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FACING TO REAL SUSTAINABILITY - CONSERVATION AGRICULTURAL PRACTICES AROUND THE WORLD

Strategic tillage in conservation agricultural systems of north-eastern Australia: why, where, when and how?

Yash Pal Dang[1] · **Anna Balzer**[1] · **Mark Crawford**[2] · **Vivian Rincon-Florez**[1] · **Hongwei Liu**[1] · **Alice Rowena Melland**[3] · **Diogenes Antille**[3] · **Shreevatsa Kodur**[3] · **Michael John Bell**[1] · **Jeremey Patrick Milroy Whish**[4] · **Yunru Lai**[1] · **Nikki Seymour**[5] · **Lilia Costa Carvalhais**[1] · **Peer Schenk**[1]

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Abstract Farmers often resort to an occasional tillage (strategic tillage (ST)) operation to combat constraints of no-tillage (NT) farming systems. There are conflicting reports regarding impacts of ST and a lack of knowledge around when, where and how ST is implemented to maximise its benefits without impacting negatively on soil and environment. We established 14 experiments during 2012–2015 on farms with long-term history of continuous NT to (i) quantify the associated risks and benefits to crop productivity, soil and environmental health and (ii) explore key factors that need to be considered in decisions to implement ST in an otherwise NT system. Results showed that introduction of ST reduced weed populations and improved crop productivity and profitability in the first year after tillage, with no impact in subsequent 4 years. Soil properties were not impacted in Vertosols; however, Sodosols and Dermosols suffered short-term negative soil health impacts (e.g. increased bulk density). A Sodosol and a Dermosol also posed higher risks of runoff and associated loss of nutrients and sediment during intense rainfall after ST. The ST reduced plant available water in the short term, which

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Yash Pal Dang and Anna Balzer contributed equally in the preparation of this manuscript.

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✉ Yash Pal Dang
y.dang@uq.edu.au

Anna Balzer
anna.k.balzer@gmail.com

Mark Crawford
Mark.Crawford@dnrm.qld.gov.au

Vivian Rincon-Florez
v.rinconflorez@uq.edu.au

Hongwei Liu
hongwei.liu0@gmail.com

Alice Rowena Melland
alice.melland@usq.edu.au

Diogenes Antille
Dio.Antille@usq.edu.au

Shreevatsa Kodur
Shreevatsa.Kodur@usq.edu.au

Michael John Bell
m.bell4@uq.edu.au

Jeremey Patrick Milroy Whish
Jeremy.Whish@csiro.au

Yunru Lai
yunru.lai@uqconnect.edu.au

Nikki Seymour
Nikki.Seymour@daf.qld.gov.au

Lilia Costa Carvalhais
l.carvalhais@uq.edu.au

Peer Schenk
p.schenk@uq.edu.au

[1] School of Agriculture and Food Sciences, The University of Queensland, St Lucia, Australia

[2] Department of Natural Resources and Mines, Toowoomba, Australia

[3] University of Southern Queensland, Toowoomba, Australia

[4] CSIRO, Toowoomba, Australia

[5] Department of Agriculture and Forestry, Toowoomba, Australia

could result in unreliable sowing opportunities for the following crop especially in semi-arid climate that prevails in north-eastern Australia. The results show that generally, there were no significant differences in crop productivity and soil health between tillage implements and tillage frequencies between ST and NT. The study suggests that ST can be a viable strategy to manage constraints of NT systems, with few short-term soil and environmental costs and some benefits such as short-term farm productivity and profitability and reduced reliance on herbicides.

Keywords Crop productivity · Environmental impact · No tillage · Soil health · Strategic tillage · Conservation agriculture

Introduction

No tillage (NT) or zero tillage (seeding with low soil disturbance and no prior tillage) is a key component of conservation agricultural systems which has provided tangible, economic, environmental and social benefits as compared to conventional tillage which involves intensive disturbance of soil prior to crop sowing (FAO 2016). The adoption of NT has progressed globally (FAO 2016) and in Australia (Llewellyn et al. 2012), particularly the north-eastern Australia (Thomas et al. 2007). However, there are concerns regarding long-term sustainability of such systems due to build-up of herbicide-resistant weed populations, increased incidence of soil and stubble-borne diseases and stratification of nutrients and organic carbon in the top soil (Dang et al. 2015b). There is an increased interest in the use of an occasional strategic tillage (ST) to combat both biotic and abiotic constraints in NT systems (Argent et al. 2013; Kirkegaard et al. 2014). The impact of ST in an otherwise NT farming system on agronomic, soil and environmental factors has either been shown to be inconsistent (Dang et al. 2015a) or studied for a relatively short period (Baan et al. 2009; Crawford et al. 2015; Díaz-Zorita et al. 2004; Liu et al. 2016; Rincon-Florez et al. 2016). Only a few studies have examined the impact of occasional ST for periods of 4 to 5 years (Kettler et al. 2000; López-Garrido et al. 2011; Wortmann et al. 2010), and these yielded inconsistent results (Dang et al. 2015a). Another important consideration is the increased risk of erosion and runoff in the case of an intense rainfall immediately following a ST operation, which could pose a serious problem especially in north-eastern Australia.

If occasional ST is necessary, research is needed to determine the critical aspects of the best timing, frequency and implement for tillage operations under local agroclimatic conditions. Timing of ST has major implications for the success or failure of tillage operations (Dang et al. 2015b). Given that crop production in north-eastern Australia heavily relies on stored soil water during the fallow period, tillage too close to sowing could result in the loss of soil water in the seeding zone (Crawford et al. 2015), which may result either in unreliable sowing opportunities or a poor crop establishment. In contrast, tillage immediately after harvest may result in incorporation or decomposition of crop residue, thereby resulting in loss of soil cover and an increased risk of erosion due to wind or water (Freebairn et al. 1991). In north-eastern Australia, primary tillage implements (e.g. mouldboard plough) that invert the soil are rarely used due to a high risk of soil erosion (Freebairn et al. 1996). Most growers adopt shallow (non-inversion) tillage using tyne and disc implements (Thomas et al. 1997). This raises two questions: (i) will shallow tillage implements be effective in managing the constraints of NT farming systems? and (ii) what frequency of tillage operations is needed to manage the constraints of NT farming systems?

Australia's north-eastern grain-growing region (NGR) that includes northern New South Wales (NNSW) and Queensland ranges from cereal growing subtropics in the east to semi-arid cropping in the west, from 32.3° S to 22.7° S. The median annual rainfall varies from 500 to 800 mm year^{-1} with rainfall distribution changing from summer dominant in the north to a relatively uniform winter-summer distribution in the south. Low and variable in-crop rainfall, heat stress and high rates of evaporation (1600–2000 mm year^{-1}) are features of the region's climate. These features make stored soil water an important driver of grain yield (Freebairn et al. 1991). The major soils in the region are grey, brown and red cracking clay soils (Vertosols) with some texture contrast soils (Chromosols, Sodosols) and a clay loam over a gradational profile with weakly structured A-horizon soils (Dermosols). Significant, but less prevalent soils include iron-rich (Ferrosols) and sandy soils (Kandosols) (Webb et al. 1997). The Vertosols, which occupy >70% of the cropping soils (McGarity 1975), have been shown to be resilient to one-time tillage (Rincon-Florez et al. 2016); however, soils that exhibit texture contrast properties (Sodosol) and weakly structured A-horizons (Dermosol) are likely to suffer negative soil health impacts within the first 3 months (Crawford et al. 2015). This raises the question: how long will it take for Sodosols and Dermosols to recover from negative impacts of occasional ST?

This research aims to quantify short- and long-term risks and benefits of occasional ST on crop productivity, soil and environment health in a range of soil types and agroclimatic conditions. It also addresses the impacts of tillage implements, timing and frequency on crop productivity, soil and environment.

Materials and methods

Experimental sites

A total of 14 field experiments were established in four different phases in north-eastern Australia during 2012–2015 on sites with a long-term history of continuous NT and controlled traffic farming (Fig. 1): (i) five sites with or without tillage treatments in otherwise NT fields in winter 2012; (ii) three sites with treatments involving different timing, frequency and type of tillage implements with each treatment factor (timing, frequency or type of tillage) in a separate experiment in a complete randomised block design in winter 2013, (iii) two sites with different types of tillage implements (strip tillage, narrow chisel and disc) and one experiment to quantify soil water loss and recovery with one-time ST in summer 2013; and (iv) three sites with or without tillage treatments to quantify runoff and loss of soluble nutrients immediately following ST under simulated rainfall in winter 2015. All tillage operations were shallow to an approximate soil depth of 0–15 cm.

Experimental design and treatments

A randomised, complete block design was used for all sites except at Warwick. At Warwick, a long-term experiment (Marley and Litter 1989) consisting of a factorial combination of tillage practice (NT vs conventional tillage), crop residue management (burnt or retained) and nitrogen (N) fertiliser rates (0, 30 and 90 kg N/ha) was longitudinally split into two, with half of the NT section receiving chisel and the remaining half left untilled as a control. In the present study, we reported results for no-till stubble retained N90 treatments only and analysed as randomised complete block design. All sites had a minimum of three replicates. A detailed description of each site and tillage implement used, timing and frequency is given

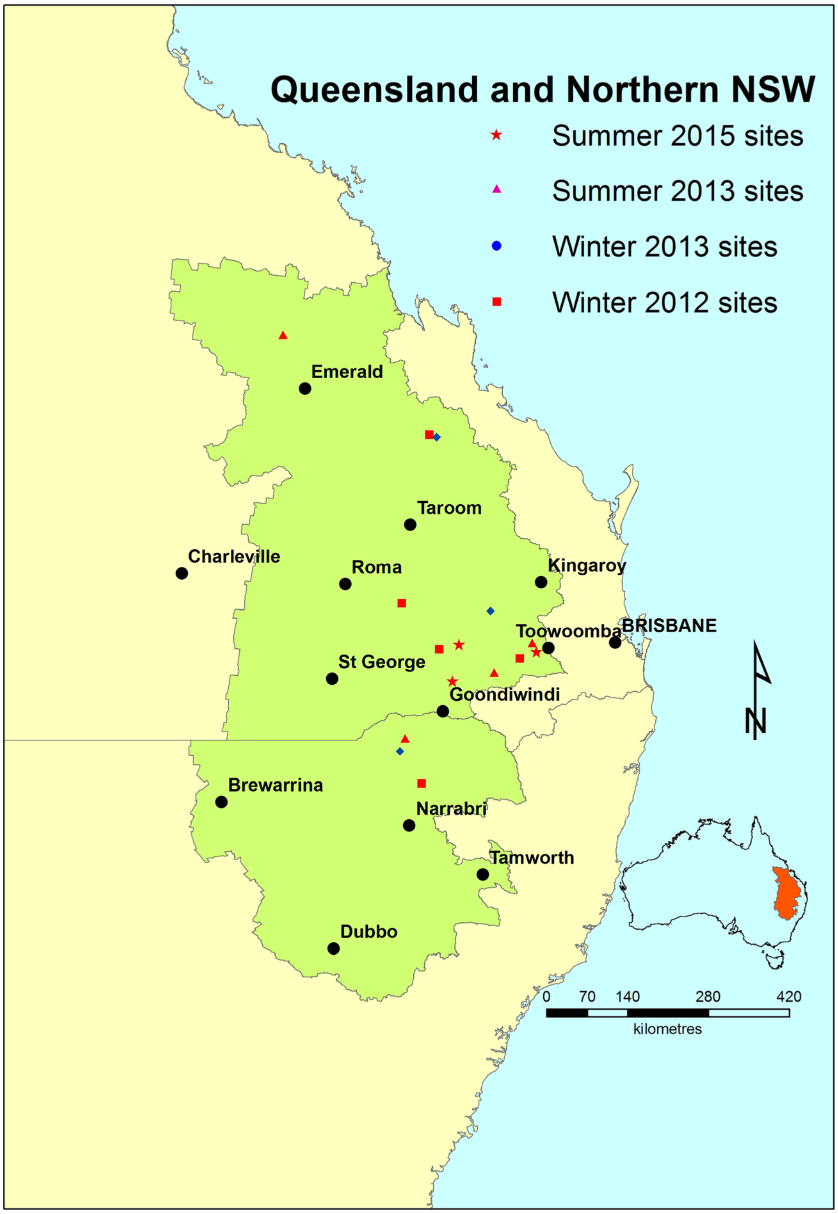

Fig. 1 Location of experimental trial sites throughout Queensland and northern New South Wales

in Table 1. The most common tillage implements used included chisel, disc, offset disc, scarifier and Kelly Prickle chain.

All selected fields during 2012 and 2013 were surveyed using an electromagnetic induction 38 (EM38, Geonics) in vertical mode. All positions were corrected for GPS antenna and kriged to a 1 × 1 m grid as described by Dang et al. (2011). The most homogeneous area of the field was ground-truthed and selected for tillage operations. Agronomic measurements included in-crop weed population at the tillering stage using a 1 m × 1 m quadrat, with four randomly placed replications and grain yield at maturity using on-farm machinery. We determined short-term soil water loss due to evaporation on a Vertosol (100 m × 12 m plots with 9-m buffer space between plots) at Felton A site (Table 1) on days 1, 2, 3, 4, 7, 9, 17, 30, 44, 60 and 65 post-tillage using an EM38 (Geonics MKII) in both vertical and horizontal modes. Volumetric water content was estimated using a pre-calibrated linear relationship between volumetric water content and EM38 readings recorded at the site.

At rainfall simulation sites during 2015, runoff was generated for at least 30 min at a rainfall intensity of 70 mm h^{-1} from four plots of NT and ST on three soil types (Table 1). The fields were managed using controlled traffic farming and had slopes ranging from 0.7 to 1.4% (Melland et al. 2016).

Soil, runoff and gas sampling and analysis

Soil samples were obtained yearly prior to sowing and analysed for physical, chemical and biological properties. Two geo-referenced soil cores from two locations were taken to a depth of 0–0.3 m at 3, 12, 24 and 36 months after the initial tillage operation on five sites in 2012. Similar samples were taken after initial tillage on three sites in 2013 and immediately following initial tillage on three sites in 2015. Soil samples were collected using a hydraulic soil sampling rig with modified hinged corer (43-mm diameter). Samples were split into depth intervals of 0–0.1, 0.1–0.2 and 0.2–0.3 m. The first set of soil samples from each replicate was oven-dried at 105 °C while the second sample was oven-dried at 40 °C. Samples were ground and passed through a 2-mm sieve. Bulk density (BD) was calculated as the mass of oven-dried soil (105 °C) per unit volume of the soil sample. The volumetric water content was calculated using the first sample, by multiplying the gravimetric water content by the BD value. The second sample was used to determine available P by the Colwell procedure (Rayment and Lyons 2011).

Total organic carbon (TOC) was determined on a subsample from the second replicate after grinding to pass through a 0.5-mm sieve (Rayment and Lyons 2011). Particulate organic carbon (POC) was determined on the 0–0.1-m layer after physical separation into <2- and >0.053-mm sizes

Table 1 Site description and tillage timing, frequency and implements used in a single-factor randomised block design

Site	Soil type	NT history	Tillage frequency	Tillage implement	Tillage timing	Crops			
						2012	2013	2014	2015
Biloela A	Vertosol	18	1,2	Chisel	29 Mar, 20 Apr 2012, 28 Jan. 10 Feb 2013	Wheat	Chickpea	Sorghum Wheat	Wheat
Condamine	Sodosol	19	1,2	Chisel	6 Mar, 18 Apr 2012	Chickpea	Wheat	Wheat	Wheat
Wee Waa	Vertosol	16	1	Chisel, prickle chain	26 Mar 2012	Chickpea			
Moonie A	Dermosol	7	1	Chisel, Disc	3 Mar 2012	Barley	Chickpea	Chickpea	
Warwick	Vertosol	43	1	Chisel	3 Mar 2012	Wheat	Wheat	Wheat	Wheat
Biloela B	Vertosol	18	1,2,3	Chisel	Dec 2012, Jan, Feb 2013		Chickpea	Sorghum Wheat	
Jimbour	Vertosol	9	1,2,3	Chisel, Disc	4 Dec 2012, 23 Jan. 20 Mar 2013		Wheat	Chickpea	
Moree	Vertosol	5	1	Kelly chain, chisel	12 Mar 13, 5 Apr 2013		Wheat		
Felton A	Vertosol	5	1	Disc	12 Aug 2013		Sorghum		
Emerald	Vertosol	7	1	Narrow chisel, offset disc	29 May 2013		Sorghum		
Yelarbon	Vertosol	5	1	Tyne, offset disc	29 May 2013		Sorghum		
Felton B	Vertosol	9	1	Scarifier	20 May 2015			Linseed Mung beans	
Billa Billa	Sodosol	15[a]	1	Cultivator, Kelly Prickle Chain	31 May 2015		Fallow	Sesame	
Moonie B	Dermosol	9[a]	1	Cultivator, Kelly Prickle Chain	4 Jun 2015		Mung beans	Wheat	

[a] The Billa Billa and Moonie B sites were strategically cultivated to shallow depths (≤150 mm) for weed control or pupae busting after cotton cropping once or twice, respectively, in the 4 years prior to the experiment

(Cambardella and Elliot 1992) followed by TOC analysis. Equivalent soil mass was used to compare TOC stocks (Wendt and Hauser 2013). For soil biological analysis, seven soil samples from each tillage treatment replicate were collected with a hand shovel from 0- to 0.1- and 0.1–0.2-m soil depths. Point scale sampling was carried out by drawing an imaginary Z shape along each plot. Samples from the same depth were composited, mixed and passed through a 4-mm sieve and stored at 4 °C until analysis. Soil microbial biomass C was determined using a fumigation-extraction method with ethanol-free chloroform ($CHCl_3$) and extracting soluble C with potassium sulphate (Beck et al. 1997). Total microbial activity was determined using a fluorescein diacetate (FDA) assay in a potassium phosphate buffer (Adam and Duncan 2001).

Samples of runoff, from rainfall simulations, were analysed for volume, sediment and nutrient contents (Rayment and Lyons 2011). Nitrous oxide (N_2O), carbon dioxide (CO_2) and methane (CH_4) fluxes were measured to quantify short-term greenhouse gases (GHG) emissions. Gases were extracted manually from chambers at 0, 25, 50 and 75 min after enclosure once per day before rainfall, within 3 h post-rainfall, and then 1, 2 and 3 days (Vertosol only) after rainfall. N_2O, CO_2 and CH_4 concentrations were measured using a gas chromatograph (GC-2014, Shimadzu, Japan), and fluxes at each sampling occasion were calculated using methods described by Chadwick et al. (2014). Further details of the runoff and gaseous emission experiments are described by Melland et al. (2016).

Profitability analyses

In the first year of tillage, the cost was deemed to be $15/ha for chisel tillage, $20/ha for disc cultivation and $10/ha for Kelly chain cultivation. Profitability was determined based on average market prices of $290 ($260–340)/t wheat, $255 ($220–300)/t barley, sorghum $230 (180–260)/t and $520 ($400–600)/t chickpea during 2012–2015.

Statistical analyses

All the experiments were conducted as a single factorial complete randomised block design. We did not attempt to study the interaction of tillage types with tillage timing and/or tillage frequency. One-way analysis of variance (ANOVA) was conducted on different tillage treatments as a single factor at each location using GenStat 17th edition (VSN International Ltd., Hemel Hempstead, UK). Least significance difference (LSD) was used to separate the treatment means and was reported at the 5% confidence level (LSD <0.05). For rainfall simulation study, two-way analyses of variance for soil type, treatment (no-till or ST) and interaction effects were conducted using GenStat 17th edition. For total enzymatic activity and microbial biomass carbon, one-way ANOVA, followed by Tukey's HSD at 95% and the LSD of $P < 0.05$, was used to compare treatments using the statistical software SPSS v20.

Results and discussion

Short- and long-term ST impacts

The impacts of ST operation(s) in an otherwise NT farming system on crop productivity, soil health and environment aspects are summerised for one-time chisel tillage on the top 0–10-cm soil depth (unless otherwise specified), which was common at most sites.

Soil health impacts

Soil structure is a key factor in soil biophysical functioning and is important in the evaluation of the impact of tillage (Kay and VandenBygaart 2002). Soil bulk density (BD) in the top 0.1-m soil depth was quite variable and not significantly affected at all the sites 3 months after one-time ST operation. However, 12 months after ST, there was a significant BD decrease in the brown Sodosol at Condamine as well as a trend toward increased BD on the grey Dermosol at Moonie. At 24 months after a ST operation, there was a non-significant decrease in BD at all the sites. However, due to extremely dry conditions prior to soil sampling during 2015, the soil BD measurements were unreliable and hence not reported. The previously published reports on the effect of one-time ST on soil BD in NT systems were contradictory. Soil BD was either unchanged (Dalal et al. 2011), increased (Kettler et al. 2000) or decreased (Pierce et al. 1994), and these effects were related to the soil conditions (Dang et al. 2015a).

Soil water storage and crop water supply are the major factors affecting grain production in the semi-arid region of north-eastern Australia (Freebairn et al. 1991). The introduction of ST in a NT farming system would potentially increase soil evaporation. In the present study, ST initially reduced the soil water content, due to evaporation. Within 4 weeks of tillage, however, sufficient rainfall replenished soil water loss and helped to recover the soil moisture to pre-till moisture status (Fig. 2). Evaporation losses due to tillage can be as high as 20 to 30 mm (Hatfield et al. 2001). Evaporation can be affected by climatic conditions above the soil surface, depth of the tilled layer, time and nature of tillage, the nature of induced surface structure and the pore geometry of the tilled layer (Jalota and Prihar 1990).

Following one-time ST, soil water content in the 0–0.1-m layer was not significantly impacted at any site or time, except at Warwick 3 months after tillage (Table 2). Soil water recovery was due to substantial rain (80–99 mm) received in the first 3 months after ST operations during 2012 and 2013 at

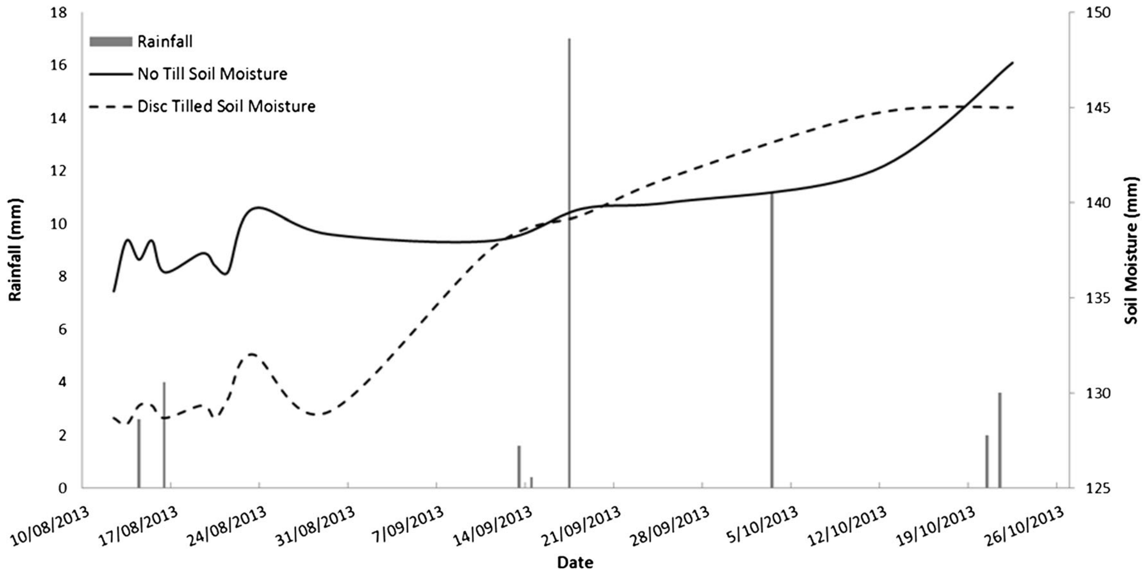

Fig. 2 Changes in the soil water content following disc tillage to a depth of 0–0.1 m in a Black Vertosol at Felton, with rainfall events indicated

most sites. The exception was a significantly negative impact at the Warwick site, despite 118-mm rainfall between ST and the time of soil sampling after 3 months. High clay content soils, like that at Warwick (65%), require more rain to refill the soil profile. No significant differences in soil water content due to ST treatments were observed prior to seeding in subsequent years, i.e. after 12 and 24 months after the ST operation. Given that crop production in north-eastern Australia heavily relies on stored soil moisture during the fallow period (Freebairn et al. 1991), the initial loss of soil water in extreme cases could present either unreliable sowing opportunities or a poor crop establishment. No-till farming systems, especially in high clay soils, usually have a much wider sowing window due to retention of adequate water for crop establishment. In most circumstances, the occurrence of rain after the tillage operation would determine the success of ST in NT farming systems. This raises the importance of timing of tillage in the farming systems context in relation to the seasonal forecast. Overall, the climatic conditions throughout the season will influence soil water, aeration and temperature and thus will have a marked influence on crop responses and yields in different seasons (Dang et al. 2015a; Thomas et al. 2007).

Table 2 Short- and long-term impacts of one-time chisel tillage in an otherwise continuous no-till system on agronomic and soil health indicators in 0–0.1-m soil layer

	Biloela A (Vertosol)				Condamine (Sodosol)				Moonie A (Dermosol)			Warwick (Vertosol)				Wee Waa (Vertosol)	Moree (Vertosol)		Jimbour (Vertosol)	
	3m	12m	24m	36m	3m	12m	24m	36m	3m	12m	24m	3m	12m	24m	36m	3m	3m	12m	3m	12m
BD	−	−	~		−	↓	−		−	+	~	−	−	+	~	−	−	~	−	~
SW	−	+	+	~	−	+	−	~	−	+	+	↓	+	−	−	−	−	~	−	~
TOC	−	−	−	~	−	−	−	~	−	−	−	−	−	+	+	−	−	~	−	~
POC	~	↓	~		~	−	~		~	−	~	~	+	~		~	~	~	~	~
P	↓	−	+	+/−	−	−	−	−	−	−	−	−	−	−	~	−	−	~	−	~
TMA	+	−	~		−	+	~/+		−	−	−	−	−	−		~	+	~	−	~
MBC	~	~	~		~	+	~		~	+	~	~	~	~		~	+	~	+	~
Weeds	↓	↓	−		↓	↑	−		↓	+	−	+	+	−		↓	+	−	+	−
Grain yield (t/ha)	+	+	~	~	↑	−	~		+	+	−	+	+	+	~	↑	+	~	+	~
Net return ($)	−	+	~	~	+	+	−		+	+	−	+	+	+	~	+	−		−	−

↓ or ↑ indicates a significant decrease or increase, respectively, at $P < 0.05$

NS non-significant, *(+)* NS increase, *(−)* NS decrease, *(~)* no result, *3m* 3 months after tillage, *12m* 12 months after tillage, *24m* 24 months after tillage, *TMA* total microbial activity (μg/mL FDA/g soil/h), *MBC* microbial biomass (μg C g^{-1} soil), *BD* bulk density (g/cm^3), *SW* soil water (mm), *TOC* total organic carbon (t/ha), *POC* particulate organic carbon (t/ha), *P* available P (Colwell-P) mg/kg

Immediately following a tillage operation, there were significantly higher cumulative CO_2 emissions over 2 days on the Sodosol (67 mg C m^{-2} and 37 μg C m^{-2} from ST and NT plots, respectively) but not on the Vertosol (209 and 215 μg C m^{-2} from ST and NT plots, respectively). However, the impact of one-time tillage on SOC was not significant ($P < 0.05$) after 3-, 12- or 24-month tillage on any of the soil types studied (Table 2). There are a number studies that indicate that large amounts of CO_2 are lost from the soil immediately following tillage due to an increase in microbial respiration, typically occurring with a release of trapped CO_2 (López-Garrido et al. 2011; Quincke et al. 2007a). However, in the long term, there is no consistent effect of one-time tillage on soil TOC in long-term NT systems. Some studies report significant loss of TOC (Stockfisch et al. 1999), whereas no loss in TOC was reported by other studies (Vanden Bygaart and Kay 2004). Any net changes in TOC will be determined by the organic matter input of the land use and the degree of organic carbon protection by soil clay minerals (Page et al. 2013).

Particulate organic carbon (POC) is considered to be more easily decomposed and is preferentially degraded over humic TOC by tillage (Grandy et al. 2006). In the present study, POC ranged from 10% of TOC in the Black Vertosol at Warwick to 30% of TOC in the brown Sodosol at Condamine. The POC content was significantly decreased in the Black Vertosol at Biloela 3 months after tillage. There was no significant impact on POC at other sites. The decrease in POC with tillage may be due to changes in incorporation of residue into soil, redistribution and decomposition or where aggregate breakdown results in increased mineralisation (Wander et al. 1998; Yang and Kay 2001). In the present study, surprisingly, there was an increasing trend in POC in Black Vertosol at Warwick with tillage after 3 months. This could be due sampling anomalies and/or the high spatial variability associated with carbon distribution in field conditions and/or high stubble load prior to tillage leading to incorporation (Conant et al. 2007).

Available soil P tended to be lower in the surface soil (0–0.1 m) at all sites 3 months after ST; however, the reduction was significant only on the Vertosol at Biloela A. At 12 and 24 months after tillage, available P was similar at all sites. Most studies have reported a general decrease in available P in the surface soil due to tillage (Standley et al. 1990). However, in the present study, use of shallow tillage and low P mobility did not result in redistribution of nutrients into the nutrient-poor subsoil.

Total microbial activity (TMA) in the top 0.1-m soil depth was quite variable and not significantly affected at any site 3 months after one-time ST operation. However, there was a significant decrease in TMA 12 months after ST as compared to 3 months after tillage in the Black Vertosol at Warwick (Table 2). Differences may be associated to changes in seasons between the collection times. Generally, FDA as a measure of TMA is considered to be a "broad-scale" measurement for enzymatic activities and may not be sensitive enough to detect changes in specific processes due to functional redundancy of soil microbial communities (Chaer et al. 2009). Alternatively, the result suggests that the soil communities were functionally stable in these soils. Furthermore, one-time ST did not affect the mycorrhizal associations or *Pratylenchus thornei* nematode populations measured in Black Vertosols at Warwick and Jimbour 12 months after tillage (results not shown) (Dang et al. 2016). There was no incidence of crown rot at most sites. However, at the Jimbour site with crown rot infection, one-time ST did not result in a significant decrease in crown rot (results not shown) (Dang et al. 2016).

Environmental impacts

On the Dermosol at Moonie B and the Sodosol at Billa Billa, there was significantly higher runoff from ST plots than from NT plots. Runoff volume was highly variable and similar between ST and NT treatments on the Vertosol at Felton B (Fig. 3). Consistent with these effects on runoff volume, infiltration rates were significantly higher on the NT plots than the ST plots on the Dermosol and Sodosol (Fig. 4). Erosion and total N loads were highest after ST on the Sodosol; however, there were no significant differences due to ST on the Dermosol or Vertosol. Total P loads in runoff were also significantly higher from ST than from NT on both the Sodosol and Dermosol. The impact of ST on runoff and nutrient loads was largely attributed to removal of groundcover by tillage and an increased vulnerability to erosion (Loch 2000; Silburn et al. 2011).

Soluble P losses were low overall (<12% of total P), and rather than reducing surface soil enrichment with P and associated soluble P concentrations in runoff, ST increased soluble P concentrations in runoff at two sites (Fig. 5). In a study by Quincke et al. (2007b), soluble P concentrations were reduced

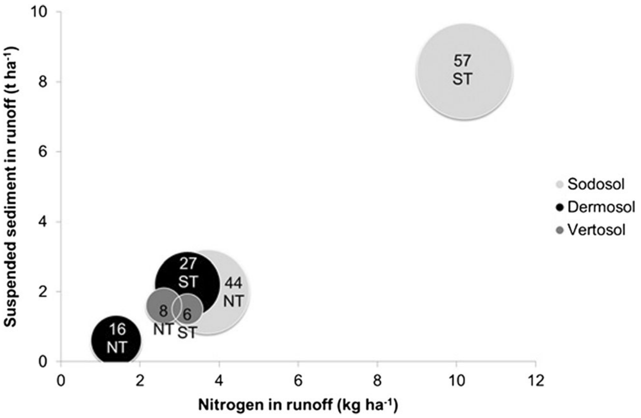

Fig. 3 Suspended sediment (t/ha) and total nitrogen (kg/ha) in runoff after strategic tillage (ST) and no tillage (NT) on a Vertosol, Sodosol and Dermosol. *Bubble sizes* and *labels* indicate the total runoff (mm) generated over 80 min of rainfall

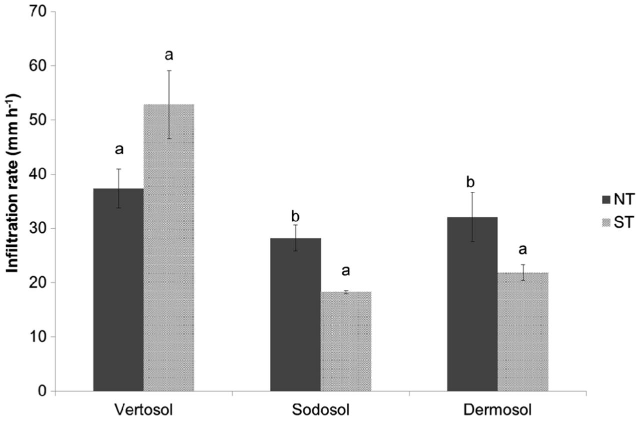

Fig. 4 Infiltration rates (mm h^{-1}) measured in the final stages of rainfall simulation events on strategic tillage (ST) and no-tillage (NT) plots on the Vertosol at Felton B, the Sodosol at Billa Billa and the Dermosol at Moonie B. *Letters* that differ denote means that are significantly different ($P < 0.05$)

by ST of NT soil; however, in that case, manure nutrients were applied to the surface and then buried by mouldboard ploughing. In contrast, P fertiliser is typically applied at the depth of planting across the NGR and this was also the case at the rainfall simulation sites. Consequently, the shallow ST exposed rather than buried residual soil P, and this increased both soluble and particulate P concentrations in runoff (Melland et al. 2016).

As well as the higher cumulative CO_2 emissions over 2 days after ST on the Sodosol, approximately three and four times more CH_4 was absorbed over the sampling periods by the NT treatment than the ST treatment in the Vertosol and Sodosol, respectively. There were no significant impacts on cumulative N_2O fluxes due to tillage, with 111 and 100 μg N m^{-2} measured from the Vertosol and 61 and 56 μg N m^{-2} measured from the Sodosol, from ST and NT plots, respectively. The N_2O fluxes were low relative to higher input cropping systems (Scheer et al. 2013), and emissions from both the ST and NT treatments may have been limited by soil mineral N availability (Schwenke et al. 2016).

An increased risk of runoff, erosion and nutrient loss from Sodosols and Dermosols after ST for weed control in cropping systems typical of the NGR are trade-offs that need consideration in ST decisions. However, the low GHG emissions measured, despite intense rainfall, suggest that ST practices in these farm systems have a low global warming potential.

Agronomic impacts

Weed populations on all the sites were significantly decreased 3 months after one-time ST in 2012 and a trend toward decreased weed density at two sites established in 2013 (Table 2). Twelve months after tillage, weed populations were significantly lower on the Black Vertosol at Biloela and the grey Dermosol at Moonie. On the brown Sodosol at Condamine, there was an increase in weed density, in particular African turnip weed (*Sisymbrium thellungii*). Twenty-four and 36 months post-ST, there were indications of lower weed populations in ST as compared to NT, but results were not significant. Most studies suggest a positive impact of tillage on reducing weed density. However, tillage has the potential to move buried weed seed to the surface soil, thus providing a more favourable environment for germination by breaking seed dormancy (Chauhan et al. 2012).

The first year after ST operation generally provided higher productivity at all the sites compared to NT; however, these results were not significant. On average, one-time ST resulted in 0.1 t ha^{-1} higher yield as compared to NT. The Brown Sodosol at Condamine recorded a marginally significant increase in chickpea yield (1.07–1.16 t ha^{-1}) after a single chisel treatment ($P = 0.08$). In the second year of ST operation, slight positive trends were observed on the Black Vertosol at Biloela, Grey Dermosol at Moonie and the Black Vertosol at Warwick. The Brown Sodosol at Condamine recorded a decrease in yield when compared to NT, likely resulting from a significant increase in the weed population. Twenty-four and 36 months after the ST operation, no significant differences were observed between NT and ST treatments. It appears that reduced weed population in the ST treatments resulted in improved grain yield, as also observed elsewhere (Kettler et al. (2000). Net return with one-time ST was generally positive at most sites (\$10–\$35 ha^{-1}) except from Vertosol at Biloela (−\$3 ha^{-1}), Jimbour (−\$17 ha^{-1}) and Moree (−\$5 ha^{-1}). However, overall total net return over the 4 years was positive for all sites. Most studies conducted in North America (USA and Canada) and Europe suggest that introducing occasional ST in continuous NT systems could improve productivity and profitability in the short term. However, in the long term, the impact is negligible or even negative (Dang et al. 2015a).

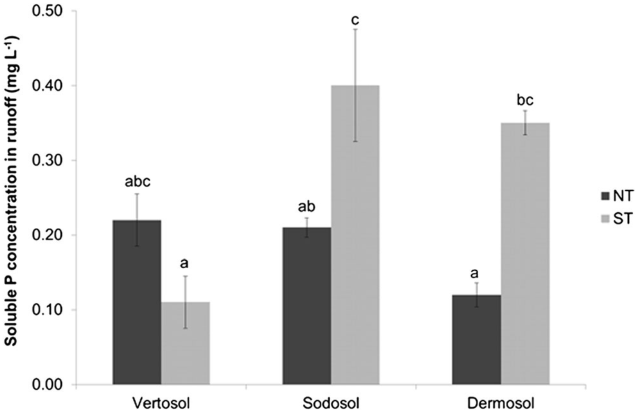

Fig. 5 Event-mean soluble P concentrations in runoff (mg/L) after strategic tillage (ST) and no tillage (NT) on a Vertosol, Sodosol and Dermosol. *Letters* that differ denote means that are significantly different ($P < 0.05$)

Implementing ST in no-till systems

ST frequency

Increasing tillage frequency resulted in significant changes to BD in the Vertosols at Biloela A and Jimbour (Table 3). At Jimbour, 3 months after chisel tillage, ST resulted in increased BD in 0–0.1-m soil depth with three passes; however, two-pass ST significantly decreased BD as compared to NT, while a single pass did not cause significant change. Results suggested that increased frequency had a greater impact on soil structure. In the Sodosol at Condamine, one- or two-pass ST significantly reduced BD as compared to NT. In general, increasing ST frequency had a significant negative impact on poorly structured soils; however, on well-structured soils, there were less significant long-term impacts. Soil water generally experienced a negative, non-significant impact after 3 months following tillage. The exception was Vertosol at Jimbour where plots undergoing three passes resulted in significantly increased soil water 3 months after tillage. The reasons for this may be due to reduced evaporation caused by decreased pore connectivity. Increasing tillage frequency did not significantly increase the water loss due to evaporation.

TOC did not significantly change in any instance, and there were no consistent changes associated with increasing tillage frequency. At Jimbour, available P significantly decreased in the 0–0.1-m soil layer with two and three chisel passes after 3 months. However, these differences were not evident 12 months post-tillage, indicating short term, increased loss with increasing frequency. POC was affected with more soil disturbances; however, results were not consistent for all years measured. Changes in TMA were neither consistent nor exaggerated with increased ST frequency. However, in the Vertosol at Biloela A, TMA significantly increased in the surface soil after both one and two ST passes.

Table 4 Changes in weed populations (number/m^2) with increasing strategic tillage operation frequency

Site	Year	No till	Strategic tillage frequency		
			Once	Twice	Thrice
Biloela A^{a}	2012	10.5 a	1.3 b	4.3 c	
Biloela A^{a}	2013	3.0 a	0.3 b	0.2 b	
Biloela A^{a}	2014	14.5 a	19.4 a	25.5 a	
Condamine^{a}	2012	14.5 a	2.3 c	6.5 b	
Condamine^{a}	2013	4.5 a	23.4 b	15.6 a	
Condamine^{a}	2014	0.75 a	1.6 a	0.9 a	
Jimbour^{a}	2013	2.3 a	0.6 a	0.5 a	0.8 a
Jimbour^{a}	2014	1.1 a	0.3 a	1.0 a	0.9 a
Jimbour^{b}	2013	2.3 a	2.0 a	0.1 a	0.8 a
Jimbour^{b}	2014	1.1 a	0.3 a	0.8 a	0.3 a
Biloela B^{a}	2013	0.0 a	0.0 a	0.0 a	0.0 a
Biloela B^{a}	2014	4.0 a	4.7 a	4.8 a	9.2 a

Values within a row with different letters indicate significant difference at $P < 0.05$ from NT at each site ($n = 4$)

[a] Chisel-type tillage

[b] Disc-type tillage

Table 3 Impacts of strategic tillage with increasing strategic tillage frequency on soil health quality parameter indicators in 0–0.1-m soil layer

	Months	Biloela A^{a}				Condamine^{a}				Biloela B^{a}			Jimbour^{a}		Jimbour^{b}	
		3	12	24	36	3	12	24	36	3	12	36	3	12	3	12
BD	1	~	+	~		−	↓	−		−	−		−	+	−	+
	2	−	−	~		−	↓	−		−	−		↓	+	+	+
	3									−	−		↑	~	↑	+
SW	1	−	−	+		−	−	−		+	+		−	+	+	+
	2	−	−	+		−	−	−		+	−		−	+	+	+
	3									+	−		+	+	+	+
SOC	1	−	~	−	~	−	~	−	~	+	−		−	−	+	+
	2	−	−	−	~	−	+	−	−	+	−		~	+	~	+
	3									+	−		~	+	+	+
P	1	−	+	+	−	−	−	−	~	~	−		−	+	↑	−
	2	−	−	+	+	−	−	−	−	+	−		↑	~	+	−
	3									~	+		↑	−	+	−

↓ or ↑ indicates significant decrease or increase, respectively, at $P < 0.05$

NS non-significant, *(+)* NS increase, *(−)* NS decrease, *(~)* no result, *3m* 3 months after tillage, *12m* 12 months after tillage, *24m* 24 months after tillage, *BD* bulk density (g/cm^3), *SW* soil water (mm), *SOC* soil organic carbon (t/ha), *P* available (Colwell-P) mg/kg

[a] Chisel-type tillage

[b] Disc-type tillage

Table 5 Changes in grain yield (t/ha) with increasing strategic tillage operation frequency

Crop	Site	Year	No till	Strategic tillage frequency		
				Once	Twice	Thrice
Wheat	Biloela A^{a}	2012	2.66 a	2.75 a	2.72 a	
	Biloela A^{a}	2014	1.49 a	1.55 a	1.42 a	
	Biloela B^{a}	2014	1.11 a	1.40 b	1.46 b	1.64 b
	Condamine^{a}	2013	1.51 a	1.48 a	1.39 a	
	Condamine^{a}	2014	0.73 a	0.71 a	0.71 a	
	Jimbour^{a}	2013	2.92 a	2.67 a	2.81 a	3.11 a
	Jimbour^{b}	2013	2.92 a	2.93 a	3.00 a	3.03 a
Chickpea	Biloela A^{a}	2013	2.02 a	2.13 a	2.16 a	
	Biloela B^{a}	2013	1.88 a	2.03 a	2.14 a	2.24 b
	Condamine^{a}	2012	1.05 a	1.14 b	1.16 b	
	Jimbour^{a}	2014	1.16 a	1.10 a	1.13 a	1.16 a
	Jimbour^{b}	2014	1.16 a	1.14 a	1.07 a	1.13 a
Sorghum	Biloela A^{a}	2014	2.48 a	2.43 a	2.53 a	
	Biloela B^{a}	2014	2.44 a	2.51 a	2.44 a	2.36 a

Values within a row with different letters indicate significant difference at $P < 0.05$ from NT at each site

[a] Chisel-type tillage

[b] Disc-type tillage

In general at most sites, increasing the frequency of chisel or disc tillage significantly decreased weed population in the first year after ST (Table 4). However, the impact of increasing frequency of tillage on weed population was not consistent for the subsequent years. At most sites, the weed population was lower with increasing ST frequency except on the Sodosol at Condamine and Vertosol at Biloela in the second year. The effect of ST on weed populations in the second year was variable and dependent on the historical weed seed bank (Crawford et al. 2015).

Grain yield at most sites tended to be increased with ST; however, results were significantly different only at two sites (Vertosol at Biloela B and Sodosol at Condamine) in the first year following ST (Table 5). At the Biloela B site, there was a significant increase in wheat grain yield in all ST plots as compared to NT in the second year following ST. Nevertheless, there were no significant differences in grain yield with increasing frequency of ST operation.

ST implements

In most cases, there were no significant differences between different ST implements including chisel, disc and Kelly chain with respect to soil BD, soil water, TOC, P or microbial activity (Table 6). In general, one-time ST decreased weed populations, but the differences between different tillage implements were negligible (Table 7).

Grain yield also did not differ significantly between different tillage implements (Table 8). In north-eastern Australia, most growers use non-inversion cultivation based on tyne and disc implements. There is evidence to suggest that the type of tillage is more trivial than the frequency and can be manipulated to address specific issues or allow for deep nutrient placement. Tyne tillage lifts and shatters the soil, removing shallow compacted layers for the purpose of effective in-crop weed management, deep placement of nutrients and alleviating soil physical constraints (Thomas et al. 1997). Disc tillage cuts

Table 6 Impacts of strategic tillage with different strategic tillage implements on soil health quality parameter indicators in 0–0.1-m soil layer

		Moonie			Wee Waa				Jimbour		Emerald	Yelarbon
		3	12	24	3	12	24	36	3	12	3	3
BD	Chisel	+	+	~	−		−		−	+	+	+
	Disc	+	+	+	~		~		−	+	+	−
SW	Chisel	~	+	+	−		−		+	+	~	~
	Disc	~	+	+	−		+		−	+	+	+
SOC	Chisel	−	−	−	~			+	−	−	+	~
	Disc	−	+	−	+			−	+	+	+	+
POC	Chisel	−				−						
	Disc	−				~						
P	Chisel	−	−	−	−		+	−	↑	−	+	+
	Disc	−	−	−	+		~	+	−	+	−	~
TMA	Chisel	−	+	−	−	−			−			
	Disc	~	~	−	−	−			~			

↓ or ↑ indicates significant decrease or increase, respectively at $P < 0.05$

NS non-significant, *(+)* NS increase, *(−)* NS decrease, *(~)* no result, *3m* 3 months after tillage, *12m* 12 months after tillage, *24m* 24 months after tillage, *BD* bulk density (g/cm^{3}), *SW* soil water (mm), *SOC* soil organic carbon (t/ha), *POC* particulate organic carbon (t/ha), *P* available (Colwell-P) mg/kg

Table 7 Changes in weed populations (number/m^2) with different strategic tillage implements

Crop	Site	Year	No till	Strategic tillage implements		
				Chisel	Disc	Kelly chain
Barely	Moonie	2012	9.2 a	1.0 b	1.2 b	
Chickpea	Moonie	2013	0.75 a	0.13 a	0.3 a	
Chickpea	Moonie	2014	0.5 a	0.6 a	1.5 a	
Wheat	Moree	2013	2.4 a	0.9 a		0.9 a
Wheat	Jimbour	2013	2.3 a	0.6 a	2.0 a	
Chickpea	Jimbour	2014	1.1 a	0.3 a	0.3 a	
Sorghum	Yelarbon	2013	0.4 a	0.0 a	0.0 a	

Values within a row with different letters indicate significant difference at $P < 0.05$ from NT at each site ($n = 4$)

and mixes stubble and soil clods to leave a fine tilth, considered effective for disease and pest reduction and fallow period weed management. Both tillage operations are shallow as compared to mouldboard tillage implement (Thomas et al. 2007).

Optimal time for ST

The impact of timing of ST on soil health indicators including TOC, P, BD and microbial activity was highly variable (Table 9). As expected, there were no significant differences between different timing on these parameters. Timing of tillage appears to be the most important factor with respect to amending loss of soil water due to evaporation. However, the present study showed no or negligible impact on soil water with respect to different timing of ST. This may be due to sufficient rainfall between tillage and soil sampling, before the sowing of crops during 2012 and 2013, to replenish soil moisture to within a range comparable to that of NT.

Table 8 Changes in grain yield (t/ha) with different strategic tillage implements

Crop	Site	Year	No till	Strategic tillage implements		
				Chisel	Disc	Kelly chain
Wheat	Jimbour	2013	2.92 a	2.88 a	2.89 a	
	Moree	2013	3.51 a	3.56 a		3.57 a
Chickpea	Moonie	2013	0.66 a	0.71 a	0.64 a	
	Moonie	2014	3.60 a	3.31 a	3.34 a	
	Jimbour	2014	1.16 a	1.12 a	1.17 a	
	Wee Waa	2012	1.45 a	1.54 a		1.47 a
Sorghum	Emerald	2013	4.80 a	4.47 a	5.41 a	
	Yelarbon	2013	2.09 a	2.01 a	2.05 a	
Barley	Moonie	2012	2.27 a	2.42 a	2.37 a	

Values within a row with different letters indicate significant difference at $P < 0.05$ from NT at each site

Table 9 Impacts of strategic tillage with strategic tillage operation at increasing number of days prior to sowing of crop soil health quality parameter indicators in 0–0.1-m soil layer

	Tillage time	Jimbour[a]		Jimbour[b]		Moree[a]		Moree[c]		Biloela[a]	
		3	12	3	12	3	12	3	12	3	12
BD	T1	−	+	−	+	~	~	+	~	−	−
	T2	↑	+	−	~	−	~	+	~	−	−
	T3	−	+	↑	~					−	−
SW	T1	−	+	+	+	−	+	~	+	+	+
	T2	−	+	+	+	+	+	−	↑	+	−
	T3	+	+	+	+					+	−
OC	T1	−	−	+	+	−	~	+	−	+	−
	T2	+	+	~	+	~	−	−	~	+	−
	T3	+	+	+	+					−	−
P	T1	−	+	↑	−	−	−	−	+	~	−
	T2	↑	−	↓	+	~	+	+	+	+	−
	T3	↑	~	+	−					+	+

(↑) significant increase, *(↓)* significant decrease, *(+)* increase, *(−)* decrease, *(~)* no change, *3m* 3 months after tillage, *12m* 12 months after tillage, *24m* 24 months after tillage, *TMA* total microbial activity (µg/mL FDA/g soil/h), *MCB* microbial biomass (µg C g^{-1} soil), *BD* bulk density (g/cm^3), *SW* soil water (mm), *OC* organic carbon (t/ha), *POC* particulate organic carbon (t/ha), *P* available (Colwell-P) mg/kg, *T1* tillage operation 7 months before sowing, *T2* tillage operation 5 months before sowing, *T3* tillage operation 3 months before sowing

[a] Chisel tillage

[b] Disc tillage

[c] Kelly disc chain tillage

The timing of tillage had no significant impact on the outcomes of weed management; however, there was low weed pressure at most sites. For this reason, significant changes could not necessarily be detected (Table 10). The timing of tillage did not affect grain yield (Table 11), which may indicate reduced risks if carried out with sufficient time for rainfall to replenish soil water prior to planting. All tillage operations were carried out during the rainfall-dominant period of the year. At Biloela, grain yield increased with the increase in the time between tillage and sowing. The converse was true at the Jimbour site.

Given that in both 2012 and 2013, the rainfall after the ST operation and sowing of winter crops was substantial to refill the soil profile, this resulted in a positive impact of ST operation on grain yield; however, the importance of timing of ST in semi-arid regions cannot be ruled out. The results following a shallow disc tillage on a Vertosol at Felton B site showed that 10–12-mm rain replenished soil water in the seed zone (Fig. 2). In contrast, on a very heavy clay soil (>65%) with 45 years of continuous NT on wheat, even 118-mm rainfall was unable to replenish soil water lost from seed zone. An analysis of historical climate data (1960–2013) on these sites showed that probability of receiving 100-mm rain between March and May (3 months before sowing

Table 10 Changes in weed populations (number/m^2) with strategic tillage operation at increasing number of days prior to sowing of crops

Crop	Site	Year	No till	Strategic tillage operation (days prior to sowing)					
				<14	14–40	40–90	90–120	120–200	>200
Wheat	Biloela B[a]	2014	4.0 a			9.2 a	4.8 a	4.7 a	
	Jimbour[a]	2013	2.3 a				1.0 a	1.0 a	0.6 a
	Jimbour[b]	2013	2.3 a				0.9 a	1.1 a	2.0 a
	Moree[b]	2013	2.4 a	0.9 a	0.8 a				
	Moree[c]	2013	2.4 a	0.9 a	0.8 a				
Chickpea	Biloela B[a]	2013	0.1 a			0.0 a	0.0 a	0.0 a	
	Jimbour[a]	2014	1.1 a				0.1 a	1.0 a	0.3 a
	Jimbour[b]	2014	1.1 a				0.4 a	0.8 a	0.3 a

Values within a row with different letters indicate significant difference at $P < 0.05$ from NT at each site ($n = 4$)

[a] Chisel-type tillage

[b] Disc-type tillage

[c] Kelly chain tillage

of winter crops) is only 40–55% as compared to 90–95% between January and May (5 months before sowing of winter crops) (Fig. 6). These results suggest that timing for ST operation in summer months (December–January) would be ideal for winter crop sowing. Therefore, decisions around timing of ST will be determined by climatic conditions (especially probability of rainfall events) after the tillage event.

Conclusions and recommendations

The research provided insight into where, how and when a ST operation is implemented in otherwise NT systems to maximise its benefits by managing constraints of NT farming systems without impacting negatively on soil and environment. Generally, a trend was observed for negative effects of ST on BD, soil water and TOC stocks in the short term. However, these effects were often not significant, even for short term (3 months), and were minimal in the intermediate period (12 months after ST). The latter indicates a relatively quick recovery of soil water in most soils, with the exception of high clay soils. The provided tillage is shallow, as in the present study, and not ongoing; the recovery of most measured parameters is relatively rapid under ST and is unlikely to undo the long-term beneficial changes associated with NT systems. In poorly structured soils, greater impacts and longer recovery periods can be expected. The major benefit of ST is the control of herbicide-resistant and hard-to-kill weeds except at some sites (e.g. Sodosol at Condamine).

Table 11 Changes in grain yield (t/ha) with strategic tillage operation at increasing number of days prior to sowing of crops

Crop	Site	Year	No till	Strategic tillage operation (days prior to sowing)					
				<14	14–40	40–90	90–120	120–200	>200
Wheat	Biloela B[a]	2014	1.11 a			1.29 b	1.35 b	1.35 b	
	Jimbour[a]	2013	2.92 a				3.04 a	2.92 a	2.67 a
	Jimbour[b]	2013	2.92 a				2.91 a	2.82 a	2.93 a
	Moree[a]	2013	3.51 a	3.54 a	3.58 a				
	Moree[c]	2013	3.51 a	3.63 a	3.51 a				
	Biloela B[a]	2013	1.88 a			1.88 a	1.98 a	2.03 a	
	Jimbour[a]	2014	1.16 a				1.20 a	1.14 a	1.10 a
Chickpea	Jimbour[b]	2014	1.16 a				1.09 a	1.12 a	1.14 a
Sorghum	Biloela B[a]	2013	1.11 a			2.33 a	2.40 a	2.51 a	

Values within a row with different letters indicate significant difference at $P < 0.05$ from NT at each site ($n = 4$)

[a] Chisel-type tillage

[b] Disc-type tillage

[c] Kelly chain tillage

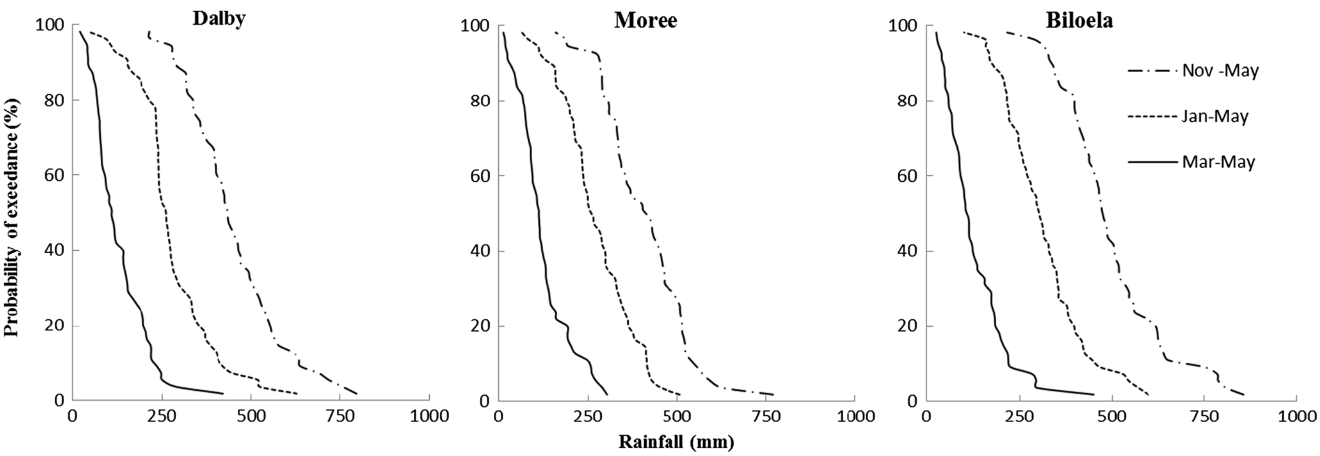

Fig. 6 Probability of rainfall exceedance during 1960–2014 at Dalby, Moree and Biloela

Our results indicate that ST has a place in conservation farming, provided that appropriate consideration and implementation are achieved. Single tillage events appear insufficient to significantly alter the long-term benefits of NT in the vast majority of cases. In some circumstances, ST will assist in overcoming certain issues associated with NT, thus improving the productivity of fields. Examples include deep banding of immobile nutrients like P and K to address a subsoil nutrient depletion or using tillage during a fallow to control hard-to-kill weeds. However, the implementation of ST requires many considerations for its success. This includes the knowledge on (i) the weed history and potential seed bank so that emergence of other weed species can be prevented; (ii) soil water status and the time required for its replenishment prior to planting; (iii) nature of soil types relative to tillage, e.g. risks of smearing (reducing infiltration), compaction and aggregate breakdown; and (iv) subsoil constraints, especially salinity and sodicity where use of any tillage implements that invert the soil may bring salts nearer the soil surface and may cause yield loss.

If tillage is necessary, the most important question to address is the best timing, frequency and implement for the tillage operation. Timing of ST has major implications for the success or failure of ST operations. Limited research on the ST timing in continuous NT suggests that farmers should analyse long-term historical rainfall data and risk management tools that have been developed. These tools are based on rainfall probabilities and seasonal forecasts using southern

Table 12 Safe implementation of strategic tillage in otherwise no-till farming systems

Purpose of tillage	Optimum tillage time	Tillage implement	References
Disease management			
Fungal disease	Post-harvest, early in fallow	Disc or blade	Obanor et al. (2013); Wildermuth et al. (1997a, b)
Root-lesion nematode	Post-harvest, early in fallow	Disc for surface soil (0–0.1 m) Frequent tillage for subsoil (0.45 m)	Thompson et al. (2010) Haak et al. (1993)
Pest management			
Winter crops	Post-harvest	Light tillage, Scarifier	Mensah et al. (2013)
Summer crops	Post-harvest, early in fallow	Chisel, disc to 0.1 m	
Weed management			
In-crop	Prior to weed flowering	Shallow tyne	Pratley (2000)
Fallow	Post seed fall, before germinating rains	Disc	McGillion and Storrie (2006)
Nutrient stratification			
Sodic soil	Post-harvest, early in fallow	Para plough	Dang et al. (2010)
Non-sodic soil	Post-harvest, early in fallow	Deep ripper tyne	Bell et al. (2012)
Stubble management	Previous crop harvest Fallow for partial removal	Prickle chain, trash cutter Offset disc	Scott et al. (2010)
Soil physical constraints			
Surface soil	Early in fallow	Cross tyne	Spoor (2006)
Subsoil	Early in fallow	Deep ripping tyne	Hamza and Anderson (2005)

Adapted from Dang et al. (2016)

oscillation index to determine probability of rainfall between ST and the sowing of the crops. Tillage too close to sowing and/or immediately after the harvest of the previous crop should be avoided. Use of inversion tillage with implements such as mouldboard plough is rare in Queensland and northern New South Wales. Most growers use non-inversion shallow tillage based on tyne and disc implements that do not invert the soil and differences between these tillage implements, and frequencies of tillage passes were in general non-significant. Generalised guidelines for the safe implementation of ST in otherwise no-till farming systems are given in Table 12.

It is clear that different tillage systems have their own advantages and disadvantages. There are a number of interacting factors involved in comparing the performance of tillage systems. The challenge for ST operation in the NT systems is to maintain economic levels of production and at the same time reduce environmental damage such as soil erosion and water pollution.

Future research needs to focus on how and when ST might fit into cropping sequence to obtain maximum benefits and minimise the potential negative consequences.

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Compliance with ethical standards

Conflict of interest The authors declare they have no conflict of interest.

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