT) farming system, is already being utilized by many landholders in the Northern Grains Region (NGR) of Australia to control weeds. But the impact on productivity (yield), both short- and long-term, has been largely under investigated. This study focused on yield data from 14 on-farm ST in NT experiments from 2012 to 2014 (3 years/4 seasons) and the comparison of the re-interpreted results of a long-term (27 years) tillage experiment. This study explored production impacts of tillage on long-term NT systems over the short and longer term. Results from tillage-frequency studies across the NGR demonstrated that overall grain yield was not significantly impacted. A long-term tillage trial at Biloela showed wheat (*Triticum aestivum*) and sorghum (*Sorghum bicolor*) grain yields were similar across no till, stubble mulch and reduced tillage treatments, these in turn were all significantly higher than aggressive tillage without stubble retention treatments. Dealing with increased herbicide resistance often associated with reduced tillage and no-till systems poses a real time issue with landholders in the NGR. This analysis of historical yield data together with the more recent strategic tillage data can aid in selecting the appropriate soil management option by providing tillage impacts on yield.

Key words : Conservation agriculture, strategic tillage, no-till, wheat and sorghum yield

Introduction

Adoption of conservation agricultural (CA) practices including no-tillage (NT) has been widely embraced in grain growing regions of Queensland (Thomas et al. 2007) and across Australian agriculture (Llewelyn et al. 2012). However, within CA farming systems, strategic or occasional tillage (ST) is being utilized for a number of reasons by landholders in the Northern Grains Region (NGR) of Australia (Argent et al. 2013). These can include but are not limited to the control of herbicide resistant weed populations and soil- and stubble-borne diseases, and to address stratification of nutrients and organic carbon near the soil surface (Dang et al. 2015a).

It can be misconstrued as to what the ST process consists of, or if there is even a place for it within CA. Strategic tillage can be best described as an opportunistic use of tillage operation/s (adequate tillage implement for desired outcome at adequate soil water level) in an otherwise NT system (Crawford et al. 2015, Dang et al. 2015a). A potential benefit is that it can provide a circuit breaker in herbicide use, addressing the build-up of resistant weed populations. However, the risk is, that poor timing or too many tillage application can lead to detrimental soil health impacts. Palm et al. (2014), states that CA is a system of agronomic practices that includes reduced tillage (RT) and NT. Reduced tillage occurs during seed bed preparation and hence a more regular tillage application, therefore strategic tillage should be a natural inclusion, as it involves far less tillage frequency than RT. Reviews such as Dang et al. 2015a, Dang et al. 2015b, and Busari et al. 2015, depicted a good representation of the process involved within the CA management system and the

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risk/benefit of including strategic tillage in these systems. These reviews also discussed the potential for productivity decline with time if a strategic tillage process is not included within CA systems. This sentiment is supported in Kirkegaard et al. (2014) which stated 'the avoidance or exclusion of ST within the CA process makes little sense if considerable overall benefits are put at risk'.

Nationally, increasing herbicide resistant weed populations have been reported as threatening crop-production profitability and sustainability across 20 million ha (Walsh and Powles 2007). Werth et al. (2011), stated that within the sub-tropical cropping region of north-east Australia, up to five weed species have evolved glyphosate resistance; namely annual ryegrass (*Lolium rigidum*), awnless barnyard grass (*Echinochloa colona*), liverseed grass (*Urochloa panicoides*), flaxleaf fleabane (*Conyza bonariensis*), and windmill grass (*Chloris truncate*). While efficient and effective herbicide use is still the preferred management style within the NGR, utilizing tillage as stated previously has re-entered CA potential management options. Other methods such as increased seeding rates and decreasing row spacing (Bajwa et al. 2016; Lemerle et al. 2004) have demonstrated positive results for productivity while addressing weed competition. While there are large amounts of literature on the benefits of CA (inclusive of NT, RT, and minimal tillage (MT) compared to aggressive tillage), very little has been published on the impacts of ST in NT systems, especially within Australia. The purpose of undertaking this tillage frequency study was to address literature gaps on the impacts of strategic tillage on productivity of CA systems.

While the yield differences of CA practices vs aggressive tillage practices have been well established in research such as: Pittelkow et al. 2015; Radford and Thornton 2011; Thomas et al. 2007; Thomas et al. 1990; Zhang et al. 2015, the differences between the CA first principle management options such as NT, Stubble Mulch (SM), RT, or ST are less well known. In considering the level of soil disturbance within CA systems, multiple management approaches can be utilized, by varying the level of tillage intensity. But how does each tillage intensity option impact crop yield? The inclusion of ST can be seen as a natural adaption within a CA management system, while still maintaining less intensive tillage processes such as SM or RT.

A good example of tillage yield impacts within the CA management system is the long-term trial reported in Radford and Thornton (2011). The aim of this long-term trial (27-year period) was to assess the efficacy of NT, RT, and SM compared to aggressive tillage. They concluded that aggressive tillage practices used in the past (disc plough, scarifier, and cultivator for all weed control) were uneconomical and lead to declining soil health. This conclusion supported the use of CA practices, and provided the opportunity to explore the potential differences between the various CA tillage approaches. It is the reinterpretation of the RT methods and the differences in yield from the Radford and Thornton trial that will aid in the forward assessment of the possible impacts of ST in NT systems.

Therefore, based on the above and previous research, three questions are presented: Firstly, how different are the tillage practices with regards to productivity in the NGR? Second, what impact does a strategic tillage have on grain yield? And lastly, if there is any yield impact due to tillage why this is the case? The aim of this study was to demonstrate the hypothesis that grain yield of NT farming systems is not significantly impacted by the inclusion of ST as a management option. The approach taken was to: compare yield from 4 seasons within a tillage frequency study in the NGR; and reinterpret data from a long-term tillage trial (Radford and Thornton 2011) to assess the difference between the various CA methods outlined above.

Materials and Methods

Tillage frequency study

Study area/details

Study sites in Australia's Northern Grain Region ranged from Emerald (22°29'38", 148°38'11") Queensland (QLD) to Wee Waa (30.23°S, 149.45°E) New South Wales (NSW) with a summer dominant rainfall distribution (Fig. 1).

Soil types at study sites are predominantly cracking clays (Vertosols, Australian Soil Classification (ASC), Isbell 2002) (Vertisols, World Reference Base (WRB), IUSS 2006) with medium to heavy texture (Table 1). Rainfall patterns within

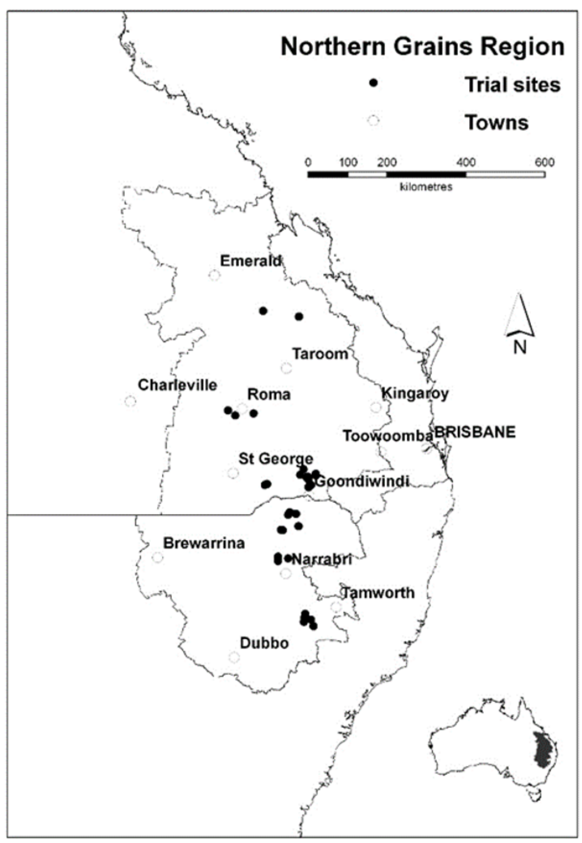

Fig. 1. Sites for tillage frequency study.

Table 1. Tillage frequency study site locations and soil type with reference sources.

Location	Soil Type (ASC)	Reference
Biloela	Black Vertosol	Crawford et al., 2015, Ricon-Florez et al., 2015
Condamine	Brown Sodosol	Crawford et al., 2015
Jimbour	Black Vertosol	Ricon-Florez et al., 2015
Moonie	Grey Dermosol	Crawford et al., 2015, Lui et al., 2015
Moree	Grey Vertosol	Lui et al., 2015
Warwick	Black Vertosol	Crawford et al., 2015
Wee Waa	Grey Vertosol	Crawford et al., 2015

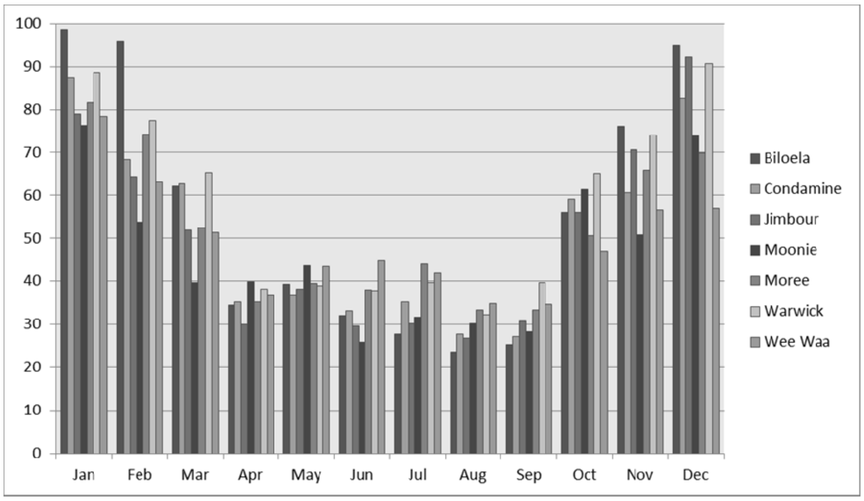

Fig. 2. Monthly rainfall means (mm) for tillage frequency study site locations (http://www.bom.gov.au).

Table 2. Site details and Climatic conditions for the Emerald, Goondiwindi and Yelarbon sites (http://www.bom.gov.au).

	Emerald	Goondiwindi	Yelarbon
Max temperature (°C)	34.8	34.1	33.2
Min temperature (°C)	6.7	4.8	5.6
Average annual rainfall (mm)	668	621	620
Summer Rainfall (mm)	325	217	224
Date of tillage	28/05/2013	12/02/2013	29/05/2013
Tillage Implements	Chisel, Offset Disc	Offset Disc	Chisel, Offset Disc
Crop 2013/14	Sorghum	Sorghum	Sorghum
In-crop rain (mm) 2013/2014	293	231	223

the NGR are predominantly summer dominant with a high probability of rain falling between the months of November and May (Fig. 2).

Soil descriptions for the remaining study sites not previously described are as follows: The Emerald Queensland (QLD) site is classed as a Black Vertosol (ASC), Vertisol (WRB), developed on tertiary deposits. The Goondiwindi Queensland (QLD) site transitions between a Grey Vertosol and a Brown Chromosol (ASC), Vertisol and Luvisol (WRB) developed on Quaternary alluvium and sands (Ross and Crane 1994). Yelarbon Queensland (QLD) is classed as a Grey Vertosol (ASC), Vertisol (WRB) developed on Quaternary alluvium.

Climatic conditions for the remaining study sites at Emerald, Goondiwindi and Yelarbon sites are shown in Table 2.

A randomized, complete block experimental design was used for the trial sites at Yelarbon, Emerald, and Goondiwindi as described in Crawford et al. 2015. Weed populations were determined at the tillering growth stage of the crop for the purpose of assessing correlations with yield. Productivity was assessed by analyzing crop grain yields for the period 2012-2014 winter cropping season and 2013/2014 summer cropping season.

Tillage application

Tillage implements utilized in the application of ST included narrow and wide chisel tyne, offset disc and prickle/disc chain to depths of 0-0.2 m. To maintain continuality with on farm management practices of control traffic the four replicates per treatment, each 100 m in length, were dependent upon sowing implement width and was between 12 and 18 m wide. The timing on the application of a ST was dependant on site access, suitable climatic, soil, and agronomic conditions. The application dates ranged from less than 14 days to greater than 200 days prior to sowing.

Aggressive tillage was defined in this study as that where: cultivation implements reach depths in the range 0-20 cm, soil inversion causes the incorporation of organic matter, energy inputs are greater than sowing practices, and it occurs more than twice in a growing season.

Statistical analyses

To determine the impact on yield during the tillage frequency study the following approach was undertaken. Yield was divided into individual crops: Barley (*Hordeum vulgare*), chickpea (*Cicer arietinum*), sorghum, and wheat (all sites; Tillage = Till or no till); Barley and Wheat (five sites; where tillage = once, twice, or zero). Each analysis looked at the factorial of season by tillage treatment. If there were significant effects then these were further explored to look at pair-wise comparisons. The Pearson correlation coefficient was used in the assessment of weed impacts on each crop yield. The statistical package *GenStat for Windows* 14th Edition (VSN International, Hemel Hempstead, UK.) and JMP 12th Edition was used to analyze the results.

Re-interpretation of a long-term tillage study

Study area/details

The Radford and Thornton (2011) study site was located at Biloela (24.37°S, 150.52°E) Queensland (QLD) on a Black Vertosol (ASC), Vertisol (WRB) developed on Quaternary alluvium. Climatic conditions for the Biloela area are described in Crawford et al. (2015). Experimental design consisted of a randomized block with four tillage treatments and four replications. The tillage treatments were split into aggressive tillage and varying degrees of conservation farming practices (SM, RT, and NT). The aggressive tillage blocks utilized a disc plough, scarifier and cultivator to assess the impact of tillage on grain productivity over 20 years and 86 treatment applications without herbicide weed control. Stubble mulch and RT utilized either chisel or blade plough (86 treatments) and rod weeder implements (53 treatments). Herbicides were utilized in varying degrees for control of weeds in the absence of tillage operations for NT treatments.

Physical and chemical properties measured were bulk density, soil water content, soil nitrate nitrogen, soil penetration resistance, and soil organic carbon. For further experimental details please refer to Radford and Thornton (2011) and Radford et al. (1995).

Re-interpretation of the long-term trial control dataset enabled the tillage practices to be assessed. Yield data from 10 wheat (*Triticum aestivum*) (1987-1999) and eight sorghum (*Sorghum bicolor*) (1984-2003) crops grown under control fertilizer conditions within the four tillage treatments were used in this re-interpretation analysis.

Statistical analyses

The re-interpretation analysis consisted of the following: Each set of analyses had two parts: Analysis of four tillage treatments over years and analysis of three tillage treatments (dropping aggressive tillage) using contrasts within the ANOVA table. When there was a significant 'treatment x year' interaction, individual least significant difference (lsd) comparisons of tillage treatments were done within each year to help interpret the results. Yield across tillage treatments were compared using linear mixed models to analyze the repeated measures over years. The most parsimonious model was chosen, with the sorghum (years treatments applied) data set using compound symmetry, sorghum (years treatments not applied) using auto-regressive process (order 1), and wheat using compound symmetry with heterogeneity of residual variances fitted across years. Contrasts were used to compare three of the tillage treatments and their interaction with year. The lsd procedure was used for pair-wise comparisons of significant terms. All testing was done at the 5% level of significance.

Results

Tillage frequency study

There were no significant differences observed in the wheat or sorghum yields during the timeframe 2012-2014 (Table 3). Chickpea yield in 2013 at Biloela for twice-tilled

Table 3. Table of overall crop means (t/ha) till or no-till for the tillage frequency study.

Crop	*No-till*	*Till*
Barley	2.27^{a}	2.11^{a}
Chickpea	1.22^{a}	1.26^{a}*
Sorghum	2.63^{a}	2.61^{a}
Wheat	2.40^{a}	2.41^{a}

*Note: Only 2 sites out of 14 displayed significant difference in yield, Condamine 2012 (tillage operation once) Biloela 2013 (tillage operation twice). Means followed by the same letter within a row are not significantly different at $P = 0.05$.

Table 4. Table of analysis of 5 site/seasons x 3 tillage treatment means (t/ha) for cereals (wheat & barley) for the tillage frequency study.

Crop	Tillage operations		
	No-till	*Once*	*Twice*
Cereals (5 sites over 3 years)	1.87[a]	1.84[a]	1.86[a]

Means followed by the same letter within a row are not significantly different at $P = 0.05$.

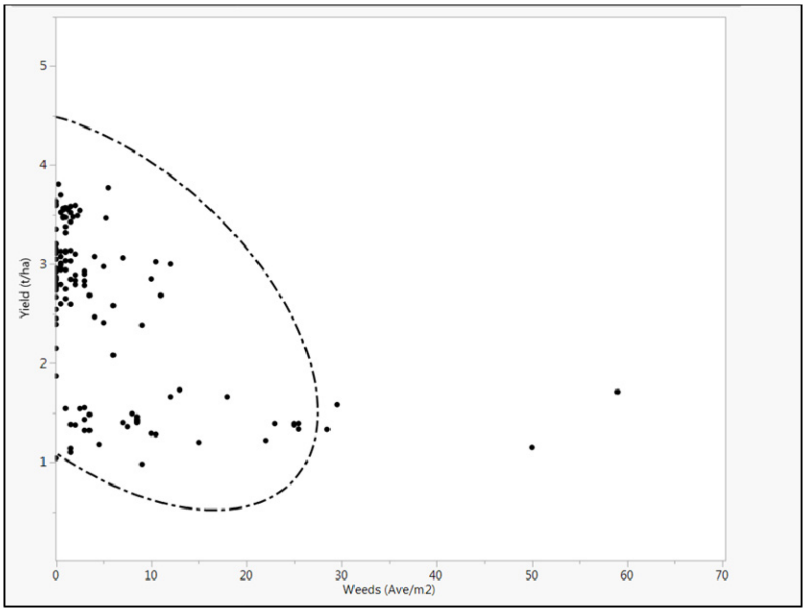

Fig. 3. Bivariate normal ellipse $P = 0.95$ for wheat yield by average weed count for all seasons.

treatments was significantly greater than NT and once-tilled treatments (NT: 1.99, once: 2.06, twice: 2.23 (t/ha). The yield data at Biloela were combined from sister sites, one set up in 2012 and the other 2013. Chickpea yield in 2012 at Condamine for once-tilled treatments was significantly greater than NT (NT: 1.07, once: 1.17, twice: 1.14 t/ha). There were no significant differences observed when the three tillage treatments for cereals (t/ha) (wheat and barley) were analyzed separately for the five site/seasons (Table 4).

A fitted bivariate normal ellipse ($P = 0.95$) for crop yield by average weed count for all seasons depicted a negative correlation for yield as weeds increased. Wheat yield depicted the highest correlation (-0.51) (Fig. 3), followed by Sorghum and Chickpea (-0.26, -0.11).

Long-term tillage study

A significant difference ($P < 0.05$) for the overall sorghum yield means (t/ha) between aggressive tillage treatment 2.43 and NT 3.27, RT 3.28, and SM 3.09 were observed during the re-interpretation timeframe for the initial analysis of four treatments. When the aggressive tillage was dropped from the analysis, no significant differences were observed in sorghum yield (t/ha) between NT, SM, and RT in the years 1984-86, 1993 and 2003. In 1987, RT (2.93) and SM (2.71) were significantly higher than NT (2.19) (LSD = 0.66). In 2001, NT (3.40) was significantly higher than RT (2.66) and SM (2.51) (LSD = 0.66), and 2002 NT (2.07) and RT (2.06) was significantly higher than SM (1.24) (LSD = 0.66). The average means (t/ha) over the length of the study were NT 3.27, RT 3.28 and SM 3.09 and they were not significantly different ($P > 0.05$). See Fig. 4 for a visual representation.

Wheat - aggressive tillage yield (2.09 t/ha) was significantly lower ($P < 0.001$) than the overall wheat yield means for RT (2.62 t/ha), NT (2.48 t/ha), and SM (2.45 t/ha). When the aggressive tillage was dropped from the analysis, no significant differences were observed in wheat yield between NT, SM, and RT in the years 1988, 1990-99. In 1987, RT treatments yields (1.10 t/ha) were significantly higher than NT (0.65 t/ha) and SM (0.67 t/ha) (LSD = 0.19). In 1989, SM treatment yields (3.87 t/ha) was significantly higher than NT (3.19 t/ha) but not RT (3.67 t/ha) (LSD = 0.61). The means (t/ha) over the length of the study were NT 2.48 and SM 2.45, with RT 2.62 significantly higher ($P < 0.05$) than NT and SM. Figure 5 demonstrates the closeness of the treatment yields.

Discussion

Tillage frequency and grain yield

The tillage frequency study was designed to capture potential short to mid-term productivity changes. Strategic tillage application in long-term NT systems did not reduce grain yields compared to NT treatments based on four seasons of

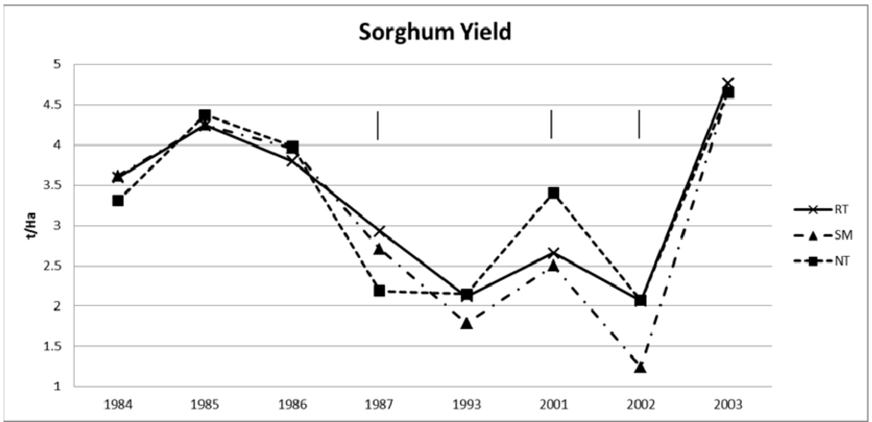

Fig. 4. Sorghum yield (t/ha) during the long term trial conducted at Biloela, QLD. Vertical lines indicate lsd at $P = 0.05$ within that season.

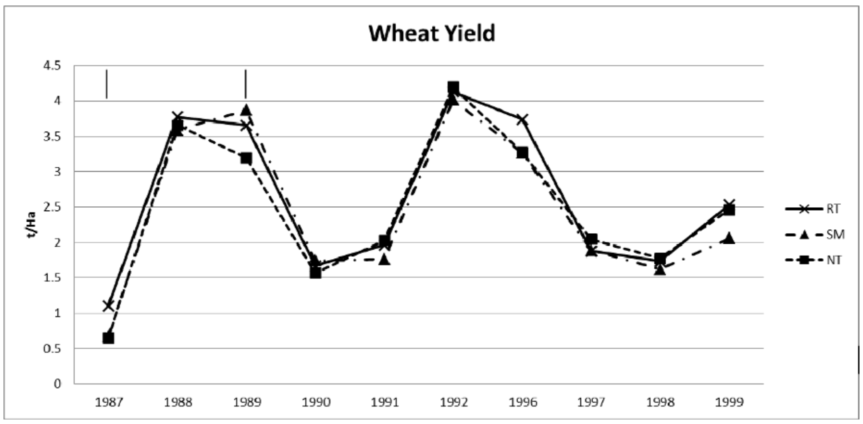

Fig. 5. Wheat yield (t/ha) during the long term trial conducted at Biloela, QLD. Vertical lines indicate lsd at $P = 0.05$ within that season.

crop yield data at 14 sites, representing a range of growing environments. In two sites out of 14, a significant increase in chickpea yield was observed at Condamine in 2012 and Biloela in 2013. At both sites there was a significant decrease in the weed population due to tillage in that season. Crawford et al. (2015) found that an occasional strategic tillage resulted in minimal soil health impacts (bulk density, soil organic carbon, volumetric moisture, available phosphorus) and positive agronomic outcomes (yield, weed control) within long-term NT systems. Observed soil water status showed minimal differences between treatments (Crawford et al. 2015); leading to the conclusion that available nutrients influenced these results. Unfortunately, this was not explored in greater detail in Crawford et al. (2015).

There can be a number of specific triggers for the introduction of an ST management option including, but not limited to, herbicide resistant weeds, nutrient stratification, and breaking up wheel track compaction. A recent survey carried out by the Australian Bureau of Statistics (ABS, 2015) indicated that of the total area of cultivated crop land in Queensland (1.46 M Ha); 49.8% was managed with no-till (NT) (apart from sowing), 17% used one cultivation, 16.7% used two cultivations, and 16.5% involved three or more cultivations. Based on this survey, up to half of the total cultivated area could be potentially subjected to a strategic tillage to address a management issue. It is therefore essential to understand which impact of tillage on NT systems lead to the accumulated soil health benefits and productivity.

Overall crop yield correlations with weed populations demonstrated a strong negative correlation in wheat (-0.51) (Fig. 3), with sorghum (-0.26), and chickpea (-0.11) depicting a non-significant correlation. There was however, no significant yield differences seen in wheat and sorghum compared to chickpea. An open canopy architecture and slow development can reduce chickpeas competitive ability against weeds in the early growth stages (Whish et al. 2002; Knights 1991). Once chickpea canopy closure has occurred, later emerging weed establishment and competition is reduced (Mohammadi et al 2005). Removal of early weed competition by ST and good follow-up herbicide application could explain the yield increases observed for chickpea in this study.

The differences in advantages provided by the contrasting tillage management systems is a conundrum faced by many landholders. Soil type and climate conditions will vary the results seen between tillage practices. Previous studies in the NGR of Australia have shown that aggressive tillage had advantages compared to NT such as reductions in weeds, pests and diseases (Radford and Thornton 2011), but had the disadvantage of reduced soil water storage (Liebig et al. 2004; Marley and Littler 1989; Radford et al. 1995; Thomas et al. 1990). Increased soil water storage associated with NT in the arid and semi-arid latitudes has clear yield advantages over aggressive tillage, whereas in tropical climates yields have demonstrated declines under NT systems (Pittelkow et al. 2015).

Hunt et al. (2013) reported for soils such as Chromosol (texture contrast, not strongly acid) and Calcarosol (calcareous throughout) (ASC), that the control of summer weeds, either by herbicide or by cultivation, resulted in large and reliable yield increases for winter crops. This was due to the provision of both additional soil water and additional mineral N. However, these soil types are vastly different to the Vertosol soils (well structured, high soil water storage capacity) that occur within the NGR. The success of any tillage depends on the interaction between soil, plant and climate; with the latter being the major driver of success (Freebairn et al. 1993; Latta and O'Leary 2003).

These results are also similar to other short to mid-term studies outside Australia such as: Paul et al. (2013), Wortmann et al. (2010), Kettler et al. (2000), and Díaz-Zorita et al. (2004). The benefit of conducting a tillage frequency study in established NT farming systems is that it enables an assessment of the soil disturbance and soil cover associated within CA practices. The presence of representative data on both the local and regional scale will ultimately aid stakeholders in their decision making process regarding individual CA practices. For the NGR and Australia as a whole there is an under representation in CA datasets relating to the understanding of tillage effects on yield under climatic variations (Pittelkow et al. 2015). While previous publications in the NGR have reported that the impacts of occasional or ST in NT systems to soil health and productivity were minimal to non-significant (Crawford et al. 2015: Lui et al. 2016: Ricon-Florez et al. 2015), they do not adequately fill the gap with regards to understanding the impacts to grain yield over the long term.

Tillage type (Long-term trial)

The long-term tillage trial at Biloela is a significant experimental resource to inform the role of tillage on grain yield, with four crops over 27 years providing a valuable empirical data set. Long-term data is valuable when exploring the possible changes an occasional tillage operation might have on soil water processes and grain yield. Within this dataset a re-interpretation of 10 wheat (years 1987-1999) and eight sorghum (years 1984-2003) crops grown under control fertilizer conditions, enabled the crop yield for the tillage treatments to be assessed over the long-term.

While there was a significant difference between the aggressive tillage treatment and the CA treatments, the differences were small within the CA practices for both wheat and sorghum crops. Only three occurrences of significant yield differences were observed in sorghum over 8 years, with no definitive pattern emerging between NT, RT, and SM treatments. Climatic conditions were reported as the major cause for these changes, with total soil water (mm), fallowing efficiency % and soil water use all depicting similar results for the three CA treatments (Radford and Thornton 2011). In 1987, RT and SM out performed NT with the opposite recorded in 2001. The season of 2002 resulted in NT and RT out performing SM. Average yields over the 8 years were not significantly different ($P > 0.05$) and only presented small yield advantages in NT 3.27 t/ha and RT 3.28 t/ha treatments over SM 3.09 t/ha. Wheat yield depicted a similar pattern having an initial significant difference in 1987 with RT outperforming NT and SM. In the 1989 season, SM and RT out performed NT.

The overall means point to RT as the most productive of the CA practices, with significantly higher yields ($P < 0.05$) than NT and SM. The aggressive tillage treatment yield was significantly less than the CA practices during the timeframe of this re-interpretation. This result is not surprising as NT out yielded aggressive tillage by 28% in the control fertilizer treatment over a 20-year timeframe (Radford and Thornton 2011). However, the yield difference between the CA practices treatments was not substantial, leading to the conclusion that occasional tillage in NT systems would not affect yield greatly.

Within the NGR, a tillage frequency study in long-term NT wheat and sorghum cropping systems found no differences in yield between treatments involving 1 or 2 tillage operations and NT treatments. This result, from a short-term study is not surprising, when considering the results from the re-interpretation of the practices within the 27-year trial of reduced tillage. As stated earlier, aggressive tillage management will vary in tillage intensity and application over time and between regions. This may lead to a valuable resource, such as long-term trials, being overlooked when searching for answers regarding tillage in NT systems as it is assumes that this management option does not apply in the present farming system. The Marley and Littler (1989) dataset based over 11 years and Thomas et al. (1990) dataset based over seven years have aggressive tillage practices that are largely considered uncommon now. They do however provide examples of NT and potential CA practices that could be re-interpreted. These resources could potentially provide more insight into answering the first question of how yields vary across tillage practices in the NGR.

In hindsight, this may have enabled a different experimental and sampling design for the tillage frequency study in NT systems. Having more access to long-term datasets may allow future research to avoid unnecessary duplication. This could then open up resources to delve deeper into soil physical, chemical, and biological properties and how much influence they have on crop yield. This re-interpretation was not undertaken to pit the soil health effects of each practice against the other. It was nonetheless, utilized to demonstrate that some level of tillage within CA systems is a feasible option, which will not significantly affect crop yield in the short-term. Positive soil health and economic benefits have been stated numerous times for research concerning aggressive tillage vs CA practices (Karlen et al. 2013; Radford and Thornton 2011; Thomas et al. 2007) but differences in yield are typically small when comparing within CA practices.

However, this study did not address the economic impacts of each practice. The possible economic outcome of selecting one of the four tillage strategies over the others is thoroughly covered in Radford and Chudleigh (2000). This data depicted minimal differences in yield over the long-term on this particular soil type and climate, leading to the conclusion that implementing an occasional ST into NT systems, as part of an overall CA practice, is a plausible management option within the NGR. Allowing for a balanced approach to farming decisions by providing information on yield impacts for the common soil group (Vertosol) will only benefit in the long-term. The availability of long term CA datasets is, however, limited to 2 locations within the NGR (the other at Hermitage Research Station, Warwick). The site at Warwick is also the last active site, meaning that re-interpretation of previous research would be a valuable tool in the future.

Tillage type and frequency

The variability or evolving nature of agricultural practices presents both challenges and opportunities for discussion of potential differences within each tillage practice. Nichols et al. (2015) stated that the Food and Agriculture Organization of the United Nations (FAO) defined three main principles that characterize CA; continuous minimum mechanical soil disturbance, permanent organic soil cover or stubble retention and diversification of crop species grown in sequences and/or associations. While these principles enable a level of consistency, defining aggressive tillage (the antithesis of continuous minimum mechanical soil disturbance) will ultimately vary with country, region and the period in history in which the term is utilized. This will continue to evolve as new technologies and management practices are developed and the attitudes of landholders adjust.

A recent international study by Salem et al. (2015) highlighted the difficulties and pitfalls of comparisons in CA practices in the literature. The use of moldboard plough is a tillage implement ill-suited to NGR soil types and conditions, and has been seldom used for decades. It is however, considered a traditional or conventional tillage practice overseas. This limits the use of international studies using this tillage implement when comparing CA tillage studies within Australia and particularly the NGR. The potential benefits of combining reinterpreted long-term studies (local or regional) that have similar tillage practices with the likes of ST or short term CA studies should not be underestimated. They provide a valuable tool to not only limit duplication in future studies but provide a pathway to past tillage practices and future directions. Similar soil type and climate conditions are an obvious starting point when undertaking the search for comparison studies.

Conclusion

The analysis of two sets of field experiments demonstrated that an occasional or strategic tillage within a no-till farming system may have an insignificant impact on grain yield in the northern grain growing region of eastern Australia. The results bring some scientific rigour to management changes already being implemented in these farming systems. This study is however, limited to the eastern part of Australia with CA tillage practices on predominantly well-structured clay soils. It only included two other soil types, which limits the robustness of the above conclusion. Future research on a wider variety of soil types in the region is recommended.

By design this manuscript focussed only on the yield mpacts of tillage practices in NT systems. Soil health impacts must always be factored in when considering tillage application in NT systems. The economic decision to implement an occasional strategic tillage is also a subjective farm management decision. They can be based on a number of factors such as: herbicide resistance; chemical cost vs tillage cost, and weather patterns. Hence, it is prudent to continue the assessment of CA practices within Queensland and wider Australia to build a quantifiable database for future decision making.

Acknowledgements

We thank the Grains Research and Development Corporation for supporting this project (ERM00003). Provide acknowledgement to Bruce Radford, Craig Thornton and DNRM's role as custodian of the 27-year Biloela long-term trial data set. The farmer/landholders: Nev and Ron Boland, Rod and Sam Hamilton, Darren Jensen, and Ken and John Stump for providing field sites, managing the trials and providing their generous support. Thanks also to the Strategic Tillage team: Suzette Argent, Anna Balzer, Mike Bell, Don Browne, Lilia C. Carvalhais, Ram Dalal, Vivian Rincon-Florez, Maria Harris, Tony King, Hongwei Lui, Phil Moody, Clement Ng, Rod Obels, Peer M. Schenk and Micheal Widderick who contributed throughout the project to the design, setup, acquisition, analysis, or interpretation of data. We would also extend our warm thanks to David Freebairn, Dan Smith and Andrew Biggs for their editing contributions.

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