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Does strategic tillage undo long term improvement in soils under no-till?

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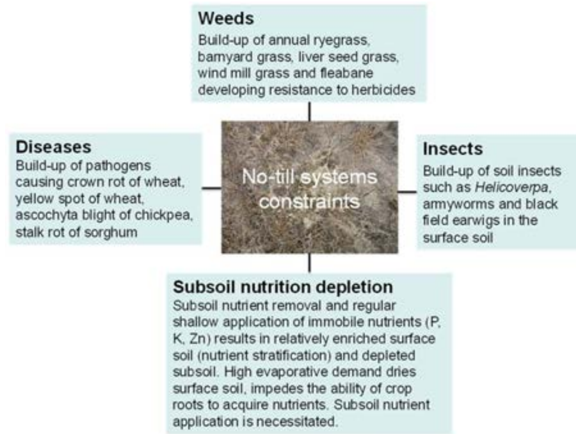
Abstract

Farmers often resort to an occasional tillage (Strategic Tillage, ST) operation to combat constraints of no-till (NT) farming systems. There are conflicting reports regarding use of ST and lack of knowledge around when ST is the most effective management option. We established 15 on-farm experiments during 2012-15 to resolve apparent contradictions and explore key factors which need to be considered. ST reduced weed populations and improved productivity and profitability in first year with no impact in subsequent years. Soil properties were mostly not impacted. However, ST also had deleterious effects, including reduced plant available water in short term. This could result in unreliable sowing opportunities. Rainfall between the ST operation and sowing is necessary to replenish lost soil water. Analysis of climate data showed that there was a 90-95% probability of receiving good rainfall in the 3-5 months prior to sowing of a wheat crop which reduces risks to cropping success. Intense rainfall poses a higher risk of runoff, and higher nutrient and sediment loads after ST. Results suggest that ST could be utilized as a viable strategy to manage constraints of NT systems, resulting in short-term improved farm profitability and reduce reliance on herbicides without impacting on soil health.

Key words: No-till, strategic tillage, productivity, profitability, soil health, environmental impacts

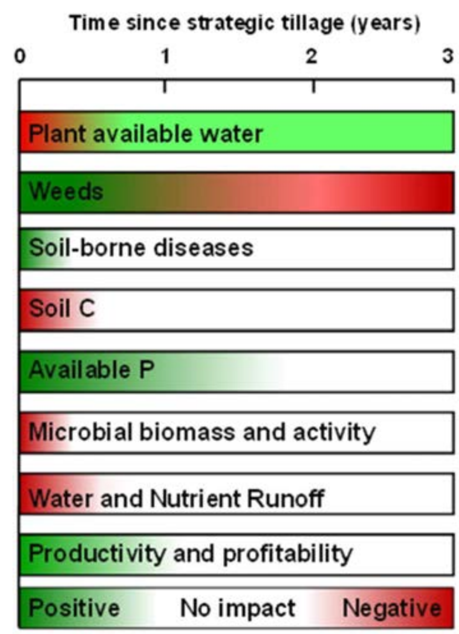
Executive Summary



No-till (NT) farming systems that include minimal soil disturbance and stubble retention offer a wide range of economic, environmental and soil quality advantages compared to conventional tillage. The adoption of continuous NT has progressed steadily in Australia and in particular Queensland and Northern NSW (NNSW). However, there are concerns regarding long-term sustainability of such systems due to both biotic and abiotic constraints. There is an increased interest in the use of an occasional strategic tillage (ST) to combat both biotic and abiotic constraints in otherwise-NT farming systems. However, growers practising strict NT predict irreparable soil damage from occasional ST.

We established 15 on-farm field experiments in Queensland and NNSW on sites with long-term history of continuous NT during 2012-15 to resolve contradictions surrounding the use of ST and explore key factors that need to be considered in decisions to implement ST in an otherwise NT system.

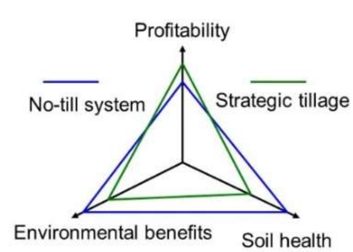
Tillage impacts in no-till systems



Immediately following ST, soil water was reduced due to evaporation, but these losses were replaced in subsequent rainfall events. In extreme cases, this loss of water may result in poor crop establishment or a missed sowing opportunity. The occurrence of rain after the tillage determines the success of ST in NT systems, highlighting the importance of the timing of tillage relative to rainfall distribution.

Tillage reduced weed pressure in the short-term, but the long-term impact was negative or negligible. In some cases, ST moved buried seed to the soil surface and thus provided a more favourable environment for weed seed germination of certain species. Tillage generally reduced disease pressure in the short-term with no impact in the long-term. Tillage resulted in a slight initial decline of soil organic carbon (SOC), and resulted in minor reductions to stratification of SOC and immobile nutrients such as P and K. Tillage had no impact on microbial activity. Tillage resulted in increased infiltration of water, and increased loss of soluble nutrients when rainfall events occurred soon after tillage due to the loss of protective surface cover. Introduction of tillage slightly improved productivity and profitability in the first year. In second year, there was no significant impact on the productivity and profitability. Highest returns were obtained with chickpea crops.

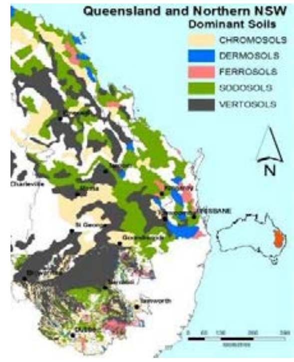
Finding the balance



Introduction of ST in NT systems may offer opportunities to improve productivity by overcoming typical nutrients and C stratification and managing diseases and herbicide-resistant weeds. The adoption of ST by the grains industry will be driven by the interactions between three aspects: system costs and profitability, soil health, and environmental benefits. Use of any tillage in NT systems must consider the balance between erosion and soil degradation impacts from tillage against the short-term profitability.

Where to do strategic tillage?

Five dominant soils types (Vertosol, 72.0%; Chromosol, 9.9%; Dermosol, 6.7%; Sodosol, 6.5%; Ferrosol, 1.7) cover almost 97% of the cropping soils in Queensland and NNSW. The impacts of ST on soil quality indicators have been generally inconsistent; however, soils that exhibit texture contrast properties (Sodosol, Chromosol) and weakly structured A-horizons (Dermosol) are likely to suffer negative soil health impacts and should be treated with caution if considering ST. Another important consideration for implementing ST is subsoil constraints. Many soils have single or multiple subsoil constraints, especially salinity and sodicity. Use of any tillage implement that invert the soil may have a serious negative impact as salts may be brought nearer the soil surface and could result in yield losses.



When to do strategic tillage?

Timing of tillage in NT systems is the major factor determining the success of ST. Tillage too close to sowing reduces plant available water. This could result in unreliable establishment or a missed sowing opportunity in marginal rainfall seasons. Rainfall between ST and sowing or immediately after sowing is necessary to replenish soil water lost. A minimum of 75-100 mm rainfall is required to replenish evaporative soil water losses following ST. The probability of receiving 100 mm rain prior to winter crop sowing is 40-55% and 90-95% for a 3 month and 5-month pre-sowing period, respectively. Tillage immediately after the harvest of the previous crop results in loss of surface cover. The optimum timing of tillage will be influenced by soil water content and the purpose of the tillage.

How to do strategic tillage?

Use of tillage implements that invert the soil is rare in Eastern Australia. Most growers use non-inversion tillage based on tine and disc, and differences between these implements and frequencies were non-significant. The tillage operation should be multi-purpose. The tillage event should occur after legume crops because legume crops generally have a small quantity of stubble, and this assists in stubble handling.

Table 1: Safe implementation of strategic tillage in otherwise no-till farming systems

Purpose of tillage	Optimum tillage time	Tillage implement
Disease management		
Fungal disease	Post-harvest, early in fallow	Disc or blade
Root-lesion nematode	Post-harvest, early in fallow	Disc for surface soil (0-0.1 m)
Pest management		
Winter crops	Post-harvest	Light tillage e.g., scarifier
Summer crops	Post-harvest, early in fallow	Chisel, disc to 0.1 m
Weed management		
In-crop	Prior to weed flowering	Shallow tine
Fallow	Prior to weed flowering	Shallow tine
Subsoil nutrition depletion		
Sodic soil	Post-harvest, early in fallow	Para plough
Non-sodic soil	Post-harvest, early in fallow	Deep ripper tine
Stubble management	Previous crop harvest	Prickle chain, trash cutter
	Fallow for partial removal	Offset disc
Soil physical constraints		
Surface soil	Early in fallow	Cross tine
Subsoil	Early in fallow	Deep ripping tine

The occasional ST could be utilized as a viable management option to minimise constraints in otherwise NT systems without impacting the long-term soil health benefits. Improved farm profitability and reduced reliance on pesticides/herbicides can be achieved if ST operations are conducted at a time that minimizes the risk of reduced soil water at seeding.

Contents

Background

The adoption of no-till (NT) farming has resulted in significant improvement to yield, productivity, cropping reliability, soil water status, soil integrity, reduced erosion and operating costs, and reduced greenhouse gas emission (Dang et al., 2015b, Derpsch et al., 2010). Due to these benefits, the adoption of NT has increased significantly in Australia and in particular Queensland and NNSW (Llewellyn and D'Emden; Thomas et al 2007). Thomas et al (2007) estimated that land under NT was 58%, and close to 100% under reduced tillage. At this time adoption was still on the rise and, depending on the specific area, NT practice appears to account for over 75% of the cropping area of Northern NSW and Queensland (Llewellyn and D'Emden, 2010). Despite the large adoption rate, and positive outcomes over all, there have been several negative issues which have become apparent after long term adoption.

Studies have shown that long term NT has the potential to increase incidence of soil and stubble borne diseases (Page et al., 2013, Thomas et al., 1997). Diseases such as crown rot and yellow spot in wheat, ascochyta blight of chickpeas, stalk diseases of sorghum, and root lesion nematodes are the most common soil and stubble borne diseases in the Queensland and Northern NSW (Dang et al., 2015b). Stubble borne diseases tend to have a lower longevity upon incorporation (Bailey and Lazarovits, 2003). Changes in practice to retain stubble, rather than burn or incorporate, have been one of the associated causes of increased crown rot incidence with the adoption of NT (Wildermuth et al., 1997). Similarly, yellow spot inoculum, and disease were significantly higher when high stubble loads are present. Increased disease incidence correlated with the adoption of NT for these reasons (Rees and Platz, 1979). Similar situations occur with aschochyta blight of chickpea (Davidson and Kimber, 2007), fusarium stalk rot in sorghum (Ryley and Keller, 2010), and nematodes (Thompson, 1992).

The build-up of hard to kill and herbicide resistant weeds has been flagged as a major issue that has evolved with long term NT use. The increase has been due to a combination of a number of factors. The risk of herbicide resistance is suggested to be greater in NT systems (Walker et al., 2004). The shift in weed populations have moved away from the dominance of weeds such as dwarf amaranth, Australian bindweed, prickly lettuce, annual rye grass, sow thistle and turnip weed (Wicks et al., 2000). Under no-till or zero-till; native millet, Queensland blue grass, liverseed grass, common sowthistle, Australian bindweed, and windmill grass appear to have a higher prevalence (Felton et al., 1994).

Glyphosate resistance has been identified in 11 species in Australia. These include annual rye grass, barnyard grass, liver seed grass, wind mill grass, and fleabane (Preston 2015). With increased herbicide usage and reduction of tillage to control weeds, risk of development is heightened. The cost of control is significant, with an estimated 29% of the total variable cost of grain production being invested in weed control (Medd et al., 1997). Integrated approaches appear to be most effective at minimizing seed banks for long term control (Powles and Preston, 2006), and the use of tillage in one strategy that may be incorporated with good success (McLean et al., 2012).

Nutrient stratification has also been noted as an emerging issue with NT systems. Immobile nutrients are the highest risk for stratification, as breakdown and application at the surface does not allow for movement through the soil. A combined effect of subsoil depletion and increased surface residue have led to the stratified phenomenon (Cowie et al., 1996, Bell et al., 2012). Initially this may assist in growth, however once the root zone moves to depth, and low surface soil moisture limits nutrient availability, this may become a restriction to growth and productivity.

Depending on the soil type, tillage may be beneficial to improve water infiltration. This is particularly true for soils which develop surface crusting (Silburn and Connolly, 1995). Tillage can assist in two ways, (i) breaking down the impermeable surface crust, and (ii) increasing surface roughness, especially where low-stubble is present (Hatfield et al., 2001). In addition, levelling by tillage to ameliorate slope, or gully erosion may assist.

In 2011/2012 these issue came to a head with an unexpectedly high rainfall year, and farmers having to deal with issues such as tram track remediation from a wet harvest, and in following years controlling weeds that were difficult to kill due to accessibility. Interest in the use of tillage, an integration into NT systems became a high point of interest. Although there was a large amount of literature comparing NT and conventional till for the aforementioned issues, there was little research having been conducted in the NGR to specifically address whether tillage could be re-integrated into no-till systems, on occasion, to deal with these issue.

A full comprehensive review of the drivers, implementation and potential implications can be found in the reviews published by Dang et al. (2015b) and Dang et al. (2015a).

Project objectives

Initial research aimed to identify and quantify the issues surrounding NT management in the NGR, and the current technology employed to deal with these issues, both tillage and non-tillage. This included determination of the attitudes and social acceptance of potential re-introduction of tillage into management systems. This included determining the attitudes toward the introduction of ST into farming systems to improve flexibility in response to specific issues, and where primary producers felt that scientific knowledge was required for their informed decision making.

The aim of the project was to determine whether a single tillage event had the capacity to remediate the issues of nutrient stratification, disease load, alterations in microbial populations, and buildup of hard to kill weeds that have become evident in long term NT systems, and the impacts a tillage event would have on the following factors:

- nutrient stratification
- soil moisture
- productivity
- profitability
- soil structure
- weed management
- disease management
- soil microbial population
- water infiltration and movement
- erosion
- cropping reliability

We established 15 on-farm field experiments in Queensland and NNSW on sites with long-term history of continuous NT during 2012-15 to resolve contradictions surrounding the use of ST and explore key factors that need to be considered in decisions to implement ST in an otherwise NT system.

The project aimed to determine the magnitude of the aforementioned effects, in addition to the time taken to return to pre-till conditions on a number of different soils, agro-climatic conditions, and differing management systems. For long term impact, core sites were assessed annually to determine the changes in the soil attributes in response to disturbance. The project also looked at the use of strip tillage for the purpose of fertilizer placement and the local changes in soil, and any potential changes in productivity. These impacts included, but were not limited to, soil chemical, physical, and biological properties, crop productivity, economic inputs and outputs, effectiveness to deal with specific issues including weed management, nutrient stratification, and disease pressure.

Dissemination of results to growers was also planned, such that they had the capacity to make informed decisions on the implementation of strategic tillage into their management systems, where appropriate and applicable. Education on making the appropriate decision to till, timing of tillage, appropriate selection of tillage implement, and required follow up management were delivered and discussed with growers and advisors. An information package was developed to empower growers to make informed decisions, comprising of a conceptual framework, for the use of strategic tillage within conservation farming systems based on an economic evaluation and risks to the soil resources in different soil types and agro-climatic conditions.

Given the wide variety of soils and management systems in the NNSW and Queensland, full comprehensive studies under all potential conditions were not possible. The selection of trial sites represented the most common soil types present in the regions, in addition to the most common management issues associated with no-till systems. Selection of sites was limited to those in which NT had been in place for a minimum of 5 years, which displayed at least one of the aforementioned issues associated with the NT management strategy.

Methodology

Market Research

Market research was undertaken to determine the specific and most identified issues associated with NT management in the northern grains region. Responses were used to develop a strategic plan to address the major issues and address knowledge gaps and key research needs.

Market research was undertaken in the form of semi-structured, qualitative, face-to-face interviews with grain producers and advisors throughout the northern grains region.

Fifty (50) face-to-face interviews were conducted with farmers (44) and advisors (6) throughout the northern grains region from July to November in 2012. The sample group was selected through contacts from key groups such as Northern Grower Alliance, Queensland and New South Wales State Government industry staff working within grains and further contacts from farmers initially approached.

A semi-structured qualitative questionnaire was developed in consultation with other project members, key stakeholders and an experienced market researcher. The questions were designed to draw out thoughts and perceptions about no tillage and strategic tillage and the threats and opportunities of both systems. Questions also helped to identify the key issues arising within a no tillage cropping system and investigated potential management options and the suitability of strategic tillage. The final questions helped to identify key strategic tillage research areas requiring attention. Brief questions were developed and prompts were provided to help if required. Table 1 shows the key topic areas questions were grouped into.

Table 1: Strategic Tillage one-on-one market research guided questionnaire.

Topic Areas	Questions
1. Current farming system	Location: Area (Ha): Cropping system: Area of NT and ST years: History - What lead to the adoption of zero tillage, motive, challenges, what was useful etc.
2. No Till	Advantages and disadvantages: Current experiences: Concerns:
3. Strategic tillage	Current experiences: Concerns: How difficult is the decision?
4. Decisions around cultivation	Why? What makes it easy vs hard?
5. Key issue areas -soil health -tram tracks -erosion -weeds -insects -disease -nutrition	How do NT and ST impact these issues? Your opinion of ST as a management option:
6. Key questions, information, and research required?	What are the key issues you would like answered to help you with decision making?

Interviewee's responses were pooled under each topic and common trends were identified and highlighted.

A second market research was undertaken to understand farmer's experiences with strategic tillage in the form of anecdotal evidence. This was undertaken in 2013 in the form of an online survey with grain producers who have experience using a strategic tillage throughout the northern grains region.

The survey was developed in consultation with other project members, key stakeholders and an experienced market researcher. The questions were designed to draw out the motives and experiences farmers had with strategic tillage and their perceptions. Questions also helped to tease out the key issues arising within a strategic tillage cropping system and investigated potential management options and the suitability of strategic tillage.

72 surveys were completed throughout the northern grains region from November 2013 to January 2014. The sample group was selected through contacts from groups and through the GRDC mailing list.

Survey responses were pooled and common trends were identified and highlighted using SPSS and Microsoft Excel.

Recommendations and conclusions were developed from the results by addressing the following questions:

1. What are the key learning's?
    a. Summary or take home messages from results
    b. How do these result compare to assumptions about cultivation?
    c. What were the stand out or interesting points?
2. What are the implications for this project?
    a. Engagement strategy (engagement process, content, context)
    b. Information needs we are required to address (what should we deliver?)
    c. Research Questions we need to answer (areas of need or interest)
    d. What are the stand out learning's?
    e. Threats and opportunities

Experimental Sites

A total of 15 on-farm experiments were established in Queensland and NNSW on sites with long-term history of continuous NT during 2012-15 (Figure 1). We established five core sites with ± tillage treatments in otherwise no-till fields in winter 2012. In winter 2013, we established three core sites with treatments involving different timing, frequency and type of tillage implements. Further, in summer 2013, we established four sites with different types of tillage implements (strip tillage, narrow chisel, and disc) and an experiment to quantify the rate of moisture loss in freshly tilled soil. In summer 2015, three sites were established with ± tillage treatments to quantify runoff and loss of soluble nutrients immedately following tillage, under simulated rainfall. All selected fields were surveyed using Geonics electromagnetic induction 38 (EM38) in vertical mode. All positions were corrected for GPS antenna and kriged to a 1x1 m grid. The most homogeneous area of the field was ground-truthed and selected for tillage operations. Soil samples were obtained prior to sowing of crops in 2012, 2013 and 2014 and analysed for physical, chemical and biological properties. In-crop measurements included weed populations, grain yield were recorded and profitability was evaluated.

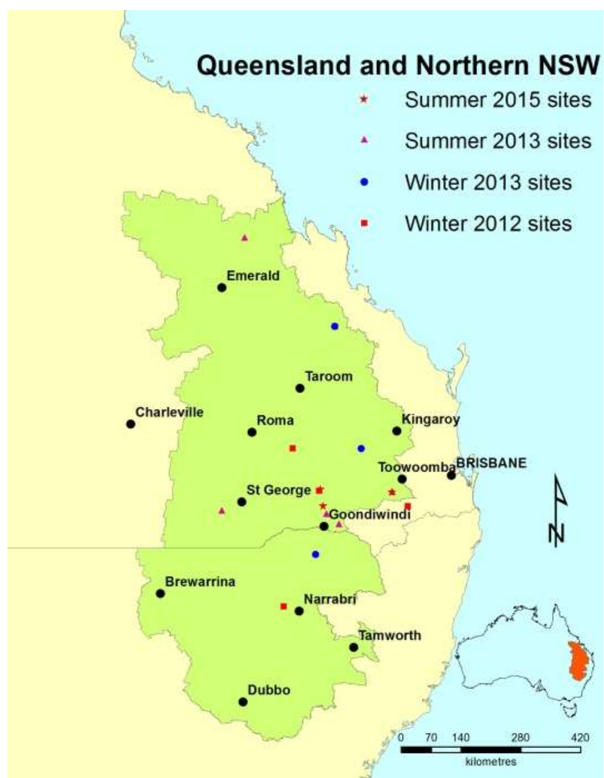


Figure 1: Trial site locations throughout Queensland and Northern New South Wales.

Winter sites 2012

Five sites under long term no-till management were selected throughout the NGR to determine the impact of different tillage implements under semi-arid, subtropical climatic conditions. Site information is given in Table 2. All sites had been under no-till management for 7-44 years and had a slope of <1%. Agro-climatic and management details of the sites are outlined in Table 2. Trials were established in a randomized complete block trial design with four replicates. The Hermitage site was a long term established site consisting of a factorial combination (2x2x3) of conventional tillage (CT) or no till (NT), stubble retained (SR) or burned (SB) after harvest, and three rates of N; 0, 30 and 90 kg N ha/year. Each plot was split longitudinally with strategic tillage applied to the western half. Only the 90 kg N, NT and ST plots were used in analysis to best represent a typical system.

Table 2: Agro-climatic conditions of winter 2012 sites.

	Biloela	Condamine	Moonie	Warwick	Wee Waa
Max Temperature (°C)	29	27.1	27.1	24.6	26.5
Min temperature (°C)	13.2	13.2	13.2	10.4	11.7
Average annual rainfall (mm)	668	624	624	689	592
Average summer rainfall (mm)	288	237	237	248	199
NT history (Years)	18	19	7	44	16
Soil Type	Vertosol	Sodosol	Dermosol	Vertosol	Vertosol
Date of Tillage	29 Mar., 20 Apr. 2012; 28 Jan., 10 Feb. 2013	6 Mar., 18 April. 2012	3 Mar. 2012	7 Mar. 2012	26 Mar. 2012
Tillage Implement	Chisel (1 pass, 2 pass)	Chisel (1 pass, 2 pass)	Chisel, Disc	Chisel (1 pass, 2 pass)	Chisel, Prickle chain
Latitude (decimal degrees)	24.34°S	26.90°S	27.79°S	28.12°S	30.23°S
Longitude (decimal degrees)	150.53°E	149.64°E	150.20°E	152.06°E	149.45°E

In 2012, all sites were assessed for total organic carbon (TOC), Colwell P, bulk density, gravimetric moisture, plant establishment, weed density, particulate organic carbon (POC), soil microbiology and yield.

In 2013, all sites were assessed for TOC, Colwell P, bulk density, gravimetric moisture, plant establishment, weed density, POC, soil microbiology and yield. Wee Waa underwent severely dry conditions, and was not assessed in 2013.

In 2013 the Condamine and Moonie sites were additionally assessed for wet aggregate stability, shear strength, penetration.

In 2013 the Warwick site underwent testing for AM and nematodes, and wet aggregate stability.

In 2014 all sites were assessed for TOC, Colwell P, bulk density, gravimetric moisture, plant establishment, weed density, POC, and yield.

In 2015 the Moonie site was abandoned due to an unexpected tillage event. All other sites were assessed for TOC, Colwell P, and gravimetric moisture. The Warwick site was also assessed for bulk density.

The Biloela, Condamine, Moonie and Warwick sites were used in HowLeaky? Simulations. The Biloela site was also used for APSIM modelling. Cropping information throughout the duration of the trial is as indicated in Table 3.

Table 3: Crops sown throughout the duration of the study period.

Year	Biloela	Condamine	Moonie	Warwick	Wee Waa
2012	Wheat	Chickpea	Barley	Wheat	Chickpea
2013	Chickpea	Wheat	Chickpea	Wheat	NA
2014	Sorghum, Wheat	Wheat	Chickpea	Wheat	NA
2015	Wheat	Wheat	NA	Wheat	NA

Winter sites 2013

Three experimental sites were established to determine the effects of timing and frequency of tillage passes on productivity, profitability, soil health and agronomic parameters. The locations, climate data, and cropping history are outlined in Table 4.

Table 4: Trial locations used for the assessment of timing and frequency of tillage. Agro-climatic conditions of timing and frequency tillage trials.

	Biloela B	Jimbour	Moree
Max Temperature (°C)	29	26.8	26.1
Min temperature (°C)	13.2	11.9	12.4
Average annual rainfall (mm)	668	606.5	582.7
Average summer rainfall (mm)	288	252.5	210
NT history (Years)	18	9	5
Soil Type	Vertosol	Vertosol	Vertosol
Tillage Date	Dec. 2012; Jan. 2013; Feb. 2013.	4 Dec. 2012; 23 Jan. 2013; 20 Mar. 2013	15 Mar. 2013; 5 Apr. 2015
Tillage Implement	Chisel	Chisel, Disc	Chisel, Kelly Chain
Latitude	24.34°S	26.91°S	29.14°S
Longitude	150.53°E	151.09°E	150.13°E

Each site was a randomised complete block trial design with four replications at Moree and Jimbour, and three at Biloela. At Moree, each block was comprised of no till (NT), cultivator in March (CCM), Kelly chain in March (DCM), cultivator in April (CCA), and Kelly chain in April (DCA). The site was known to have issue with crown rot and herbicide resistant barnyard grass. Plots were 24m x 100m. Tillage was carried out to a depth of approximately 15-20cm depth using the landholder's equipment.

The Biloela trial site was established on a black Vertosol in December 2013. Plots were 12m x 100m. The soil is described as a Haplic Epipedal Black Vertosol (ASC) containing 49% clay, 13% silt and 38% sand in the top 0.3 m (Crawford et al., 2015). Each block was comprised of no till (NT), single pass tillage (TT1/TF1) (December), single pass tillage (TT2) (January), single pass tillage (TT3) (February), two frequency tillage (TF2) (December, January), or three frequency tillage (TF3) (December, January, February).

The Jimbour trial was comprised of 48 plots, of 12m width and 25m length. Treatments were no-till, disc, and tine tillage. Each tillage was carried out either once in December, January, or February, two times (December and January), or three times (December, January, March) to determine the effects of timing, frequency and type of tillage, as indicated in Table 5. Tine tillage was to a depth of approximately 20cm using the implements shown in Figure 2.

Table 5: Tillage treatments applied at Jimbour west, each treatment was replicated 4 times.

Treatments:	Description:
NT	No-till
DF1/DT1	One-time disc tillage in early December 2012
DT2	One-time disc tillage in January 2013
DT3	One-time disc tillage in March 2013
DF2	Two-time disc tillage in December 2012, January 2013
DF3	Three-time disc tillage in December 2012, January and March 2013
TF1/TT1	One-time tine tillage in early December 2012
TT2	One-time tine tillage in January 2013
TT3	One-time tine tillage in March 2013
TF2	Two-time tine tillage in December 2012, January 2013
TF3	Three-time tine tillage in December 2012, January and March 2013

In 2013, all sites were assessed for TOC, Colwell P, bulk density, gravimetric moisture, soil microbiology, plant establishment, weed density, POC, and yield. The Biloela and Jimbour sites were additionally assessed for micronutrients and exchangeable cations. The Biloela and Moree sites were also assessed for pH and EC.

In 2014 all sites were assessed for TOC, Colwell P, bulk density, gravimetric moisture, POC, soil microbiology, and yield.

The Jimbour and Moree sites were used for APSIM modelling to predict soil moisture status and yield under different tillage regimes, with crops planted throughout the duration indicated in Table 6.

Table 6: Crops sown in timing and frequency trials.

	2013	2014
Biloela	Chickpea	Sorghum, Wheat
Moree	Wheat	NA
Jimbour	Wheat	Chickpea

Figure 2: Tillage implements used for disc tillage (left) and tine tillage (right) at the Jimbour West Site.

Summer 2013 Sites

Four summer trail sites were established in 2013, the location and agro-climatic data for the respective sites is indicated in Table 7.

Table 7: Climatic and location data for Summer Trial sites, retrieved from the closest Bureau of Meteorology comprehensive collection station.

	Emerald	Yelarbon	Felton	Goondiwindi
Max Temperature (°C)	29.7	27.2	22.6	27.2
Min temperature (°C)	16.7	12.8	11.4	12.8
Average annual rainfall (mm)	613	605	944	605
Average summer rainfall (mm)	308.4	251.4	373.2	251.4
NT History			5	
Soil Type (ASC)	Vertosol	Vertosol	Vertosol	Vertosol
Tillage Date	29 May 2013	29 May 2013	12 Aug 2013	Apr. 2013
Tillage Implement	Offset disc, narrow chisel	Tine, offset disc	Offset disc	Deep nutrient placement
Latitude (decimal degrees)	22.49°	28.51°	27.84°S	28.30°S
Longitude (decimal degrees)	154.63°	150.62°	151.74°E	150.35°E

The Emerald and Yelarbon sites were established to determine effect of different tillage implements under summer cropping regimes. Both sites were a randomised complete block trial with four replicates. Each block at the Emerald site was comprised of no till (NT), narrow chisel (Ch1), and single pass offset disc (D1). Plots were 60m in length and 12m width.

Figure 3: Deep nutrient placement at the Goondiwindi South site, November 2013

Each block at the Yelarbon site was comprised of no till (NT), single pass chisel tillage (Ch1), and single pass disc tillage (D1). Plots were 100m length and widths were 12m in accordance with controlled traffic. Tillage operations were performed using the landholder's equipment at both.

Both sites were assessed for TOC, Colwell P, bulk density, gravimetric moisture, and yield. The Yelarbon site was additionally assessed for wet aggregate stability, shear strength, and penetration strength.

The Felton Site was established to determine the nature of short term moisture loss after tillage. The trial was established with 3 replicates of alternating no till (NT) and single pass disc tillage (ST). Plots were 100m in length and 12m width. BD and soil moisture was determined on days 1, 2, 3, 4, 7, 9, 17, 30, 44, 60, and 65 days' post tillage. In conjunction with physical measurements, electromagnetic surveys were carried out using a Geonics EM38MKII in both the vertical and horizontal modes, with depth slicing at 0.1m, 0.2m, and 0.3m above the soil surface. Calibration curves were established to determine the rate of soil moisture loss between tillage treatments, and interpolation of the soil moisture status based on EM readings was carried out using a linear calibration curve.

Duplicate trials were established at Goondiwindi to assess the impact of strategic tillage for banded nutrient placement. Each trial design was 6 replicates of alternating planting into the nutrient band (ON) and off the nutrient band (OFF). MAP was applied to a depth of approximately 20cm at a rate of 80kg/Ha Urea + 40kg/Ha MAP. 100m was planted either directly into the banded nutrient strip, or between strips in a skip row fashion with sorghum cv MR43. Farmer practice was to plant directly on to the nutrient strip on the 9/12/2013 (South) and 17/12/2013 (North).

Soil samples for each plot were collected from the nutrient band and from adjacent soil between nutrient bands. Soil was assessed for OC, Colwell P, NH_4-N, and NO_3-N. Flag leaf and leaf blade samples were collected for analysis of micronutrients by nitric acid digest on ion-coupled plasma spectroscopy.

Rainfall Simulation Sites

Three experimental sites were selected to undergo rainfall simulation to determine the risk associated with intense rainfall after a strategic tillage. The soils were a Black Vertosol at Felton, a Sodosol at Billa Billa and a Dermosol at Moonie (Table 8). The Sodosol and Dermosol had been strategically cultivated for weed control and/or pupae busting after cotton cropping in the last five years.

Table 8: Site history and characteristics of sites selected for rainfall simulation.

	Felton	Billa Billa	Moonie
Latitude (decimal degrees)	27.83°S	28.12°S	27.77°S
Longitude (decimal degrees)	151.74°E	150.29°E	150.23°E
Max Temperature (°C)	22.6	27.1	27.1
Min temperature (°C)	11.4	13.2	13.2
Average annual rainfall (mm)	944	624	624
Average summer rainfall (mm)	373.2	237	237
NT history (Years)	20	15	9
Soil Type	Vertosol	Sodosol	Dermosol
Tillage Date	20 May 2015	31 May 2015	9,12 Jun. 2015
Tillage Type	Scarifier	Cultivator	Kelly Prickle Chain
Simulation Dates	25-29 May 2015	1-5 Jun. 2015	9-12 Jun. 2015

The ST treatment applied at each site was a single pass of cultivation resembling that which might be used for weed control, and this was compared with a NT control. For the ST treatment, the soil was cultivated to approximately 150 mm depth on the Vertosol using a scarifier and to about 100 mm depth on the Sodosol and Dermosol using a cultivator and Kelly prickle harrow (Table 8, Figure 6).

Figure 6: (Left) Runoff after cultivation for weed and disease control of a paddock with a long history of no tillage (Strategic Tillage) was compared with runoff from a paddock with a long history of no tillage (No Tillage) during the winter fallow. (Right) Tillage equipment used at a) Felton and b) Billa Billa and Moonie.

Sampling and analysis

Physical properties

Bulk Density: Soil bulk density was measured using a modified, hinged soil corer with a diameter of 43mm and hydraulic soil coring rig. Soil cores were sliced into sections of 10.0cm, to a depth of 0.30m. The true length of each core was measured at three (3) positions around the circumference to the nearest millimeter. Soil samples were immediately placed in water tight bags, and cold stored until weighing. Wet weights of soil cores and bags were determined, and soils were dried at 105ºC for a minimum of four days. Soil samples were weighed immediately after removal from the oven. Soil bulk density was determined using the following equation (1):

$$\text{Bulk density } (g/cm^3) = \frac{\text{Dry soil weight } (g)}{\text{Soil volume } (cm^3)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Soil moisture: Gravimetric water content was calculated from the mass of dry soil, subtracted from the weight of wet soil, shown by equation (2). The soil volumetric water content was calculated by multiplying the gravimetric water content by the soil bulk density for each depth.

$$\theta d = \frac{(\text{wet soil weight}) - (\text{dry soil weight})}{(\text{dry soil weight})} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Wet aggregate stability: Soil samples were collected from field sites using minimal disturbance techniques, by cutting away a vertical soil face. Samples were collected to a 10cm depth by slicing horizontally into the soil and lifting gently. Soils were placed in containers for transportation. Soils were dried for a minimum of four days at room temperature. Soils were gently sieved to obtain the fraction of soil aggregates >4.75mm<2.0mm. 50.0g of the aggregate fraction were placed on a sieve stack comprising sieve apertures of 2.0mm, 1.0mm, 0.5mm, 0.25mm, and 0.125mm. Soils were sieved mechanically in normal tap water for a period of 30minutes at a rate of 30RPM and a range of motion of approximately 3cm. At completion the aggregates remaining on each sieve were collected and dried at 105ºC. The weight of each fraction was determined. Mean weight distribution of aggregates was calculated by summation of the percent, by weight, of particles in a given class size, multiplied by the mean particle diameter, as indicated in equation (3).

$$\Sigma\ (\%\text{weight} \times \text{mean diameter}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Infiltration rates were calculated based on the fraction of aggregates after sieving in the category <125µm (Loch and Foley, 1994).

Soil shear strength: Soil shear strength was used as a measure of soil strength. A Shear Vane Tester 16-T174 (Envco, New Zealand) was used for all measurements. A 25mm cross sectional attachment with a 50mm length was used for all measurements. Measurements were conducted at three points in each plot along a transect across the trial for consistency. Torsional force required to shear the soil was measured in Torque (N.m) by twisting the instrument at the 50mm depth. Wheel tracks and soil anomalies were avoided.

Soil penetration: Soil penetration strength was determined using a penetrometer. Three replicates per plot were carried out. The penetrometer was inserted at 90° to the surface of the soil and the cone index was recorded as the maximum PSI required to penetrate the soil at each point. Soils were measured whilst at approximately field capacity. All due care was taken to avoid measuring on wheel tracks and other soil anomalies.

Chemical properties

Soil sample Collection: Soil cores were collected as per soil bulk density, ensuring that no carbon based contaminants contacted the sampling equipment. Two cores were collected per plot and bulked. Samples were dried at 40^{0}C, and mechanically ground to pass through a <2mm sieve.

Chemical analysis: Samples were analysed for available phosphorous content by the Colwell method 9B2 (Rayment and Lyons 2011). TOC was determined by the combustion method 6B3 (Rayment and Lyons 2011). Equivalent soil mass was used to compare TOC stocks (Wendt and Hauser 2013). Soil samples for EC, pH, micronutrient/cations were prepared similarly, and analysed using the methods 3A1, 4A1, 12A1 and 15A1 respectively (Rayment and Lyons, 2011).

POC: Soil particulate organic carbon was determined on the 0–0.1 m layer only and quantified by physical separation of sizes <2.0 and >0.053 mm (Cambardella and Elliot 1992). A homogenous 10g subsample of the 40ºC dried <2mm soil was used in the analysis. Soils were dispersed by mixing samples in 50mL of 5g L^{-1} sodium hexametaphospate for 12 hours on a rotary shaker. Samples were passed through a 53µm sieve and rinsed with distilled water until the eluent was clear. The >53µm fraction was retained and dried at 40ºC. Samples were manually ground to <0.5mm, and the TOC was determined on a 0.5g subsample (method 6B3)(Rayment and Lyons 2011).

Plant sample collection: Flag leaf samples and leaf blade samples were collected randomly along the length of each plot. 50 of each leaf type were collected and dried at 65^{0}C. Samples were ground to <2.0mm.

Plant chemical analysis: Plant nutrient analysis was carried out for aluminium, boron, calcium, copper, iron, potassium, magnesium, manganese, sodium, sulphur, and zinc using the method elements nitric microwave digest ICP (Rodushkin et al., 1999).

Biological properties

Mycorrhizal associations: Plants and root zones were collected to a depth of 0.2m using a standard digging fork, with minimal disturbance to the root zone. Vegetative matter above the crown was dried at 60^{o}C for 48 hours to determine dry weight. Soil was separated carefully from the root zone by washing in tap water to minimise root loss and damage. Water containing soil was then diffused with 5g L^{-1} sodium hexametaphosphate. The soil solution was then decanted through 425-µm mesh sieve, repeated 5-6 times to recover all root material. Roots were blotted dry with standard paper towel to obtain the fresh weight of root matter. A 0.5-0.6g subsample of fine roots was selected randomly and stained as described by Phillips and Hayman (1970) for quantitation of mycorrhizal infection. The stained roots were examined under a dissecting microscope using a gridline intersect method detailed in Giovannetti and Mosse (1980) to estimate both the proportion of infected roots, indicated by presence of hyphae, and the total length of root in each sample. A minimum of 200 root/gridline intersects were assessed per sample.

Nematode populations: Soil samples were collected as described for mycorrhizal association analysis. A 100-150g subsample of field moist soil, broken into aggregates of <5mm, was collected for each extraction. Soil moisture was determined for each sample by oven-drying a 100g subsample at 105^{o}C for 48h. Nematode samples were processed as described by the Whitehead tray method (Whitehead and Hemming, 1965) for 48 h at 22°C. Nematodes were recovered on a 20µm-mesh sieve. *Pratylenchus thornei* were morphologically identified (Fortuner, 1977) and counted in a 5mL counting chamber under a compound microscope at ×40 and ×100 magnification. Non-plant parasitic or free-living nematodes were counted cumulatively. Counts were expressed on a dry-soil weight basis after correction for soil moisture content.

Microbial soil sampling: Five randomised soil samples per plot were collected in separate sealed bags from the top 0-0.1m and 0.1-0.2m soil depth, using a hand shovel. Soil samples from the same plot were composited, sieved to <4mm and stored at 4°C for further analysis. All visible litter material was manually removed prior to sieving.

FDA hydrolysis: Soils were analysed for *Fluorescein diacetate (FDA)* hydrolysis activity using the method developed by Adam and Duncan (2001). In brief, two grams of soils were mixed with 15mL of 60 mM potassium phosphate (pH 7.6) in a 50mL tube. To start the reaction, 200 µL FDA (1000 µg/mL) was added. This mixture was gently shaken and placed in an incubator/shaker (N-BIOTEC Inc.) for 1 h at 30°C and 150 rpm. To stop the reaction, 1 mL of the mixture was added to a new 2 mL-microcentrifuge tube with 1 mL of a 2:1 chloroform: methanol solution. All analyses were carried out in triplicates. This solution was then centrifuged for 3 min at 10,000 *g*. A volume of 250 µL per sample was aliquot in a 96-well plate. The absorbance at 450 nm was measured using a microliter plate reader (BMG Lab, Rotenberg, Germany). The blank was prepared by adding 15 mL of 60 mM potassium phosphate (pH 7.6) and 200 µL FDA (1000 µg/mL).

Microbial Biomass: Soil microbial biomass C was determined using the fumigation-extraction method (Beck et al. 1997). Ethanol-free chloroform ($CHCl_3$) was used to fumigate 10 g (oven-dry equivalent) of soil from each plot. Soils were kept in a desiccator for 36 h in the dark at room temperature. After fumigation, soluble organic C from fumigated and unfumigated samples was extracted with 50 mL of 0.5 M potassium sulfate (K_2SO_4) by shaking on an orbital shaker for 1 h at 250 rotations min^{-1} (rpm). Samples were then centrifuged at 12,000 *g* for 5 min to be later filtered through a Whatman grade 1 filter paper. A total of 45 mL of extract per sample was sent for total organic C analysis to the analysis services unit at Gatton campus, University of Queensland. Microbial biomass C was calculated as the difference between fumigated and unfumigated samples divided by the constant soil-specific calibration coefficient K_{EC} of 0.45. Results were transformed using the Hellinger transformation to accomplish normality.

Microresp™ substrate utilisation potential: Substrate induced respiration was measured for all treatments using the Microresp™ system (James Hutton Institute, Invergowrie, Scotland UK) as per Campbell et al. (2003). Soil samples were weighted and aliquoted to a deep-well microplate (~ 0.4 g of soil per well) before adding the solution with a substrate and incubating for 6 h with cresol red indicator to quantify CO_2 production. Tested substrates included three amino acids (arginine, alanine and aminobutyric acid), six carbohydrates (fructose, trehalose, glucose, xylose, cellubiose and mannitol), five carboxylic acids (citric acid, malic acid, methyl pyruvate, oxalic acid and galacturonic acid) and one polymer (Tween40). Each substrate was diluted in water and balanced to deliver 30 mg of substrate C per gram of soil water. Detection plates with cresol red were measured at 570 nm in a microplate spectrophotometer (Biotek, Winooski VT, USA).

DNA extraction: DNA was isolated from soil by combining a sonication step prior to using the MoBio Kit PowerLyzer™ (MOBIO Laboratories, CA). Briefly, five grams of fresh soil was added to a 50mL tube containing 5mL of Phosphate-Buffered Saline (pH 7.2). Samples were vortexed until mixed and then sonicated at low frequency for 5 minutes with alternating 30 second intervals of burst and rest. Settling was allowed for 10 seconds and the supernatant was transferred to a 1.5mL Eppendorf tube which was centrifuged for 1 minute at 9,500 *g*. An amount of ~ 0.3 g of soil was transferred to the glass bead tubes supplied with the commercial kit. The following step of soil DNA extraction was performed according to the manufacturer's instructions for low biomass soils. Final concentrations of DNA samples were measured using Qubit® fluorometric quantitation 2.0 (Life Technologies, CA).

Terminal Restriction Fragment Analysis (T-RFLP): After DNA extraction, samples were amplified using universal 16S ribosomal primers 27F (5' - AGA GTT TGA TCM TGG CTC AG -3') and 1492R (5'- TAC GGY TAC CTT GTT ACG ACT - 3'). The 27F primer was fluorescently-labelled with 6-carboxyfluorescein (6-FAM) at the 5' end. The PCR was carried out in a 20 µL reaction containing 0.2 µM of each primer, 0.2 µM dNTPs mix and 1 unit of Phire ® Hot Start II DNA polymerase. PCR cycling conditions were 30 seconds at 98°C followed by 27 cycles of 5 seconds at 98°C, 5 seconds at 54.5°C and 20 seconds at 72°C, and finalising with 1 min at 72°C. PCR products were verified on 1% agarose gels. Fluorescently-labelled PCR products of two independent reactions were combined and digested with 1 unit of the restriction enzyme *Msp*I (*Moraxella* sp. I). Digested amplicons were desalted with a purification kit (Wizard® SV Gel and PCR Clean-up System, Promega) and sent to AGRF (Australian Genome Research Facility Ltd., Melbourne, Australia) for fragment analysis.

Agronomic measurements
Weed density & crop establishment: Weed density was determined at each site on a per square meter basis with a minimum assessment of 2 randomly placed 1.0 x 1.0m squares per plot. Weed counts were carried out in crop, simultaneously to establishment. Weeds were identified where possible. Establishment counts were conducted over a minimum of 2 random 1m lengths. The number of emerged plants were counted per meter and averaged.

Figure 5: Left) Weed counts were carried out using 1.0x1.0m squares randomly placed in each trial plot and right) sow thistle (*Sonchus oleraceus*) common after tillage at many of the sites assessed.

Productivity: Productivity was determined at the Hermitage, Moonie, Jimbour, and Emerald sites by the use of a small plot trial harvester, and at all other sites farmer's harvesters were used with either yield mapping technology or a weigh bin. Size of crop area collection was measured to the nearest 0.1m to accurately determine yield per hectare.

Profitability: In the first year of tillage the cost was deemed to be $15/Ha for tine or chisel tillage, $20/Ha for disc cultivation, and $10/Ha for Kelly chain cultivation. Profitability was determined based on market prices of $280/t wheat, $260/t barley and $550/t chickpea in 2012. In 2013 profit was based on market prices of $400/t chickpea and $320/t wheat. In 2014 profit was based on market prices of $230/t sorghum, $270/t wheat, and $400/t chickpea.

Cropping Reliability

APSIM modelling: APSIM farming systems model (McCown et al., 1996) was used for modelling. Simulations were carried out for the Biloela, Jimbour West, and Moree sites, using data from the Bureau of Meteorology Thangool, Dalby, and Moree data collection locations respectively. 4 tillage scenarios were assessed. These were: no-till, conventional till 1 month prior to sowing, 3 months before sowing, or 5 months before sowing. All tillages were with a disc implement to a depth of 200mm. Simulations were run over the period of 1961 to 2013 for a continuous wheat-fallow system. Sowing was simulated for May 1st each year, at a density of 100 plants/square metre with theoretical urea application of 150kg/Ha.

The effect of tillage on soil roughness and the amount of rainfall required to remove roughness was simulated via CN reduction and CN rain parameters, set respectively at 10 units and 400 mm (Littleboy et al., 1996).

An additional analysis was carried out in the years 1972-2014 under two comparisons of NT and CT, with tillage in the first week of December. Outcomes between the two treatments were compared in the 30% of driest years, and 30% wettest years, and average (% all others) where 1 year was harvest to harvest date. Soil data for each site was retrieved from the APSOIL database (https://www.apsim.info/Portals/0/APSoil/APSRU-Australia-Soils.soils). 7 year crops rotations were used comprising; 3 years of wheat, followed by one year of fallow and three years of sorghum, where sowing dates were between May 1st and June 31st for wheat and 7th December and 31st of January for sorghum. Sowing was based on 20mm rainfall occurrence, or end of sowing period if insufficient rainfall was received. Sowing density for sorghum was 1000plants/square metre.

The effect of tillage on soil roughness and the amount of rainfall required to remove this roughness was simulated via CN reduction and CN rain parameters, set at a value of respectively 5 units and 200 mm according to Littleboy et al. (1996).

Environmental Impacts

HowLeaky? simulations: Howleaky? (McClymont et al., 2013) analysis was performed for determination of potential water and sediment losses. Simulations were run for the period of 1 January 2000 – 1 January 2013. Parameters used for analysis were for strategic tillage once every three years. The soil model parameters were kept uniform and differences in leaf area index simulated due to changes in timing, type and frequency of tillage.

Rainfall simulation and sampling: Rainfall was simulated using an A-Frame simulator based on that described by Loch et al. (2001) to generate runoff from small paired *in situ* plots of 2.75 m length x 0.75 m width, 0.1 m apart). The simulator had three Veejet 80100 nozzles which produced droplets with kinetic energies similar to intense (>40 mm/h) natural rainfall and were mounted on an oscillating manifold. The nozzle pressure was regulated to 60 kPa and the rainfall intensity was controlled by regulating the frequency of successive spray passes across the plots. Plot frames were installed to 100 mm soil depth at Felton and to 50 mm depth at Billa Billa and Moonie where the depth of tillage was shallower. All plots were located between permanent and/or temporary traffic lanes (Figure 6).

Rainfall was applied to plots within nine days of a tillage treatment. Rainwater was used to supply the rainfall simulator. Paired plots were replicated twice for the treatment and control at each of three sites at a rainfall intensity of 70 mm/h which approximated the intensity of a 1 in 10-year storm return interval over 30 minutes or a 1 in 100-year storm return interval over 60 minutes of rainfall at each location. To allow at least 30 minutes of runoff to occur on each plot, rainfall was applied for 70, 80 or 90 minutes.

Samples of runoff were collected at intervals from 2 to 10 minutes throughout the hydrograph via a metal collection tray (Figure 6b). The time taken to collect each sample was recorded and the samples were weighed and retained for suspended sediment analysis. A separate composite sample was collected by sampling runoff for 2, 3 or 4 seconds based on the runoff rate per plot, every 2 minutes throughout the duration of each runoff event. This sample was a flow-weighted event-mean concentration. The event-mean sample was analysed for nutrient chemistry. A sample of runoff was collected at the cessation of rainfall at Felton and Moonie from two NT and two ST plots for particle size distribution analysis. For runoff from Billa Billa, particle size distribution was analysed on suspended sediment samples collected towards the end of the runoff event. The time to initiation of ponding was recorded visually for each plot. The runoff rate was calculated as the volume of runoff, estimated from the weight of samples, collected at each collection interval, divided by the time taken to collect the sample. Event-mean concentration (EMC) samples were filtered through a glass fibre pre-filter and then a 0.45 µm glass fibre filter. Both filtered and unfiltered samples were stored at 4°C until analysis. Chemical analysis occurred within three months of sample collection.

Chemical and physical parameters of the unfiltered runoff analysed were total P (TKP) and N (TKN) after Kjeldahl digestion, pH and EC, particle size distribution by laser diffraction and total suspended solids (TSS) by gravimetric analysis (Eaton and Franson (2005). Chemical parameters of the filtered runoff analysed were; nitrate plus nitrite (NO_3-, NO_2-), ammonia (NH_4), and PO_4 by flow injection colorimetric analysis, total P (DKP) and N (DKN) after Kjeldahl digestion (4500-N org D in Eaton and Franson (2005).

a b

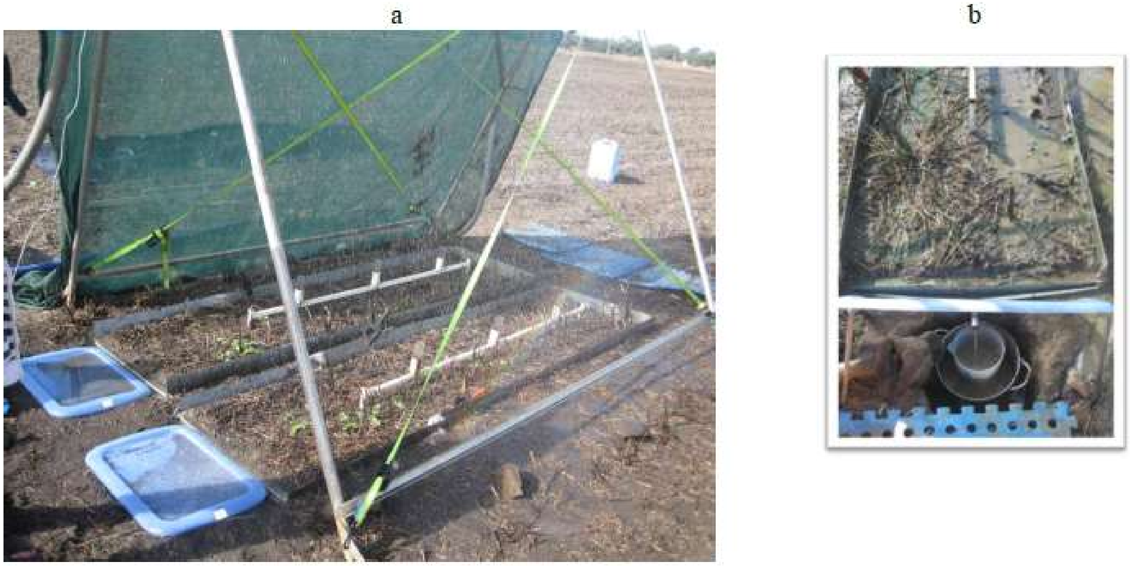


Figure 6: Simulated rainfall was applied to paired rainfall plots (a) and runoff was collected via metal gutters at the downslope edge of the plots (b).

Figure 7: Instrumentation used to characterise rainfall simulation plots and treatments included profile microrelief measurements before (a) and after (b) tillage, biomass (c) and soil (d) collection, filtration of runoff samples (e) and single-ring infiltrometers (f).

Pre-rainfall measurements: Infiltration rates were measured using two methods. The first method was by calculation of the difference between rainfall and runoff volumes at measured time intervals using the rainfall simulators. A final infiltration rate was estimated as the mean infiltration rate of measured rates that changed by less than 5 mm/h towards the end of the hydrograph. The final infiltration rates were used to calculate a runoff curve number (CN) (Connolly et al., 2002) for each plot. Final runoff rates (mm/h) were also calculated as the mean runoff rate for the same measurement times as those used to calculate the final infiltration rate.

The second method used to measure infiltration rates was the single ring ponded infiltrometer method (Parr and Bertrand, 1960, Tricker, 1978) (Figure 7f). In the single ring method, rings of 265 mm diameter and 250 mm height were refilled with water when they approached emptiness. The effect of increasing the head during refilling on the infiltration rate was ignored in calculations of steady-state infiltration rates. Infiltration rate as a function of time was approximated by fitting power curves to measured data (Equation 4),

$$I_t=at^n \quad \text{……………………………………………………………………………………………………..(4)}$$

where I is instantaneous infiltration rate (mm h) at time t (h) and *a* and *n* are constants. Infiltration rates predicted by the fitted curves at t=5, t=10 and t = 20 were calculated.

Biomass and groundcover: Above-ground biomass was harvested from two 0.25 m x 0.25 m quadrats per paired plot. Harvested biomass was dried at 60°C for 48h then weighed and biomass calculated as dry matter per hectare. A photograph was taken of each runoff plot and the groundcover estimated visually.

Soil Chemistry: Three soil samples of 0-5 cm depth were collected and combined from each paired plot for soil chemical analyses. A randomly located single soil sample of 0-10 cm depth from each paired plot was also collected for soil chemical analysis. Soil was dried at 40°C and sieved to <2 mm prior to chemical analysis. A separate soil sample of 0-10 cm depth was collected from each of two plots per treatment per site and stored in an ice-box and then at 4°C prior to analysis of KCl-extractable nitrate and ammonium N.

Soils were analysed for pH (4A1), EC (3A1), Colwell P (9B2), phosphate buffering index (9I2a and 9A4a), organic carbon (6B3), Total N (7A2), Total P (9A3a), nitrate & ammonium (7C2), Ca, Mg, K, Na exchangeable sodium, cation exchange capacity (15C1), air dry moisture content (2A1), total moisture content (2B1). All methods detailed in parentheses are described by Rayment and Lyons (2011). Particle size analysis was carried out (Australian Standard 1997) and ratio of total silt and clay percent as per Baker and Eldershaw (1993).

Soil moisture: Three intact soil samples of 0-5 cm depth were collected from each paired plot using 50 mm diameter bulk density rings and used to measure gravimetric soil moisture content and soil bulk density. Gravimetric soil moisture content was also measured on samples collected at 0-10 cm depth and then at 5 cm increments to 25 cm (Felton and Billa Billa) or 10 cm increments to 40 cm (Moonie) depth.

Surface roughness & slope: Surface roughness before rainfall was measured using a microrelief meter (Figure 7a, b). Three randomly selected profiles of 32 elevations spaced 25 mm apart per treatment per site were measured perpendicular to the plant rows. Roughness was estimated as the squared deviation of each pin height from the mean pin height (centimetres) of each profile, based on methods of Allmaras et al. (1966). Plot slope was calculated from elevations measured using a survey level.

Soil shear strength: Soil shear strength was measured using a shear vane. Ten measurements at Moonie and 15 measurements at Felton and Billa Billa were conducted for each treatment. Soil moisture was measured at each point of measurement using a capacitance probe.

Post-rainfall measurements: Approximately 24 hours after the cessation of rainfall, a soil sample of 0-10 cm depth was collected from each of two plots per treatment per site and stored in an ice-box and then at 4°C prior to analysis of KCl-extractable nitrate and ammonium N. Gravimetric soil moisture content was measured on samples collected approximately 24 hours after the cessation of rainfall at 0-10 cm depth and then at 5 cm increments to 25 cm (Felton and Billa Billa) or 10 cm increments to 40 cm depth (Moonie).

Statistical Analysis: Two-way analysis of variance tests for site (Felton, Billa Billa and Moonie), treatment (ST or NT) and interaction (site x treatment) effects were conducted using Genstat 17th Edition (VSN International Ltd, 2014). Assumptions of normality and equal variance were tested by visual inspection of residuals and data were transformed using the natural logarithm where necessary. Paired t-tests were also used to test for within-site treatment effects when interaction effects were observed graphically but were not identified by the two-way ANOVAs. All differences described in this report were significant at the 95% confidence level ($p < 0.05$) except where specifically mentioned otherwise.

Results

Market Research

Initial face to face interviews revealed that the primary areas of research that were required were the effects of strategic tillage on water infiltration and penetration; soil water capacity; subsoil constraints; soil compaction; disease; soil properties (biota, chemistry, physical) soil health; crop yield; organic matter and carbon; effects on different soil types; and time to recovery after tillage.

Producers noted that they would require a better understanding of the best ways to undertake a strategic tillage. This included selection of the most appropriate cultivation tool and their individual impacts, when to time tillage with respect to soil moisture, time of year, ground cover, and previous crops. In addition, respondent queried how many passes of tillage would be required, and the duration required for parameters to return to pre-till conditions, and what follow-up crops would respond well.

Nutrient stratification and nutrient placement was raised as an issue that needed addressing, and whether tillage could be utilised safely in application, or could amend stratified nutrients. Stubble management was raised as a problem that tillage may amend, and how soil would respond both chemically and biologically was important.

Weeds appeared to be a major driver in the research into strategic tillage. Farmers consistently noted that weed management was becoming an increasingly difficult and expensive exercise, and desired information on the effectiveness of mechanical management compared with chemical methods, and whether tillage had a place in strategic weed management. Feather topped Rhodes was one of the major weeds identified as being a problem by those who were interviewed.

No-till and control traffic farming typically go hand in hand, and given the wet harvest leading to several noted issues, respondents noted that erosion in tramlines and compaction in wet seasons were notable.

In the second market research, in the form of an online survey, 48 respondents qualified by being farmers who had used a strategic tillage within a typically zero or minimum tillage system. 60 farmers identified themselves as dry land grain producers. 9 farmers identified themselves as dry land cotton producers. These farmers also identified themselves as dryland grain producers as well. 5 farmers identified themselves as both irrigated cotton and grain producers. Another 6 farmers identified they also produce hay, sheep or beef as well as dryland grain.

The location of respondents spread across the whole Northern Grains Growing region. There was a slight emphasis on areas around Toowoomba and only a few from central Queensland.

The respondents reason for undertaking tillage were renovation of rough country (31.9%), weed control (24.4 %), herbicide resistance (12.6%), stubble retention (8.4%), nutrient management (8.4%), integrated pest management (5%), hard setting soil (5%), and disease (4.3%).

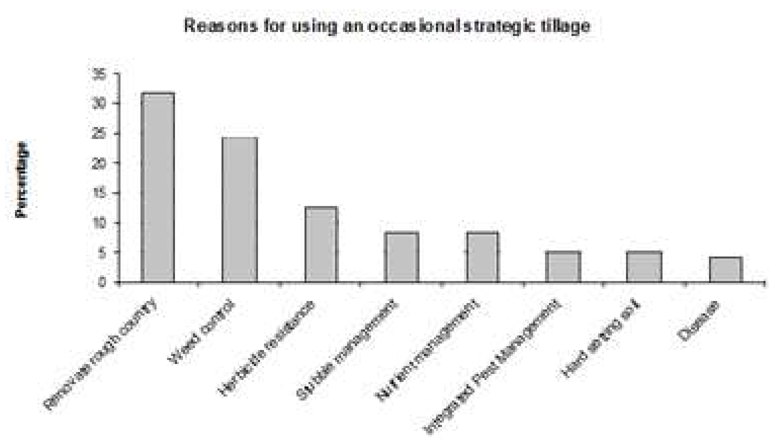
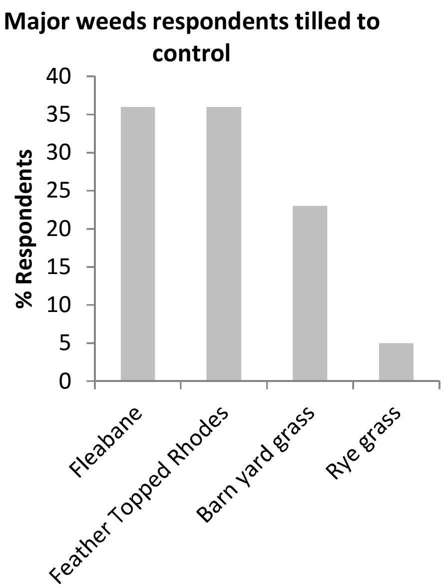


Figure 8: Percentage of respondents who used strategic tillage for varying issues identified in market research round 2.

Respondents who selected 'weed control' as a primary reason for using a strategic tillage identified fleabane (36%), feather Topped Rhodes (36%), barn yard grass (23%), and rye grass (5%) as the major weeds.

When ranking the most important considerations for tillage decision (1-7), the average rank scores were 5.48 for soil moisture status, 5.00 for current ground cover, 4.32 for chance of heavy rainfall event/s after a strategic tillage, 4.09 for next crop in rotation, 3.61 for chance of follow up rainfall, 3.16 for soil health, 2.34 for effectiveness of a previous strategic tillage.



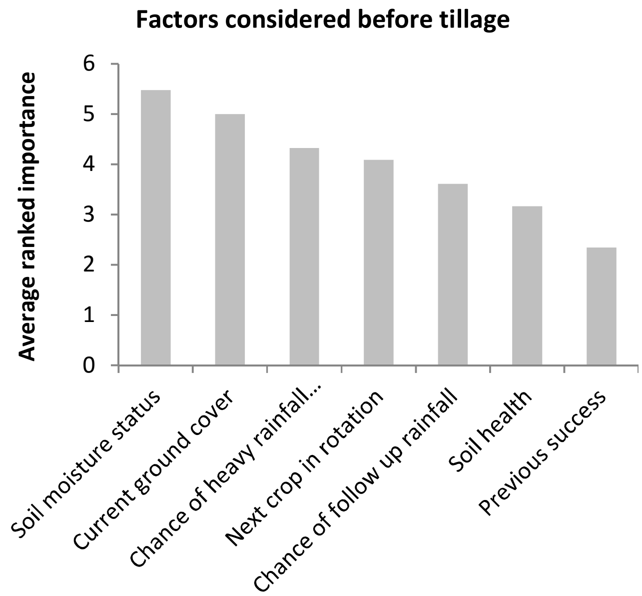


Figure 9: Major weeds which tillage was used to control in Northern NSW and QLD (left) and consideration of factors prior to tilling (right).

A heavy scarifier/chisel tine was the most used implement no matter the issue being addressed, and respondents felt that a high level of control was achieved irrespective of the issue being addressed. When respondents were asked what the effect a strategic tillage had on production and yield 30.2 percent identified a slight improvement in production of the proceeding crop and 7.0% said it improved greatly. 18.6% said yield reduced slightly and 2.3% said yield decreased greatly. 23.3% said yield did not improve or decrease and a further 18.6% said they were not sure.

Respondents almost unanimously responded that they would use a strategic tillage again to control weeds, to renovate rough country, herbicide resistance, integrated pest management and hard setting soils.

Winter 2012 Sites

Physical properties: Soil bulk density showed a mean decrease with both respective tillage treatments at Condamine and Moonie at 3 months after tillage. This result was not statistically significant due to the high variability of soil surface topography caused by tillage. At 12 months after tillage the Condamine site maintained this decrease which was significant. The Moonie site returned to a bulk density comparable to pre-till conditions. The two Vertosols, Hermitage and Biloela, showed no change in soil bulk density, as shown in Figure 10. Soil structure appeared to recover, indicated by no differences in bulk density observed at 12 or 24 months after tillage. Due to very low moisture in the soil at Condamine and Biloela, bulk density was not measured 36 months after tillage, however was assessed for gravimetric moisture. The Moonie site underwent and unexpected tillage and was excluded from soil collections in 2015. 36 months after tillage the Hermitage site showed no difference in bulk density between the strategically tilled and untilled control.

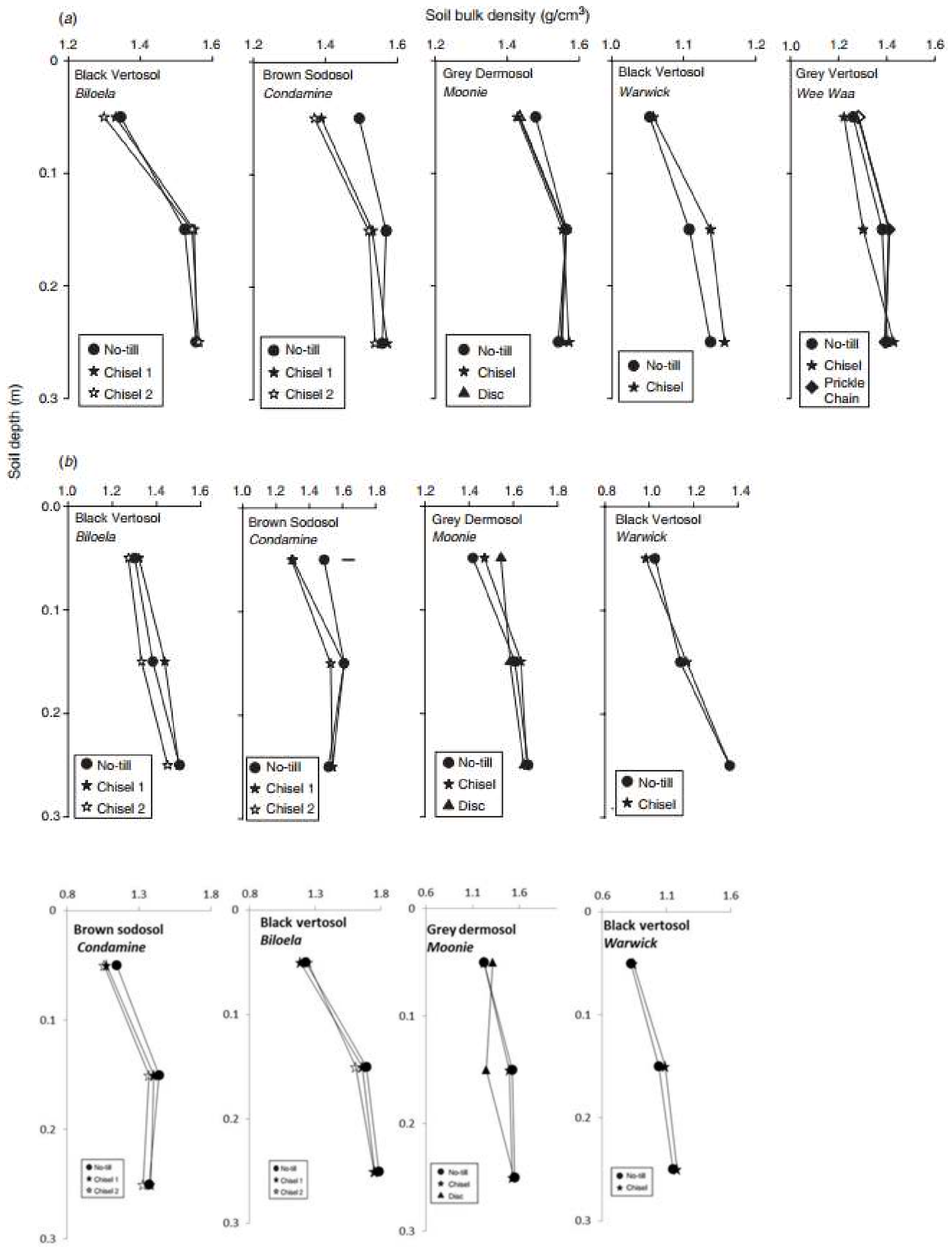


Figure 10: Soil bulk density at the winter 2012 sites 3 months (top), 12 months (center) and 24 months (bottom) after tillage. Horizontal bars indicate statistical difference at p<0.05.

Soil water content was not significantly impacted at all sites three months after imposition of tillage except for in the Black Vertosol at Warwick where there was a significantly negative impact in the 0-0.1 m layer. No differences in soil water content due to tillage treatments were observed prior to seeding in the winter season of 2013 or 2014. In comparison, three months after tillage (in the 2012 season) the Black Vertosol at Biloela demonstrated similar results after the repeat tillage treatment the following year. However, due to ongoing dry weather conditions, a comparison between the three and 12 month results was not possible for the Grey Vertosol at Wee Waa. (Figure 11). Although bulk density and gravimetric moisture did not change with tillage at the Hermitage site in 2015, there appeared to be a statistically significant increase in the volumetric moisture in the strategically tilled plots 36 months after tillage (data not shown). The reasons for this are unclear and was likely a sampling anomaly considering the lack of difference in the years prior.

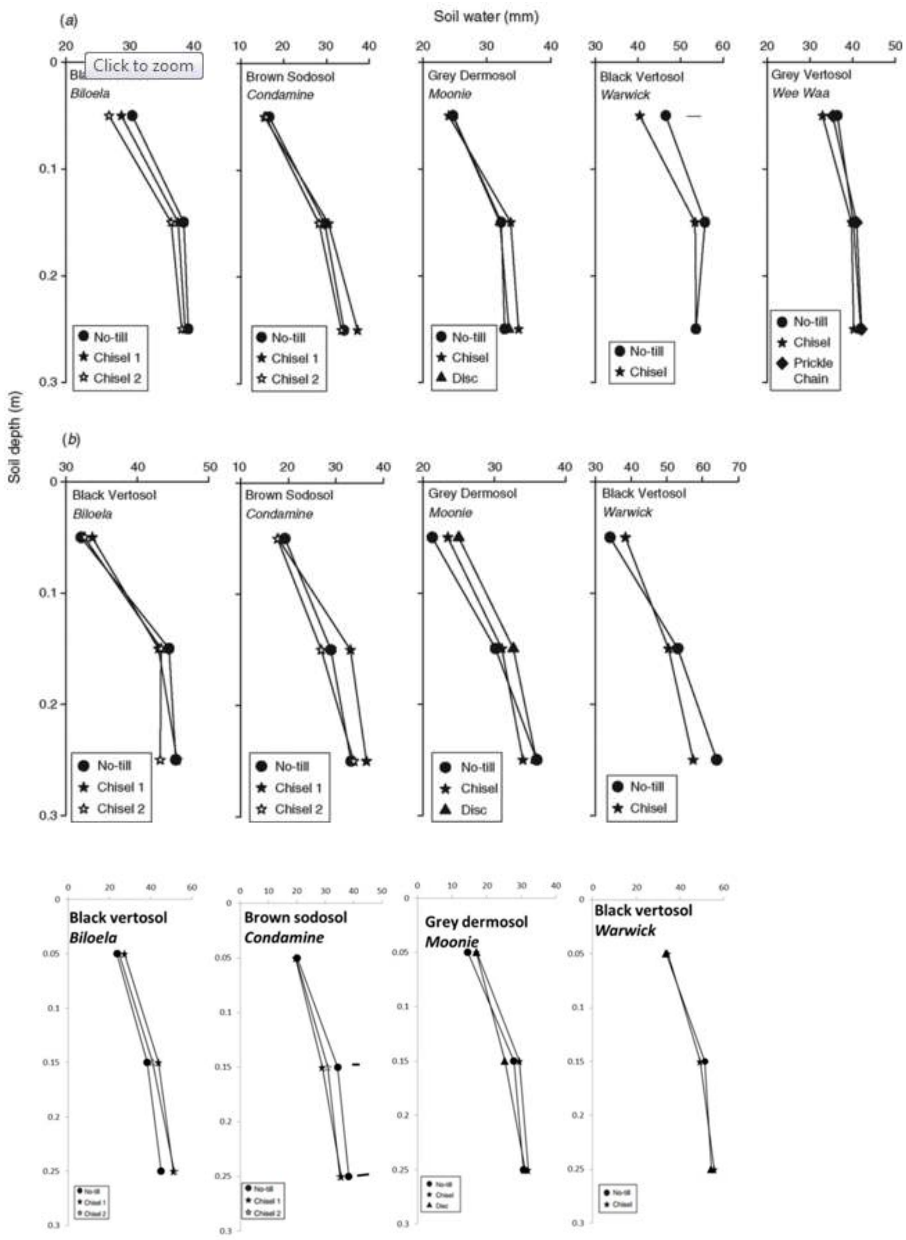


Figure 11: Volumetric moisture content, 3 (top), 12 (center) and 24 (bottom) months after tillage. Horizontal bars indicate significant difference at $p<0.05$.

The stability of aggregates at Moonie appeared to be reduced by the imposition of both single chisel and offset disc tillage, as indicated by the significant reduction in mean weight distribution (MWD) from the no till control, shown in Table 9. Despite this, the percent of aggregate fragments <125µm was not significantly decreased. Single or double pass tillage on the hard setting Sodosol at Condamine did not significantly affect the mean weight distribution, or fraction of aggregates <125µm.

Table 9: Aggregate stability at Condamine and Moonie 12 months' post-tillage; Differing lower case, superscript letters indicate significant difference at significant difference ($p<0.05$).

	Condamine		Moonie	
	MWD	% < 125µm	MWD	% < 125µm
No Till	0.744[a]	40.5[a]	0.519[a]	31.0[a]
Chisel 1 pass	0.730[a]	38.0[a]	0.393[b]	33.6[a]
Chisel 2 passes	0.645[a]	40.8[a]	-	-
Offset Disc	-	-	0.425[b]	32.9[a]

Infiltration rates were calculated on the % < 125µm size fraction recorded from the aggregate stability (Table 10). Only small changes in theoretical infiltration were seen, however may be significant in an in-situ circumstance. Both soils have generally weakly structured topsoil; however, the hard-setting nature of the Condamine Sodosol likely contributed to its higher resistance to the effects of tillage.

Table 10: Predicted infiltration rates at Condamine and Moonie.

	Condamine		Moonie	
	High energy rainfall (mm h^{-1})	Low energy rainfall (mm h^{-1})	High energy rainfall (mm h^{-1})	Low energy rainfall (mm h^{-1})
No Till	15.3	35.1	20.4	44.6
Chisel 1 pass	16.5	37.3	18.8	41.7
Chisel 2 passes	15.2	34.8	-	-
Offset Disc	-	-	19.3	42.5

Soil Chemical Properties: Three and 12 months after the imposition of tillage, available P (measured as Colwell extractable P) results were similar in the Brown Sodosol, Grey Dermosol and self-mulching Black Vertosol with only slight reductions observed. One-time tillage tended to lower available P in the surface 0-10 cm of soil at all sites prior to sowing in 2012. However, the difference was only significant at the Biloela site (Figure 12). On the Grey Vertosol at Wee Waa a non-significant increase in available P was observed in the prickle/disc chain treatment at all sampled depths compared to the chisel treatment where a non-significant decrease was observed. Repeat tillage of the Black Vertosol at Biloela after 12 months did not result in any significant reduction compared to the three-month sample in 2012. There was also a large concentration of available P found in the soil surface (0 – 0.1 m) at all sites relative to their sub soils. At 24 and 36 months after tillage there were no differences between untilled and tilled treatments (data not shown). Overall there were no significant differences in available P observed at all sites over the two-year sampling timeframe.

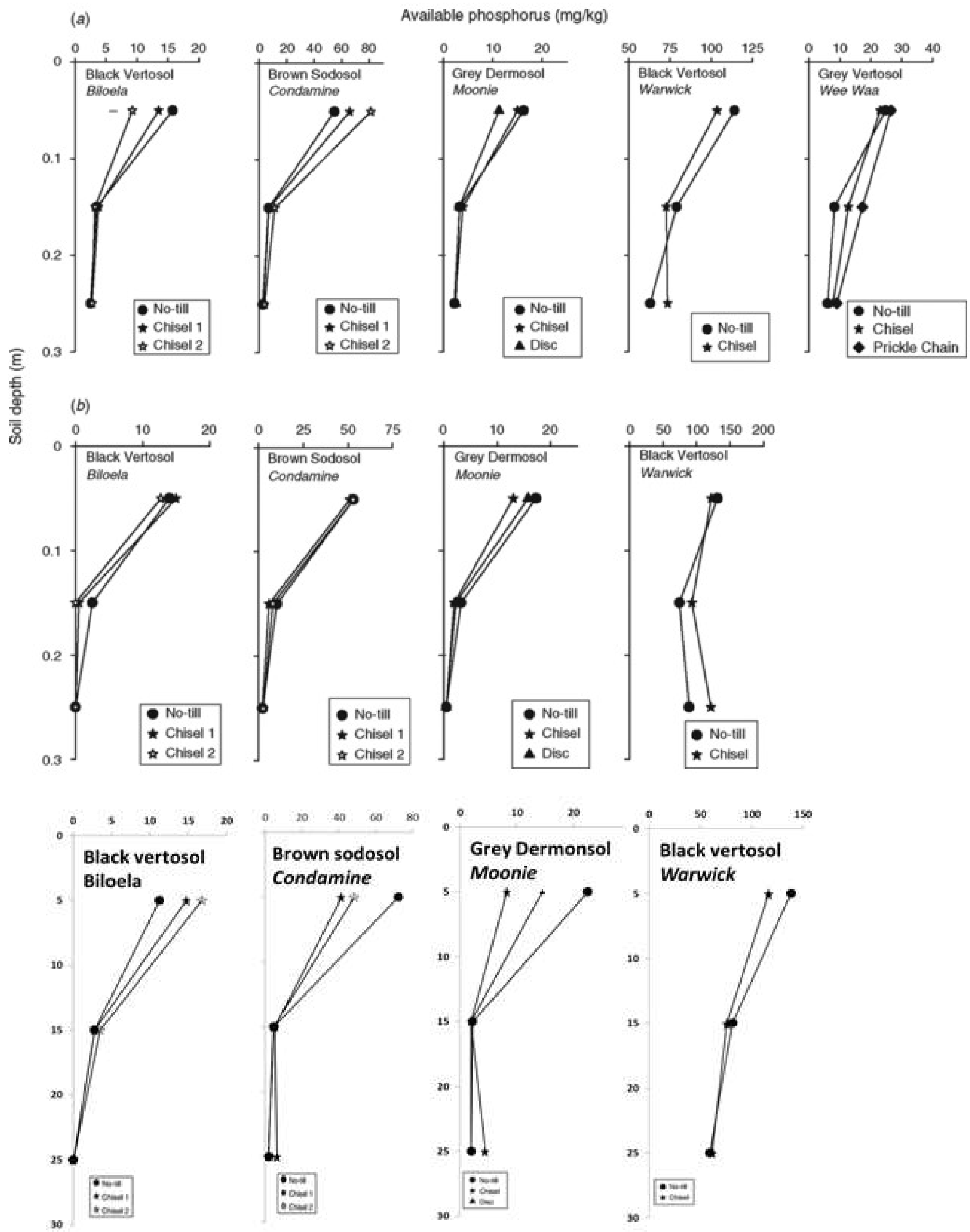


Figure 12: available P 3 (top), 12 (center) and 24 (bottom) months after tillage. 36 months after tillage no differences were evident. Horizontal lines indicate significant differences at p<0.05.

The effect of tillage on total organic carbon (TOC) was not significant ($P < 0.05$) for any treatment at any depth at all sites after three and 12 months, with the exception of Wee Waa (Fig. 13). In the Grey Vertosol at Wee Waa, a significant increase was observed in the prickle/disc chain treatment at 0-0.1 m and 0.1-0.2 m. This result may have been observed due to sampling anomalies, as the tillage treatment impacts only the 0-0.1 m layer and would not cause the differences seen at depth. Further sampling would address this but due to ongoing dry weather conditions this site has not been re-sampled. These results are consistent with several previous studies indicating that single or double pass occasional tillage is unlikely to have substantial impacts on the carbon status of the soil. Soil TOC was not affected by single or double pass tillage of any type in the 24 or 36 months after tillage at the sites sampled.

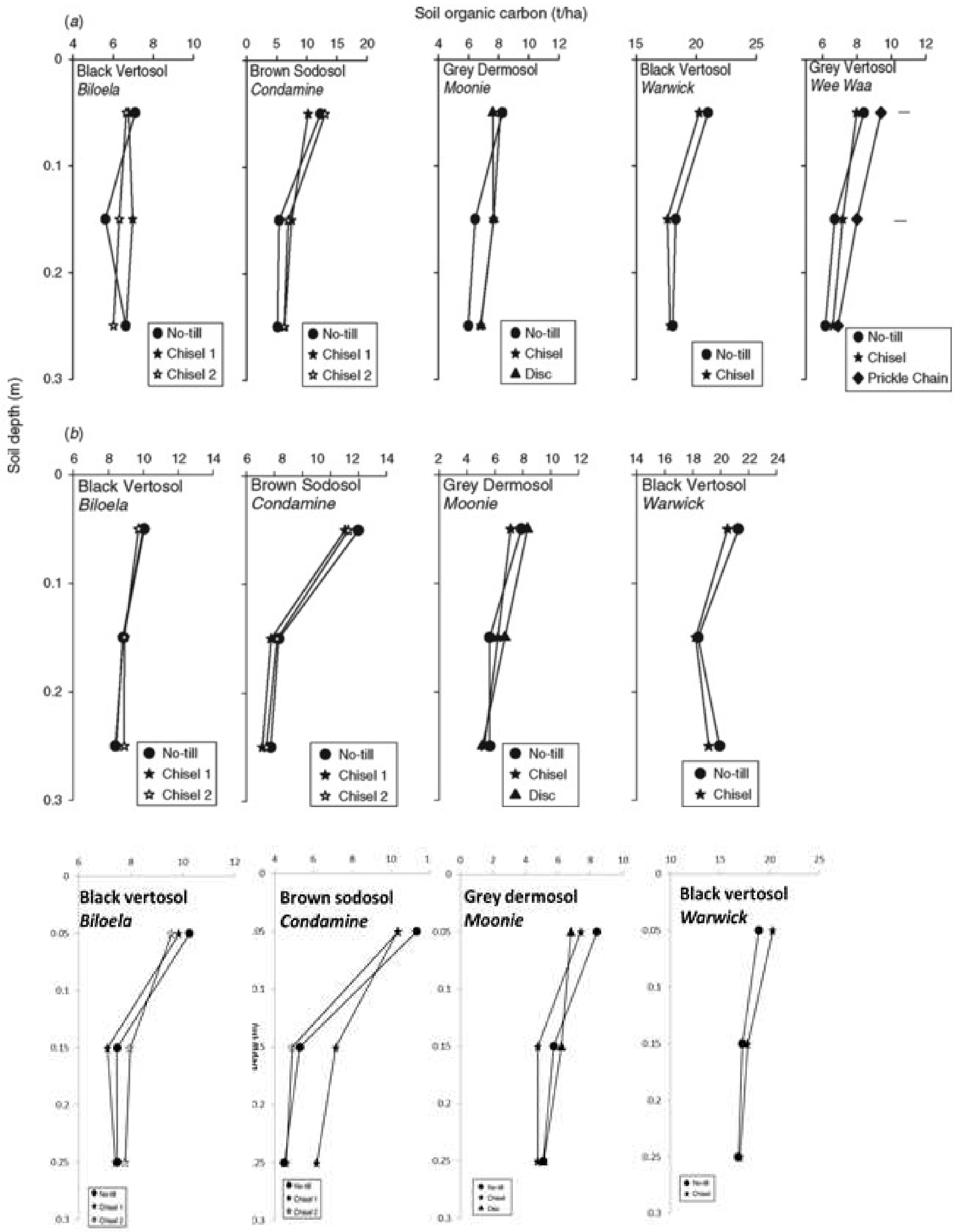


Figure 13: Soil organic carbon 3 (top), 12 (center) and 24 (bottom) months after strategic tillage. Horizontal lines indicate statistical difference t p<0.05

Particulate organic carbon showed a decreasing trend with single chisel passes, however no results were significant at the Condamine, Hermitage, Wee Waa or Moonie sites. At the Biloela site, 2 pass chisel tillage significantly decreased the particulate fraction in the 0-0.1m soil depth layer, as shown in

Table 11. Reduction was by an average of 41.9% with two chisel passes from the NT control. Single pass tillage reduced POC by 13.6% however this was not significant. As only the surface soil was assessed it is not clear whether this was redistributed to the lower depth layer, or oxidation resulted in loss of soil carbon.

Table 11: Particulate organic carbon levels, indicated in t/Ha. Differing lower case letters indicate a significant difference between treatments at a site, $p<0.05$.

	Biloela	Condamine	Moonie	Warwick	Wee Waa
No till	1.32[a]	3.21[a]	2.09[a]	2.00[a]	1.54[a]
Chisel 1 pass	1.14[a]	3.14[a]	1.90[a]	2.55[a]	1.35[a]
Chisel 2 pass	0.78[b]	2.63[a]	--	--	--
Offset Disc			1.58[a]		--
Kelly Chain	--	--	--	--	1.56[a]

Soil Biological properties: At the Moonie site, the main effect of tillage was not statistically significant (Fig. 14); however, there was a significant interaction between tillage and sampling depth (p = 0.016, ANOVA). This interaction was attributed to a slight increase in microbial biomass carbon (p = 0.042, +34.40%) by chisel tillage compared with the NT at 0-10 cm depth as shown in Figure 14. At 10-20 cm depth, however, chisel tillage did not influence MBC relative to the NT. Offset disc tillage did not influence microbial biomass carbon at either depth compared with the NT.

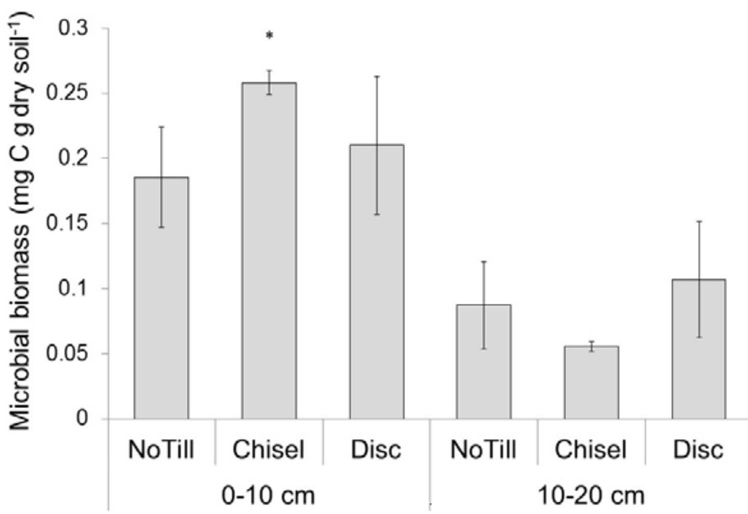


Figure 14: Microbial biomass carbon, Moonie. Shown are mean values (n=4) with SDs as error bars. The asterisk represents a statistically significant difference in comparison to the no-till control.

Tillage effects on total soil microbial activity at Moonie are shown in Figure 15 as the rate of FDA hydrolysis. No tillage effects on total soil microbial activity were observed. There appeared to be a higher microbial activity in the surface soil at all sites.

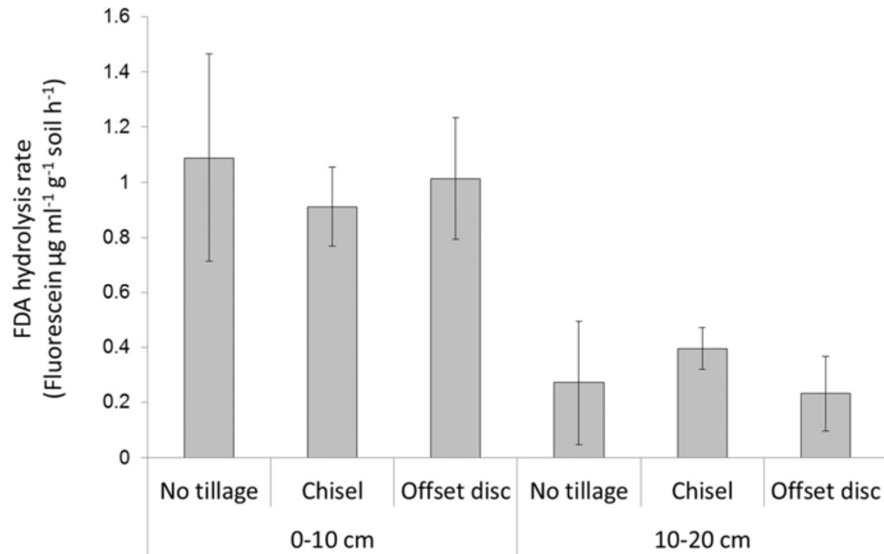


Figure 15: FDA Hydrolysis rate of soils at the Moonie site.

Tillage did not affect significantly affect microbial N or C biomass at the Condamine site. Significant differences existed between the 0-10cm depth and 10-20cm depths indicating that the majority of microbial biomass exists in the surface soil, Table 12. Similarly, there were no significant effects on soil total microbial activity caused by tillage at the Condamine site as indicated in Table 12.

Table 12: Variations of MBC (mg C g dry soil^{-1}), MBN (mg N g dry soil^{-1}), and TMA (fluorescein µg mL^{-1} g^{-1} soil h^{-1}) at the Condamine site. Differences between treatments indicated by lower case letters, and differences between depths with upper case letters, p<0.05. Errors represent standard deviations of each mean (n=4).

	Depth	No Till	Chisel 1	Chisel 2
MBC	0-10cm	0.49±0.11^{aA}	0.63±0.09^{aA}	0.63±0.06^{aA}
	10-20cm	0.13±0.03^{aB}	0.12±0.01^{aB}	0.09±0.01^{aB}
MBN	0-10 cm	0.015±0.006^{aA}	0.019±0.005^{aA}	0.019±0.010^{aA}
	10-20 cm	0.007±0.002^{aB}	0.008±0.002^{aB}	0.008±0.002^{aB}
TMA	0-10 cm	2.31±0.19^{aA}	2.36±0.33^{aA}	2.57±0.56^{aA}
	10-20 cm	0.85±0.14^{aB}	0.97±0.35^{aB}	1.52±0.47^{aA}

Tillage effects on total soil microbial activity are shown in Figure 16 for the Moonie site. The red box in Figure 17 indicates that the utilisation rate of D+ cellubiose was significantly greater in the chisel tilled soils (9.02 µg CO_2-C g^{-1} h^{-1}) when compared with the non-tilled control soils (3.24 µg CO_2-C g^{-1} h^{-1}) in the 0-10 cm depth. The blue box indicates a marginally significant (p = 0.079) higher average utilisation of carbon substrates in chisel tilled soils (8.42 µg CO_2-C g^{-1} h^{-1}) than non-tilled soils (4.87 µg CO_2-C g^{-1} h^{-1}) at 0-10 cm depth.

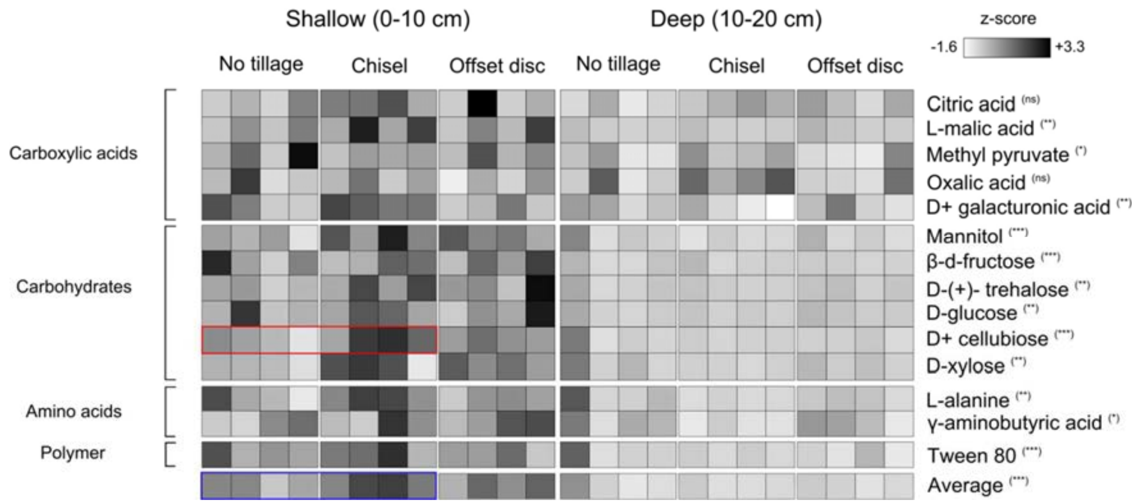


Figure 16: Heatmap summarising variation in the substrate utilisation profiles between samples at Moonie. The significance of this effect is reflected by the asterisks following each substrate name (*P* > 0.05 [(ns)], *P* < 0.05 [(*)], *P* < 0.01 [(**)], *P* < 0.001 [(***)]).

Substrate utilisation at the Condamine site was altered by tillage as shown in Figure 17. The green boxes indicate that the utilisation of β-d-fructose, D-glucose and L-malic acid were marginally significantly ($p < 0.1$) greater in the chisel-tilled soils at 10-20 cm depth when compared with that of the NT. The pink box showed a significantly higher average carbon substrate utilization rate in two-time chisel-tilled soils at 10-20 cm than that of the NT. Soil microbial respiration responded similarly to all compounds between depths other than oxalic acid.

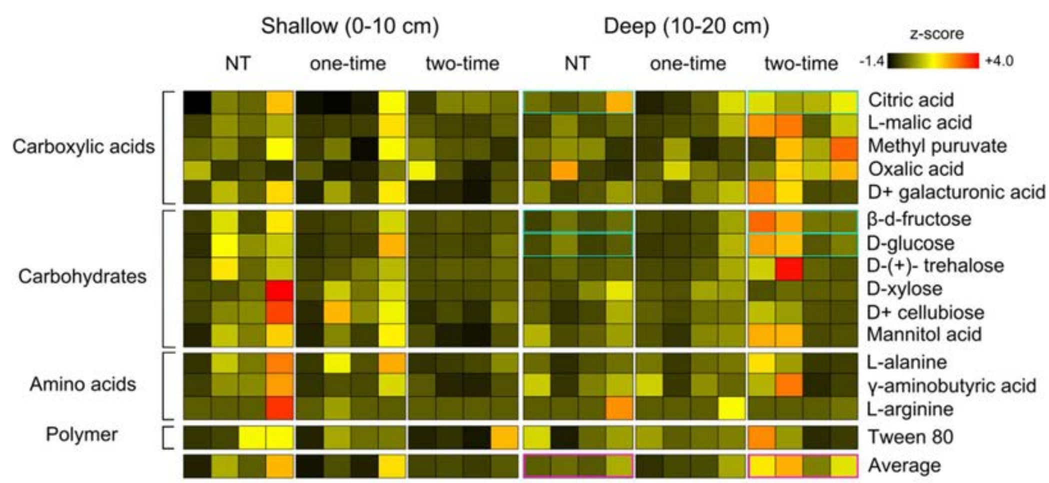


Figure 17: A heatmap summarising variation in the substrate utilization profiles between samples at Condamine based on the z-score transformed C-utilization (CO_2 evolution) data, p<0.1.

Tillage effects on soil microbial structure were shown in Figure 18 (Moonie), Figure 19 (Condamine). The community structures varied widely between the surface soil (0-10cm) and the subsoil (10-20cm). No significant changes were found based on tillage application.

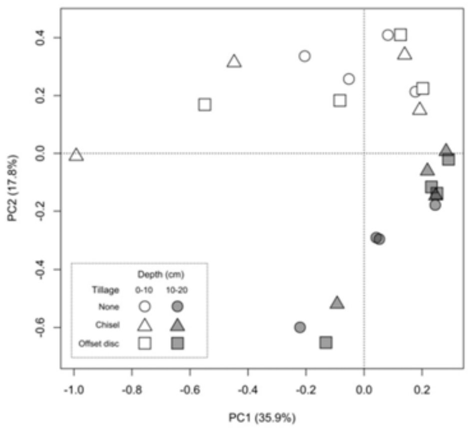


Figure 18: PCA ordination summarising differences in the composition of bacterial communities between samples as indicated by T-RFLP analysis of full-length 16S rRNA gene amplicons.

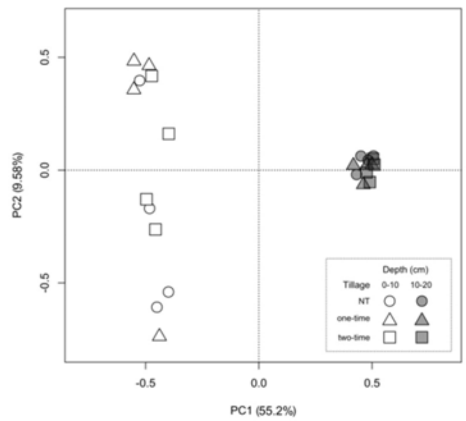


Figure 19: PCA ordination summarising differences in the composition of bacterial communities between samples as indicated using T-RFLP analysis of full-length 16S rRNA gene amplicons

Strategic tillage did not affect the mycorrhizal associations at the Hermitage site. Furthermore, the use of strategic tillage did not affect the nematode populations in soil as indicated in Table 13.

Table 13: Effect of tillage treatments on the number of *P. thornei* with ln(x+1) transformed means that are not significantly different at P=0.05 level (back transformed means in parenthesis) followed by the same subscript (Lai, 2013).

Tillage Treatments	Mean
No-till_ Untilled treatments (NT_UT)	4.31 (73.3)[a]
No-till_ Strategic ally tilled treatments (NT_ST)	3.57 (34.4) [a]
LSD (5%)	2.15

Agronomic measurements: Weed population was significantly decreased 3 months after tillage at Biloela, Condamine, and Moonie. 12 months after tillage there was maintained decreases in weed density at Biloela for 1 and 2 pass chisel treatments. At Moonie no differences were apparent 12 months after tillage. At Condamine there was a significant increase in weed density with 2 chisel passes and a non-significant increase with 1 chisel pass 12 months after tillage. At Condamine the predominant weed species which was increased were African Turnip Weed, Indian Hedge Mustard, and milk thistle. Residual effects of tillage do not appear to last more than 24 months, as indicated by the lack of statistical difference in weed populations 24 months after tillage at all sites (Table14). Establishment of plants was not significantly different at the first or second sowing after tillage at any site, with any treatment.

Table 14: Average in-crop weeds population (number/m^2) 3, 12, and 24 months after tillage in long-term NT. Within sites, means followed by the same letter do not differ significantly at p < 0.05. Lower case letters depict comparisons between treatments in the same sampling season

	Biloela			Condamine			Moonie			Warwick		
Months	3	12	24	3	12	24	3	12	24	3	12	24
NT	10.5[a]	3[a]	14.5[a]	14.5[a]	4.5[a]	0.75[a]	9.2[a]	0.75[a]	0.5 [a]	-	2.4[a]	-
Chisel 1 pass	1.25[b]	0.3[b]	19.4[a]	2.25[b]	23.4[b]	1.62[a]	1.0[b]	0.125[a]	0.62 a	-	4.4[a]	-
Chisel 2 passes	4.25[c]	0.2[b]	25.5[a]	6.5[c]	15.6[a]	0.87[a]	-	-	-	-	-	-
Offset disc	-	-	-	-	-	-	1.2[b]	0.25[a]	1.5 [a]	-	-	-

Figure 20: Population of *Sonchus oleraceus* in *Triticum aestivum* crop in (a) long-term NT plots, and (b) long-term NT plots with strategic one-time tillage at the Biloela trial site.

Figure 21: No till (left) showing presence of established fleabane, vs 2x chisel tillage (right).

There were positive trends observed in productivity for the Black Vertosol at Biloela (wheat), Grey Dermosol at Moonie (barley), Black Vertosol at Warwick (wheat) and the Grey Vertosol at Wee Waa (wheat) after one pass of the chisel tine; however, these were not statistically significant. The Brown Sodosol at Condamine recorded a marginally significant increase in chickpea yield (1.07 – 1.16 t/ha) after a single chisel treatment (P = 0.08), but the second tillage did not further improve or reduce productivity. Grain yields overall showed no statistical differences in response to tillage in the 2012 season (Table 15). In 2013, 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 weed population. Weed density and the impact of tillage on weed populations is a likely cause for the increase in yield seen on the Black Vertosol at Biloela, Grey Dermosol at Moonie and the Black Vertosol at Warwick. No statistically significant changes in yield were noted at 24 months after tillage.

Table 15: Yields (t/ha) for core sites. Differing lower case letters in a given year and site, indicate significant differences at p<0.05. [1]Wheat grain; [2]Chickpea grain; [3]Barley grain, [4]Sorghum.

	Biloela				Condamine			Moonie			Warwick		
	2012[1]	*2013[2]*	*Apr 2014[4]*	*Oct 2014[1]*	*2012[2]*	*2013[1]*	*2014[1]*	*2012[3]*	*2013[2]*	*2014[2]*	*2012[1]*	*2013[1]*	*2014[1]*
No-Till	2.66[a]	2.02[a]	2.48[a]	1.49[a]	1.05[a]	1.51[a]	0.73[a]	2.27[a]	0.66[a]	3.6[a]	2.75[a]	3.02[a]	0.14[a]
Chisel 1 pass	2.75[a]	2.13[a]	2.43[a]	1.55[a]	1.14[b]	1.48[a]	0.71[a]	2.42[a]	0.71[a]	3.31[a]	2.85[a]	3.39[a]	0.38[a]
Chisel 2 pass	2.72[a]	2.16[a]	2.53[a]	1.42[a]	1.16[b]	1.39[a]	0.71[a]	-	-	-	-	-	-
Offset Disc	-	-	-	-	-	-	-	2.37[a]	0.64[a]	3.34[a]	-	-	-

Based on farmer costs of tillage for the 2012 season the net returns per hectare from one-time tillage using either chisel or offset disc in long-term no-till systems were estimated to range from $-24.9 to $103.6 due to yield differences (Table 16). Condamine, Moonie and Warwick long term net gains were $28.65 – $103.6 (Chisel 1 pass); net losses $2.52 – $24.9 (Offset Disc and Chisel 2 passes). Long term costs were calculated on the initial cost: benefit of tillage together with 2013 yield differences. At Biloela, where a repeat tillage occurred there was a net gain due to increased yield and high chickpea prices.

Table 16: Impacts of strategic tillage on the profitability (± $/ha) of cropping in long-term no till systems.

	Biloela				Condamine			Moonie			Warwick		
	2012[1]	2013[2]	Apr 2014[4]	Oct 2014[1]	2012[2]	2013[1]	2014[1]	2012[3]	2013[2]	2014[2]	2012[1]	2013[1]	2014[1]
Chisel 1	-3.75	40.1	-11.5	16.2	36.9	28.5	-5.7	22.7	48.5	-116	11.1	103.6	64.8
Chisel 2	-12.5	40.3	11.1	-18.9	8.7	-24.9	-5.7	--	--	--	--	--	--
Offset Disc	--	--	--	--	--	--	--	5.73	-2.52	-104	--	--	--

Modelling of predicted yield outcomes is shown in Table 17. In the majority of cases the lack of significant differences predicted was consistent with the lack of significant difference of true yield. Deviations to this were for the true versus predicted chickpea yield at Condamine in 2012. The prediction was for no differences, however true yield was significantly increased in both the single and double pass chisel strategic tillages. Also in 2012, at the Biloela site, there was no significant increase in the true yield of the chisel 2 pass treatment that was predicted by APSIM modelling.

Table 17: Table of predicted means (T/Ha) for Wheat, Chickpea and Sorghum for the strategic tillage trial. Numbers followed by the same letter within a column are not significantly different at $P<0.05$

Crop	Site	Year	Tillage operations		
Wheat			*Once*	*Twice*	*No-till*
	Biloela	2012	2.744[a]	2.658[a]	2.729[a]
	Biloela	2014	1.367[a]	1.552[a]	1.326[a]
	Condamine	2013	1.477[a]	1.392[a]	1.722[a]
	Condamine	2014	0.708[a]	0.708[a]	0.733[a]
	Warwick	2012	3.14[a]	-	3.103[a]
	Warwick	2013	3.394[a]	-	3.023[a]
	Wee Waa	2012	1.508[a]	-	1.459[a]
Chickpea					
	Biloela	2013	2.059[a]	2.228[b]	1.988[a]
	Condamine	2012	1.165[a]	1.139[a]	1.069[a]
	Moonie	2013	0.674[a]	-	0.658[a]
Sorghum					
	Biloela	2013	2.442[a]	-	2.543[a]

Environmental impacts: Howleaky? predictive models indicated that in 2012, the average annual sediment delivery off site (t/ha) is represented by (A); and simulated annual runoff (mm) is represented by (B), in Table 18. The Condamine site recorded the largest average annual sediment delivery off site (t/ha) and simulated annual runoff (mm). Tillage increased predicted sediment loss at all sites, with all treatments. Additionally, there was increased run-off with all tillage treatments.

Table 18: Results of *Howleaky?* simulation to predict sediment and water runoff for the period 2000-2013.

	Biloela		Condamine		Moonie		Warwick		Wee Waa	
	A	B	A	B	A	B	A	B	A	B
No-Till	0.20	33.3	1.1	56.9	0.28	18.3	0.13	14.9	0.29	33.1
Chisel 1	0.21	33.7	1.2	57.2	0.28	18.6	0.14	15.3	0.30	33.5
Chisel 2	0.21	33.8	1.2	57.3	-	-	-	-	-	-
Offset disc	-	-	-	-	0.28	18.6	-	-	-	-
Chain harrows	-	-	-	-	-	-	-	-	0.30	33.7

Winter 2013 Sites

Physical properties: At the Jimbour site, tillage had varying short term effects on soil bulk density depending on the type and timing of tillage as indicated in Figure 21. 3 times chisel (TF3) and disc tillage (DF3) increased bulk density, 2 times chisel tillage (TF2) decreased bulk density, and chisel tillage in January (TT2) also increased bulk density in the surface soil. At depth there were increases due to two pass chisel tillage (TF2), in the February tillage treatment (TT3), and in the three pass disc treatment (DF3). After 12 months no statistical differences were evident, indicating rapid recovery of the soil. The majority of effects were confined to the surface soil. At the Biloela site there were no statistical differences in bulk density in the 3 or 12 months after any tillage treatment, or at the Moree site. Despite this, trends emerged which indicated that soil bulk density was more greatly affected by the cultivator (CCA, CCM) as opposed to the Kelly Disc Chain (DCM, DCA) at the Moree site, and any indications of this were restricted to the surface soil.

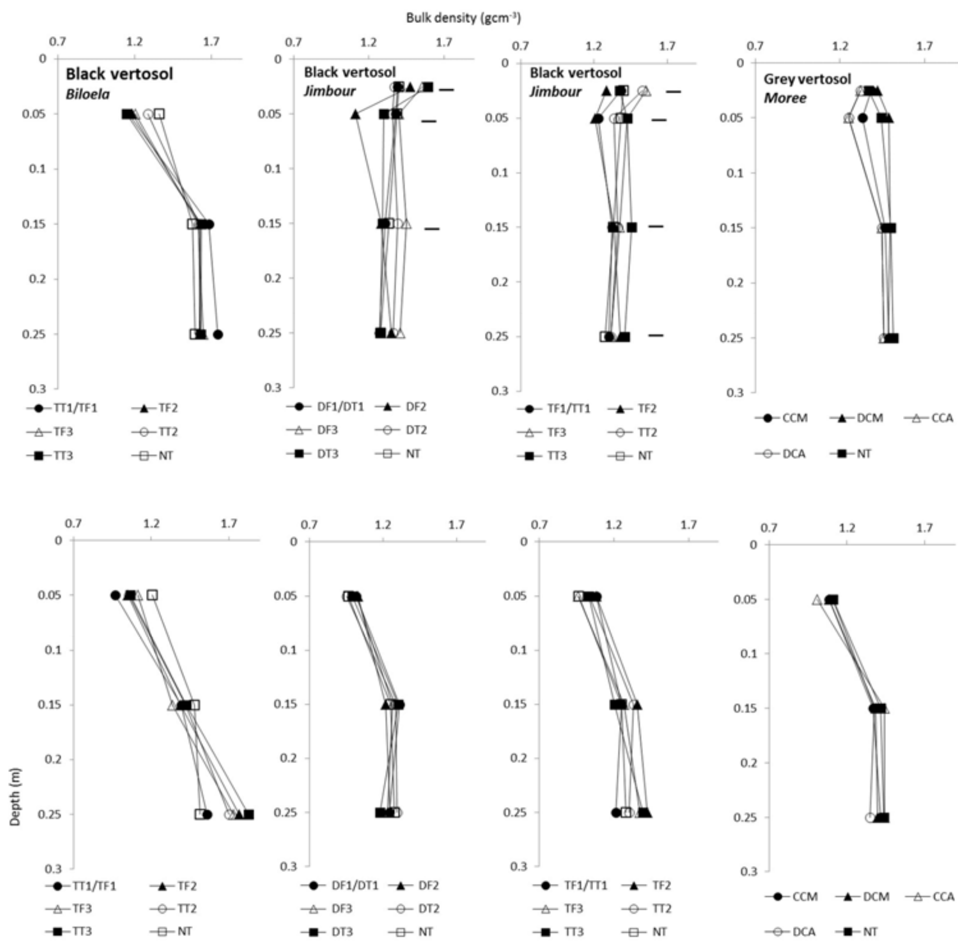


Figure 21: Soil bulk density 3 months (top), and 12 months (bottom) after tillage at sites. Horizontal bars indicate significant difference from the NT control within a site at p<0.05.

Soil moisture appeared to be variably affected at the Jimbour site (Figure 22). It appeared that the changes in volumetric moisture closely reflected the significant changes in bulk density; hence the alterations may have been caused due to soil compaction and not changes in moisture holding capacity. Results from the gravimetric moisture analysis confirm this, based on the lack of statistical significance of gravimetric moisture with treatment. There appeared to be no differences 12 months after tillage at the Jimbour site which would indicate rapid recovery if soil moisture was lost.

At the Moree site, any differences in volumetric moisture content were restricted to the surface soil. 3 months after tillage there were no significant differences in soil volumetric moisture with any tillage treatment, as indicated in Figure 22. In the following year small decrease with Kelly disc chain application (DCA) resulted in reduced moisture. Although statistically significant, this result is likely not agronomically significant, as the difference was <3mm. Overall effects were minor and in the majority of cases not significant. At the Biloela site moisture was not affected by tillage in either year, by any treatment.

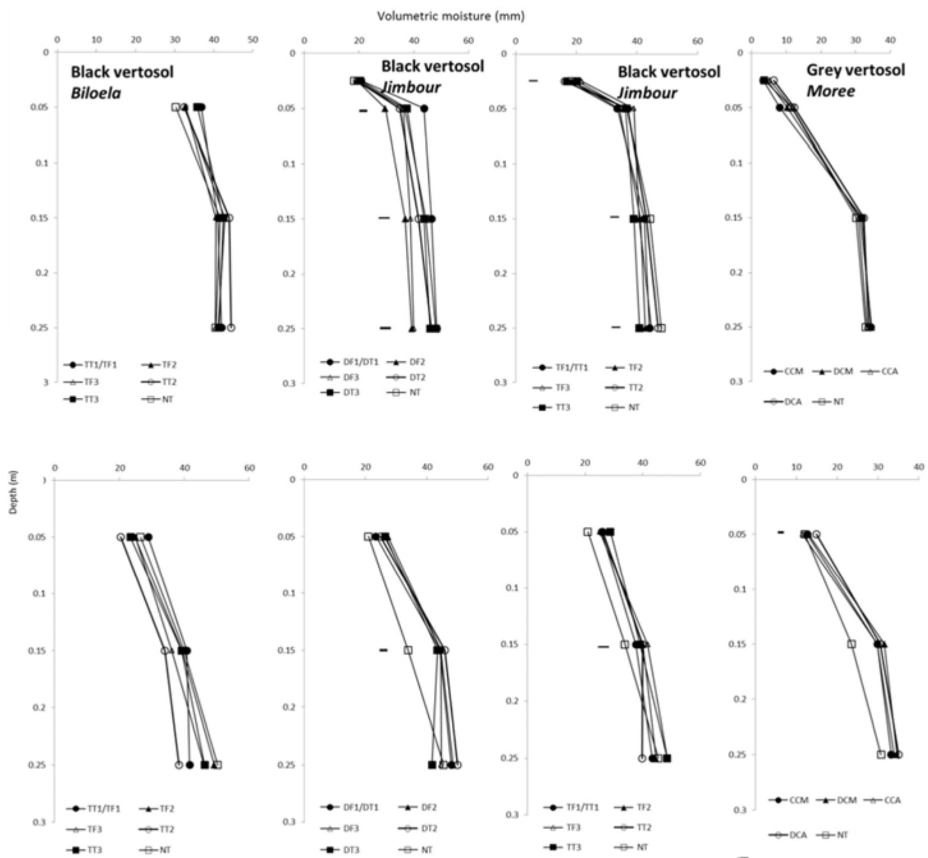


Figure 22: Soil volumetric moisture 3 months (top), and 12 months (bottom) after tillage at sites. Horizontal bars indicate significant difference from the NT control within a site at p<0.05.

Predicted soil moisture losses based on APSIM modelling for the Biloela site indicate that there should be little to no moisture loss on a wheat-fallow cropping rotation following a strategic tillage, in a simulation period from 1961-2013. From the data it appears that tillage closer to sowing results in an overall risk of soil moisture loss, although this was not significant. Results are shown in Table 18. The largest risk was at the Moree site, with the highest moisture losses being in the 30% wettest years.

Table 18: Predicted moisture losses with different strategic tillage practice of 1 month before sowing (mbs), 3mbs, and 5mbs.

	NT	Reduction in soil moisture (mm)		
Biloela		1 mbs	3 mbs	5 mbs
30% driest years	633	0	0	0
Average years	634	0	0	0
30% wettest years	637	0	0	0
Mean	635	0	0	0
Dalby (Jimbour)				
30% driest years	877	0	0	0
Average years	874	0	0	1
30% wettest years	879	0	0	0
Moree				
Mean	876	0	0	1
30% driest years	671	1	1	2
Average years	678	1	2	3
30% wettest years	674	1	1	4
Mean	673	1	2	3

Soil chemical properties: 3 months after tillage there were several significant changes in phosphorous concentration at the Jimbour site. Cultivation-type tillage appeared to increased available P in the TF2, TF3, TT2, and TT3 treatments in the 0-5cm depth layer, and TF2, TF3, and TT2 in the 5-10cm depth layer. The only decline was noted in the January disc tilled plots (DT2) at the 0-5cm depth. These results are indicated in Figure 23. These changes were no longer evident after 12 months. All plots showed significant stratification of phosphorous in the 0-10cm layer which was not ameliorated by any tillage treatments. Phosphorous stratification remained 12 months after tillage. At the Moree and Biloela sites tillage had no impact on soil available phosphorous either 3 or 12 months after tillage.

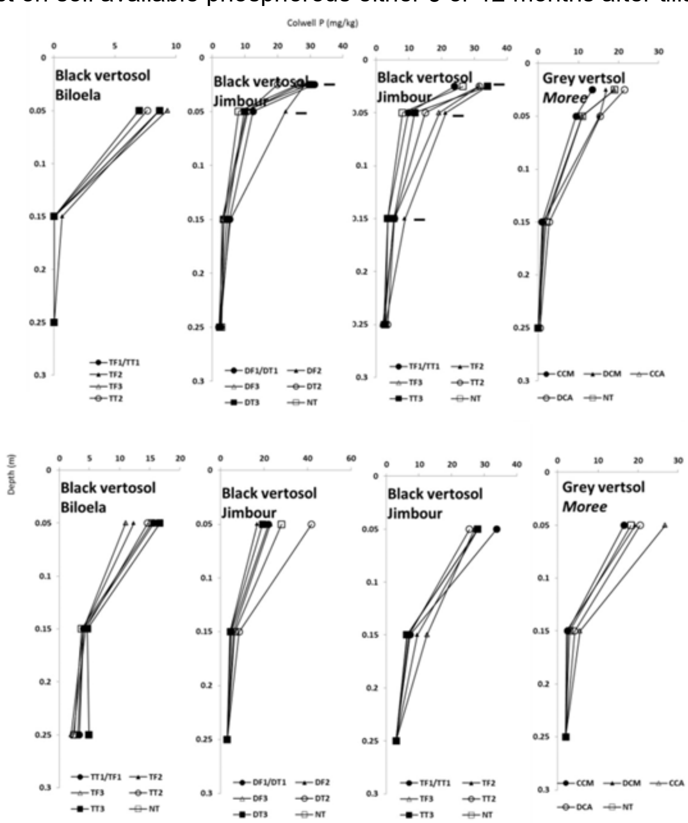


Figure 23: Available Colwell P (mg/g soil) with tillage treatments. Horizontal bars indicate significant differences at p<0.05.

Three months after tillage there were no significant changes in TOC neither at Moree, Jimbour nor at the Biloela site (Figure 24). Subsequent samplings at 12 months after tillage also showed no significant changes to soil carbon associated with tillage. Sampling below 20cm was not possible at 24 months after tillage at the Jimbour site.

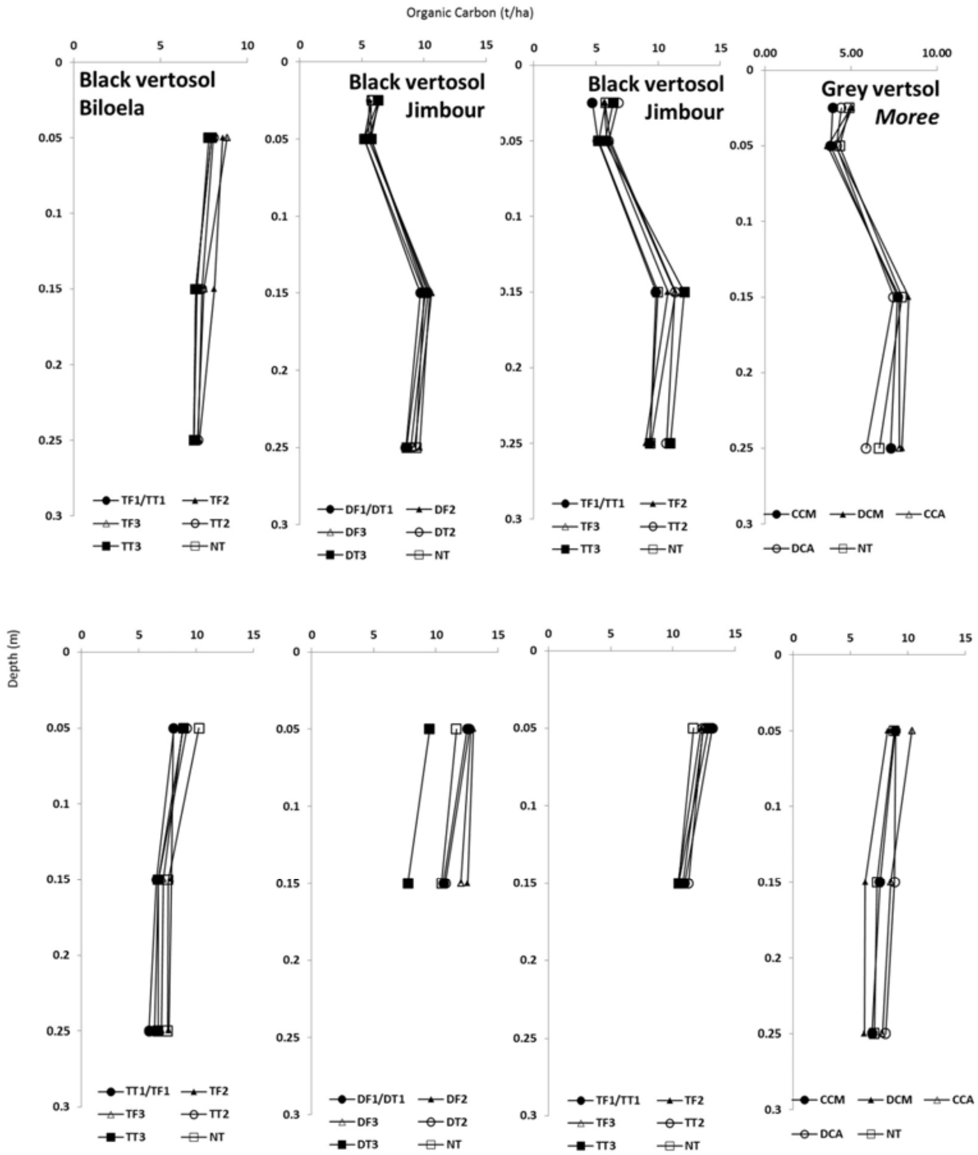


Figure 24: Soil total organic carbon 3 (top) and 12 (bottom) months after tillage. No significant differences were seen at p<0.05.

Results of pH and EC analyses at Moree showed significant changes with tillage. Soil EC (p<0.10) and pH (p<0.05) appeared to be affected by tillage in the 3 months' post tillage. pH was increased in the 0.1-0.2m depth layer with both cultivation treatments, in addition to an increase in the 0.2-0.3m layer with cultivation treatments in both March and April (CCM, CCA), and the late stage (April) Kelly disc chain tillage (DCA), as indicated in Table 19.

Table 19: Effect of tillage on soil pH at Moree. Differing lower case letters indicates statistically different from the NT control at $p<0.05$.

	0-0.05m	0.05-0.1m	0.1-0.2m	0.2-0.3m
T1-No Till	7.23 ^{a}	7.25 ^{a}	7.85 ^{a}	8.23 ^{a}
CCM	7.43 ^{a}	7.75 ^{a}	8.35 ^{b}	8.65 ^{b}
DCM	7.33 ^{a}	7.33 ^{a}	7.78 ^{a}	8.4 ^{a}
CCA	7.48 ^{a}	7.50 ^{a}	8.25 ^{b}	8.7 ^{b}
DCA	7.43 ^{a}	7.20 ^{a}	7.65 ^{a}	8.55 ^{b}

Changes in EC resulted in significant reductions in depth layers to 0.2 in the April tillage using Kelly disc chain (DCA). Reductions also occurred in the 0-0.1m depth layer in the April cultivation (CCA), and the 0.1-0.2m depth layer of the Kelly chain treatment in March (DCM). The only significant increase seen was in the April cultivation (CCA) at 0.1-0.2m, shown in Table 20.

Table 20: EC (dS/m) changes associated with tillage at the Moree site, 3 months' post-tillage. Differing lower case letter indicates a significant change from the NT control at the given depth, $p<0.05$.

Treatment	0-0.05m	0.05-0.1m	0.1-0.2m	0.2-0.3m
T1-No Till	0.1 ^{a}	0.1 ^{a}	0.09 ^{a}	0.12 ^{a}
CCM	0.08 ^{a}	0.08 ^{a}	0.11 ^{a}	0.14 ^{a}
DCM	0.11 ^{a}	0.07 ^{b}	0.11 ^{a}	0.14 ^{a}
CCA	0.08 ^{b}	0.11 ^{a}	0.12 ^{b}	0.18 ^{a}
DCA	0.07 ^{b}	0.05 ^{b}	0.06 ^{b}	0.13 ^{a}

At Biloela, 3 months after treatment, there were no significant differences in soil TOC % or available P caused by tillage; however, P stratification was also evident at this site. At Biloela pH and EC were not affected by tillage. This may suggest that the interaction with tillage and climate or other factors is important and determining the pH and EC responses, shown by the different responses at Biloela and Moree.

Soil biology: Soil microbial biomass in the surface soil was not impacted by tillage at the Moree site (Table 21). There was higher microbial biomass in the surface soil, consistent with nutrient stratification. Enzymatic activity, as indicated by FDA (fluorescein diacetate) hydrolysis, was not affected by tillage at the Moree site, also shown in Table 21. Similarly, the Biloela site did not have significant alterations in total microbial enzymatic activity following tillage in the 0-10cm soil layer (results not shown).

Table 21: Impacts of ST on microbial biomass carbon (mg C g dry soil^{-1}) and FDA hydrolysis rate (fluorescein µg mL^{-1} g^{-1} soil h^{-1}) at Moree. Error represent standard deviations (n = 4). Lower and upper case letters indicate differences between tillage treatments and soil depths, respectively, $p<0.05$.

	Depth	NT	CCM	DCM	CCA	DCA
MBC	0-0.1m	0.10±0.02^{aA}	0.11±0.00^{aA}	0.11±0.01^{aA}	0.12±0.01^{aA}	0.13±0.03^{Aa}
	0.1-0.2m	0.04±0.02^{aB}	0.04±0.01^{aB}	0.04±0.00^{aB}	0.03±0.01^{aB}	0.02±0.01^{Ab}
FDA	0-0.1m	0.67±0.06^{Aa}	0.60±0.03^{aA}	0.76±0.11^{aA}	0.69±0.12^{aA}	0.76±0.06^{aA}
	0.1-0.2m	0.44±0.10^{aB}	0.36±0.07^{aB}	0.35±0.04^{aB}	0.46±0.06^{aB}	0.41±0.03^{Ab}

Eight carbon substrates including β-d-fructose, D-(+)-trehalose, D-glucose, L-malic acid, D-xylose, D+ cellubiose, L-alanine and mannitol were utilized differentially between depths. Substrate utilisation by the microbial community was not affected by tillage at the Moree site, as indicated in Figure 25. Figure 26 shows the principle component analysis of the microbial community composition. Large differences were evident between the two soil depths; however, no consistent trends emerged between the treatments.

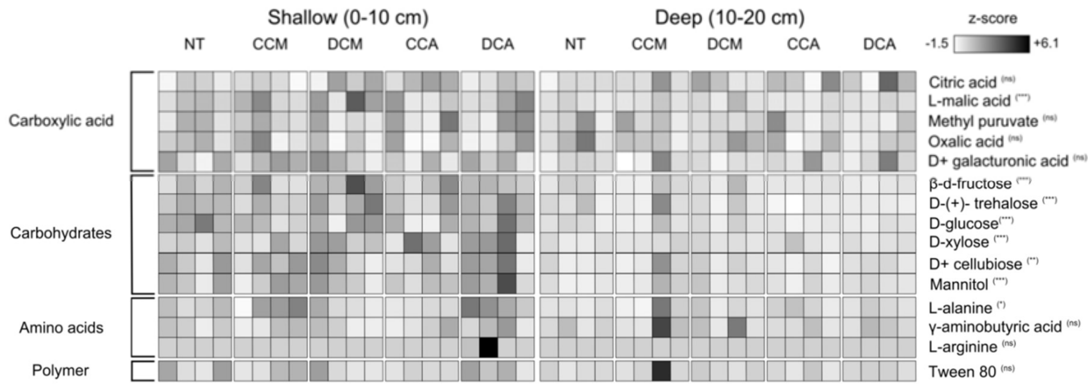


Figure 25: Heatmap summarising variation in the substrate utilisation profiles between samples based on the z-score transformed C-utilization (CO_2 evolution) data. The significance of this effect is reflected by the asterisks following each substrate name ($P > 0.05$ (ns), $P < 0.05$ (*), $P < 0.01$ (**), $P < 0.001$ (***)).

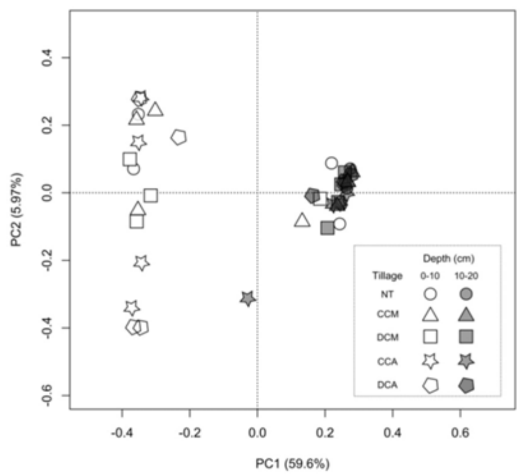


Figure 26: A principle component analysis (PCA) ordination summarising variation in the composition of bacterial communities between samples based on the T-RFLP analysis of full-length 16S rRNA gene amplicons.

Length of AM associated roots per plant was decreased with tine tillage at the Jimbour site, however only significantly at in the TF1 treatment after the first sampling (Table 22). No differences were observed at the second sampling (Table 23). No *P. thornei* were found at the Jimbour site for assessment, however there was no effect on free living and other nematodes.

Table 22: Impact of different tillage operations at different times and frequency on arbuscular mycorrhizal fungal communities at first sampling in Jimbour, Queensland with back transformed means in parentheses. Differing superscript letter indicate significant difference at p<0.05.

Treatments	Colonization	Length of roots	Length of AM roots	Dry weight of tops
DF1/DT1	24.4	6.27 (526)	4.85 (127)[a]	0.914
DF3	19.8	6.38 (591)	4.72 (111)[a]	1.06
DT3	21.3	6.57 (710)	4.98 (144)[a]	1.00
NT	21.9	6.28 (534)	4.74 (114)[a]	0.905
TF1/TT1	17.5	5.89 (362)	4.01 (54)[b]	1.20
TF3	12.4	6.32 (557)	4.20 (66)[a]	1.03
TT3	16.3	6.31 (547)	4.50 (89)[a]	1.21

Figure 27: AM colonization of wheat roots (left) under 20x magnification, and *P. thornei* (right), under stereomicroscope.

Table 23: Impact of different tillage operations at different times and frequency on arbuscular mycorrhizal fungi communities at second sampling in Jimbour, Queensland with back transformed means are shown in parentheses, differing superscript letters indicate significant difference at $p<0.05$.

Treatments	% colonization level	length of root /plant (cm)	length of AM roots /plant (cm)	dry weight of tops/plant (g)
DF1/DT1	36.8	6.77(866)	5.76(317)^{a}	3.47
DF3	42.7	7.36(1574)	6.51(670)^{a}	5.19
DT3	39.8	7.36(1574)	6.43(619)^{a}	5.21
NT	36.7	6.69(802)	5.64(282)^{a}	4.05
TF1/TT1	31.3	6.95(1037)	5.72(303)^{a}	4.04
TF3	33.7	7.55(1906)	6.46(637)^{a}	6.36
TT3	31	7.17(1305)	5.97(389)^{a}	5.57

Agronomic measurements: At the Moree trial site, both single and double pass Kelly disc chain or chisel tillage trended toward a decrease in weed density 3 months' post-tillage, however results were non-significant. Similarly, at Jimbour, one, two, or three passes did not significantly reduce weed density using either offset disc or chisel. Despite the lack of statistical significance, the general trend was for reduced weed pressure both 3 and 12 months after the initial tillage event, as shown in Table 24. At Biloela, an unusually low weed pressure in the first year of tillage led to no significant results. 12 months' post tillage, at both different tillage frequencies and timings, no statistical significant changes were evident. Establishment was not affected by tillage at any of the summer trial sites.

Table 24: Average in-crop weeds population (number/m^{2}) 3 and 12 months after frequency tillage in long-term NT at different frequencies and timings. Differing superscript letters indicate significant difference sat $p<0.05$ within a site and year.

	Jimbour		Biloela			Jimbour		Biloela			Moree
	3	12	3	12		3	12	3	12		3
NT	2.3^{a}	1.1^{a}	0.1^{a}	4.0^{a}	NT	2.3^{a}	1.1^{a}	0.1^{a}	4.0 ^{a}	NT	2.4^{a}
TF1/TT1	0.6^{a}	0.3^{a}	0.0^{a}	4.7^{a}	TF1/TT1	0.6^{a}	0.3^{a}	0^{a}	4.7 ^{a}	CCM	0.8^{a}
TF2	0.5^{a}	1^{a}	0.0^{a}	4.8^{a}	TT2	1.0^{a}	1.0^{a}	0^{a}	4.7 ^{a}	CCA	0.9^{a}
TF3	0.8^{a}	0.9^{a}	0.0^{a}	9.2^{a}	TT3	1.0^{a}	0.1^{a}	0.1^{a}	6.8 ^{a}	DCM	0.8^{a}
DF1/DT1	2.0^{a}	0.3^{a}	-	-	DF1/DT1	2.0^{a}	0.3^{a}	-	-	DCA	0.9^{a}
DF2	0.1^{a}	0.8^{a}	-	-	DT2	1.1^{a}	0.8^{a}	-	-		
DF3	0.8^{a}	0.3^{a}	-	-	DT3	0.9^{a}	0.4^{a}	-	-		

No statistical differences in yield were evident at Jimbour, in the two crops following tillage. The profitability did not reach statistical significance at $p<0.05$ however no till had the highest profit, and multiple disc tillages resulted in the lowest profit in the first year at Jimbour. In the following year there appeared to be a maintained reduction in profitability for the majority of tillage treatments.

In 2013 under chickpea, chisel tillage, applied 3 times led to a significantly increased yield at the Biloela site (Table 25), resulting in a predicted net increase in profit of $99/Ha. The majority of tillage treatments in the first crop (Chickpea) after tillage al Biloela resulted in an increased profit, excepting the TT3 treatment. The following year, when cropped under sorghum, no differences in yield were evident. The only treatment with a predicted increase in profit was the single tillage pass treatment. All other resulted in a net loss relative to NT. In the winter season of 2014, wheat yields were increased where tillage had been applied in the previous year, indicating a residual effect from the 2013 tillage event. The highest increase was seen with three pass chisel tillage, with a 48% increase in yield compared with the no till. In all cases this resulted in a net increase in profit relative to NT. This suggests that the crop planted may have varying responses. At Moree there were no statistical differences in yield. The resulting profits were variable as indicated in Table 26.

Table 25. Impact of tillage imposition on grain yield (t/ha) in long-term no-till systems at Jimbour West and Biloela. Differing lower case letters indicate statistical difference at p<0.05 within a year and site. Refer to materials and methods for dates of tillage. Comparisons between sites are not valid. [1]Wheat grain; [2]Chickpea grain; [3]Barley grain; [4]Sorghum

	Jimbour West		Biloela			Moree	
Treatment	2013[1]	2014[2]	2013[2]	April 2014[4]	October 2014[1]	Treatment	2013[1]
NT	2.92[a]	1.16 [a]	1.88[a]	2.44 [a]	1.11 [a]	NT	3.51[a]
DF2	3.00[a]	1.07 [a]	-	-	-	CCM	3.58[a]
DF3	3.03[a]	1.13 [a]	-	-	-	CCA	3.54[a]
DT2	2.82[a]	1.12 [a]	-	-	-	DCM	3.51[a]
DT3	2.91[a]	1.09 [a]	-	-	-	DCA	3.63[a]
DF1/DT1	2.93[a]	1.14 [a]	-	-	-	-	-
TF1/TT1	2.67[a]	1.10 [a]	2.03[a]	2.51 [a]	1.40 [b]	-	-
TF2	2.81[a]	1.13 [a]	2.14[a]	2.44 [a]	1.46 [b]	-	-
TF3	3.11[a]	1.16 [a]	2.24[b]	2.36 [a]	1.64 [b]	-	-
TT2	2.92[a]	1.14 [a]	1.98[a]	2.4 [a]	1.35 [ab]	-	-
TT3	3.04[a]	1.20 [a]	1.88[a]	2.33 [a]	1.29 [ab]	-	-

Net profit and losses are indicated in Table 26. Due to the costs of tillage there was generally a decrease in profit for the crop directly following tillage. Tillage operations varied in profitability success in the following year.

Table 26: Net profit/loss compared with NT control.

	Jimbour West		Biloela			Moree	
Treatment	2013[1]	2014[2]	2013[2]	April 2014[4]	October 2014[1]	Treatment	2013[1]
NT	0	0	0	0	0	NT	0
DF2	-14.4	-36	-	-	-	CCM	7.4
DF3	-24.8	-12	-	-	-	CCA	-5.4
DT2	-52	-16	-	-	-	DCM	-10
DT3	-23.2	-28	-	-	-	DCA	28.4
DF1/DT1	-16.8	-8	-	-	-	-	-
TF1/TT1	-95	-24	45	16.1	78.3	-	-
TF2	-65.2	-12	74	0	94.5	-	-
TF3	15.8	0	99	-18.4	143.1	-	-
TT2	-15	-8	25	-9.2	64.8	-	-
TT3	23.4	16	-15	-25.3	48.6	-	-

The predicted yields at Biloela, Jimbour, and Moree sites are indicated in Table 27. The only predicted significant difference in yields was at the Biloela site in 2013 under a chickpea crop. Predicted yield was significantly increased in the two pass tillage treatment. No significant differences at any other sites were predicted. The predicted increase was not reflected in the true yield at the Biloela site. The predictive model did not reflect the increase in true yield seen in the two and three pass chisel treatments at the Biloela site under wheat in 2014.

Table 27: Predicted yields at Biloela, Jimbour and Moree after differing strategic tillage operations. Differing lower case, superscript letters indicate a significant difference in predicted yield, compared with the no-till control, at p<0.05.

Crop	Site	Year	Tillage operations		
Wheat			*Once*	*Twice*	*No-till*
	Biloela	2012	2.74^{a}	2.66^{a}	2.73^{a}
	Biloela	2014	1.37^{a}	1.55^{a}	1.33^{a}
	Jimbour	2013	2.88^{a}	2.96^{a}	2.84^{a}
	Moree	2013	3.56^{a}	-	3.51^{a}
Chickpea					
	Biloela	2013	2.06^{a}	2.23^{b}	1.99^{a}
	Jimbour	2014	1.13^{a}	1.12^{a}	1.17^{a}
Sorghum					
	Biloela	2013	2.44^{a}	-	2.54^{a}

Probability of rainfall occurrence at each site is indicated in Figure 27. The highest probability at all sites was during the period of November-May, being in a summer dominant rainfall region. These results would suggest that the optimal time for tillage is during the high rainfall probability time to ensure soil moisture status is acceptable. Additionally, mindfulness of high intensity storms should be considered.

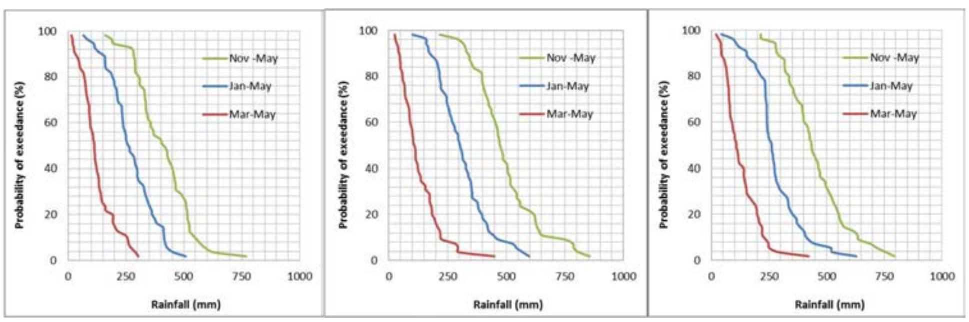


Figure 27: Probability of rain based on historical data for Moree (left), Biloela (centre), Dalby (right).

Summer 2013 Sites

Physical properties: Soil bulk density and volumetric moisture content were not significantly affected by chisel or offset disc tillage at the Yelarbon site 3 months' post tillage. Similarly, there were no significant effects on either parameter at the Emerald location caused by either offset disc or chisel tillage (Figure 28). Both sites are identified as Vertosols, and this supports the evidence that these soil types are recalcitrant to structural deterioration under one-time tillage.

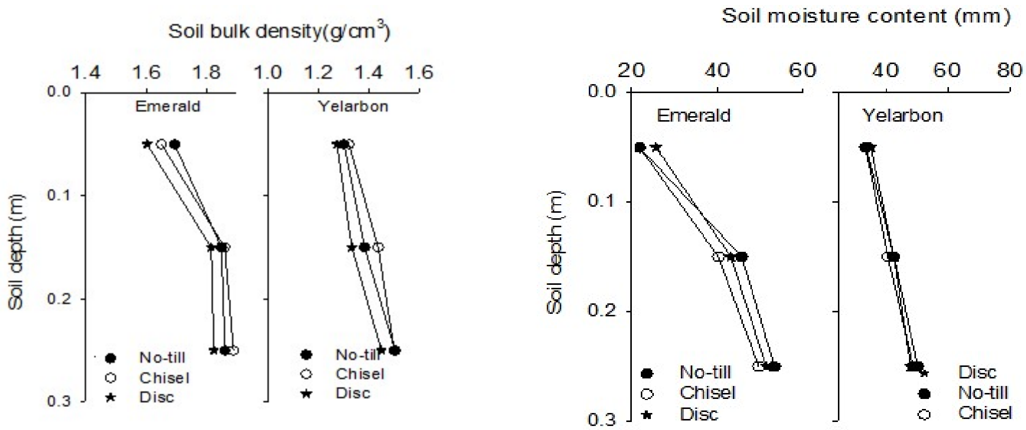


Figure 28: Soil bulk density (left) and soil moisture (right) 3 months after tillage at the Emerald and Yelarbon sites, showing no statistical differences. Horizontal lines indicate significant difference at $p<0.05$.

The wet aggregate stability 3 months after tillage at Yelarbon, as indicated by the percentage of aggregates <0.125mm after wet sieving, was not affected by a single pass chisel or offset disc tillage, nor was the mean weight diameter significantly impacted, as indicated in Table 28. Despite significance not being reached, tillage did appear to trend toward decreasing mean weight distribution. The primary fraction which resulted in this decrease was a reduction in the percentage of water stable aggregates between 2 and 4mm diameter.

Table 28: Mean weight distribution of aggregates in the surface soil at Yelarbon with tillage treatments. Differing superscript letters indicate significant differences at $p<0.05$.

Treatment	No Till	Chisel 1	Offset Disc
%<0.125mm	44.1^{a}	43.6^{a}	45.8^{a}
MWD g.mm	0.465^{a}	0.361^{a}	0.356^{a}

Shear strength of the soil at the Yelarbon site was significantly decreased by both one-time chisel tillage and offset disc tillage, as shown in Table 35. The results were a 33.7%, and 35.3% reduction respectively, when compared with the no till control.

Table 29: Shear strength of soil after strategic tillage. Different superscript letters indicate significant difference at $p<0.05$.

	No Till	Chisel 1	Offset Disc
Shear Strength (kPa)	56.7^{a}	37.6^{b}	36.7^{b}

At Felton, an initial moisture loss, as indicated by EM survey data, was seen with tillage. This was consistent with expectations. Soil moisture was decreased with tillage however was able to recover with sufficient rainfall events (46.2 mm). The recovery occurred between 17 and 30 days' post tillage. After this point the moisture appeared to be similar between the disc and no-till treatments.

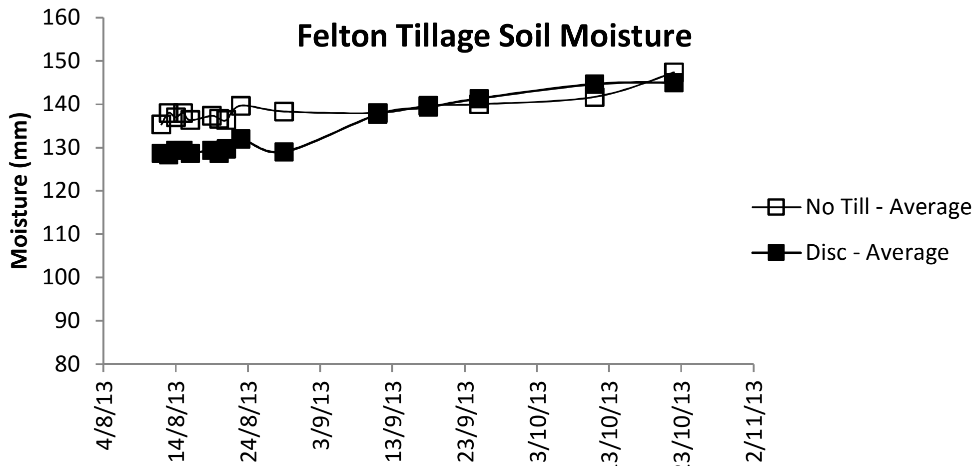


Figure 29: Soil moisture loss based on EM data at the Felton site showing recovery after 30 days.

The majority of water loss occurred in the topsoil, to a depth of 0.1m, and to a lesser extent the 0.1-0.2m soil. Minimal soil moisture losses were seen below this depth. Rainfall sufficiently reversed soil moisture loss, and if carried out at an appropriate time, considering the requirement and likelihood of rainfall between sowing and planting, it may be appropriate.

Soil chemical properties: At Yelarbon, soil Colwell P was not affected at any depth due to single pass tine of offset disc tillage. When the total soil carbon was assessed using the ESM method, there appeared to be a significant change in the total soil carbon. Offset disc tillage significantly reduced the carbon in the 0-0.1m depth layer, and significantly increased with chisel tillage in the 0.1-0.2m depth layer (Table 30), however only at $p<0.10$. This is likely an interaction of small changes in carbon content and soil bulk density which, when these factors combine, lead to a statistical difference in the total carbon content. Offset disc and chisel tillage resulted in no statistical change in soil Colwell P, organic carbon %, or total organic carbon at the Emerald site (data not shown).

Table 30: Soil total carbon content at Yelarbon, shown in t/ha. Differing lower case letters indicate statistically different results at $p<0.10$.

	0-0.1m	0.1-0.2m	0.2-0.3m
No Till	6.15[a]	4.07 [a]	3.38 [a]
Chisel	6.32 [a]	5.52 [b]	4.19 [a]
Offset Disc	4.82 [b]	3.97 [a]	3.09 [a]

No significant differences were obtained in soil P levels on the fertiliser bands and of the bands (Table 31), however the trend was toward higher P on the nutrient band, as expected. Although nutrients had been placed at depth there still appeared to be a significant stratification of phosphorous in the surface soil. 'ON' treatments refer to direct planting into the nutrient band, and 'OFF' refers to planting between nutrient bands in the soil. Sampling was directly from the nutrient band 'ON', or between the nutrient bands 'OFF'.

Table 31: Soil available phosphorous and nitrate levels comparing soil collected from on the fertiliser band and off the fertiliser band in strip tillage trials. Differing lower case letter indicate significant differences at $p<0.05$.

		South		North	
	Depth (m)	ON	OFF	ON	OFF
Colwell P (mg/kg)	0.05	51.3 [a]	26.3 [a]	43.7 [a]	20.0 [a]
Colwell P (mg/kg)	0.2	7.7 [a]	8.7 [a]	5.0 [a]	7.7 [a]
NO_3 Nitrate (mg/kg)	0.05	7.0 [a]	6.7 [a]	7.67 [a]	4.67 [a]
NO_3 Nitrate (mg/kg)	0.2	9.7 [a]	3.3 [a]	11.67 [a]	6.33 [a]

Plant nutrient concentrations did not differ between treatments for any of the minerals tested (Al, B, Ca, Cu, Fe, K, Mg, Mn, P, S, Zn) in the flag leaf or the leaf prior to flag leaf. Due to location, a comparison to a completely unfertilised area was not possible. This may have provided more insight into the effects of strategic tillage for nutrient banding.

Agronomic measurements: At the Yelarbon site, tillage had no statistical effect on weed density or plant establishment after sowing as indicated in Table 32. Similarly, there were no differences in establishment rates at either Goondiwindi site.

Table 32: Weed and establishment rates of sorghum plants at the Yelarbon site. Differing letters indicate significant differences at $p<0.05$.

	No Till	Tyne	Offset Disc
Weed count (plants/m^2)	0.375 [a]	0 [a]	0 [a]
Establishment (plants/m^2)	20.25 [a]	20.75 [a]	21.25 [a]

No statistical differences in yield were evident between tillage treatments at the Emerald or Yelarbon sites, however there was a much higher variability at the Emerald site. Data is shown in Table 33. The mean yield in the offset disc treatments was higher than that of no till, however, this did not reach statistical significance.

Table 33: Impact of offset disc and chisel tillage on sorghum grain yield (t/ha) in long-term no-till systems, on Vertosol soils. Different superscript letters indicate a statistical difference at $p<0.05$ between treatments for a given site. [1]Sorghum

	No Till	Chisel	Offset Disc
Emerald[1]	4.8[a]	4.47[a]	5.41[a]
Yelarbon[1]	2.09[a]	2.01[a]	2.05[a]

No statistical difference in yield was evident between the two planting regimes at the Goondiwindi site. It is likely that nutrient accessibility is equal between the two treatment types due to proximity to the nutrient bands, supported by the pant nutrient uptake levels. The average yield of ON treatments being 2.93 ± 0.07 t/Ha, and the OFF treatments 2.89 ± 0.06 t/Ha in the Southern Trial and 2.07 ± 0.18 t/Ha, and 2.20 ± 0.05 t/Ha in the Northern trial. Yields differed between the two trial sites and is likely a factor of differing rainfall and planting dates between the two sites.

Table 34: Predicted yields at the three summer sites established in 2013 were not statistically different with the application of strategic tillage. This reflected the outcomes seen in field trials, where no significant differences were evident. Differing superscript letters indicate significant differences within a site, $p<0.05$.

Crop	Site	Year	Tillage operations		
Sorghum			*Once*	*Twice*	*No-till*
	Emerald	2013	3.471[a]	-	3.344[a]
	Goondiwindi	2013	2.501[a]	-	2.545[a]
	Yelarbon	2013	2.031[a]	-	2.089[a]

Rainfall Simulation Sites

Soil chemical and physical properties: Plot slopes were twice as high at Felton (1.4%) than at the other two sites (Figure 30) and there were no differences between mean treatment plot slopes within each site, making hydrological comparisons between treatments possible. The soil surface was rougher after tillage than before, as expected, at all sites (Figure 30). There was no more than 5% green weed on average before tillage at all the sites and there was no green weed at the surface after tillage, indicating the tillage reduced the weed coverage as intended. Total groundcover was lower (11%) after tillage than before (50%) across all sites and was lower at Billa Billa than the other two sites (Figure 30). Concomitantly, above-ground biomass was lower at Billa Billa (2.7 t/ha) than at Felton (4.9 t/ha) or Moonie (6.7 t/ha).

There was no significant reduction in surface biomass after tillage. Soil shear strength was lower at the soil surface after tillage than before, and was lowest at Felton (Vertosol) and highest at Billa Billa (Sodosol) (Figure 30). There were no differences between treatments in gravimetric soil moisture (0-10 cm) content before or after rainfall (data not shown).

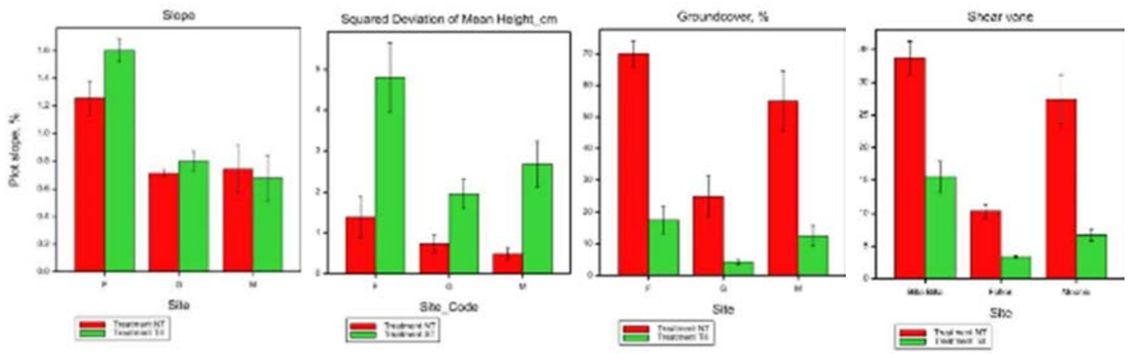


Figure 30. Slope of plots; surface roughness squared deviation from mean height; groundcover; and Surface soil strength shear vane units, under No till (NT) and Strategic Tillage (ST) treatments at Felton (F), Billa Billa (G) and Moonie (M).

The silt plus clay dispersion ratio (R1), bulk density and Colwell P were affected by tillage. Tillage only increased the proportion of dispersed silt plus clay (R1) at Moonie whereas Felton was more resilient to disaggregation (lower R1 and R2) and Billa Billa was more naturally dispersive (highest R1 and R2) (Figure 31). Bulk density (0-5 cm) was higher under NT in the Sodosol than after tillage. Tillage increased the plant availability of P (Colwell P) in the top 0-5 and 0-10 cm of the Vertosol (Felton) and Dermosol (Moonie) (Figure 31).

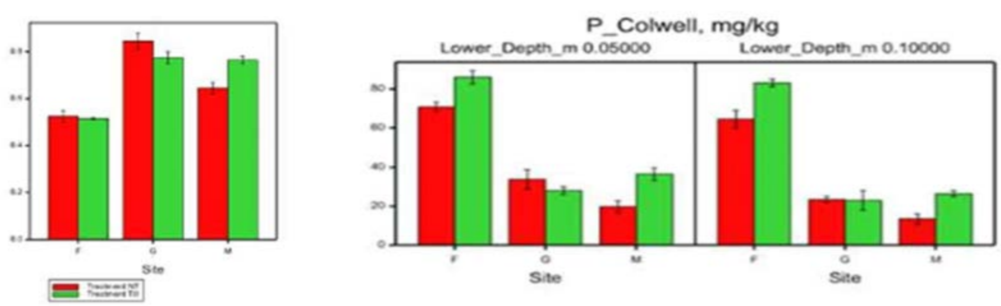


Figure 31: Silt plus clay (R1) dispersion ratio 0-10 cm (left) and Colwell P (mg/kg) in 0-5 cm and 0-10 cm (right), before rain, at Felton (F), Billa Billa (G) and Moonie (M)

Hydrological behaviour: There was no difference between NT and ST in the time to surface ponding after rainfall initiation (Figure 32) and the time to ponding was shorter (P < 0.100) at Billa Billa (3 min) than the other two sites (11 min at Felton and 12 min at Moonie).

The time between rainfall and runoff initiation (Figure 32) was similar between ST and NT at all sites indicating that effects of surface roughness and/or disaggregation from tillage did not markedly increase ponding and surface water detention. Runoff began sooner at Billa Billa (8 mins after rainfall initiation) than at Moonie (39 min) or Felton (50 min) despite the Felton Vertosol having a steeper slope, higher antecedent moisture content and similar or higher groundcover. Differences in patterns of pre-rainfall and post-rainfall soil moisture content beneath soils suggest the Vertosol had a larger potential to store the rainfall within the soil profile than the other two sites.

After 80 minutes of rainfall, there was more runoff from ST plots than from NT plots at Billa Billa and Moonie but not at Felton (Figure 32). Runoff volumes were highest at Billa Billa (53.9% of rainfall) and lowest at Felton (7.5% of rainfall). Runoff volume from one ST plot at Felton was omitted from the analysis due to incomplete capture of the outflow. Runoff curve numbers followed the same pattern across sites but there was no treatment effect. There was no difference in the final runoff rate between ST and NT treatments (Figure 43). Differences between treatments in runoff volume and final runoff rates were broadly the inverse of differences in final infiltration rates (Figure 44) at each site as expected given the similarities in the time to runoff initiation between treatments.

A comparison of the final infiltration rates with infiltration rates measured over longer periods of time under ponding in the infiltrometers suggested that none of the rainfall simulations reached steady state but that those at Felton were approaching steady state (data not shown).

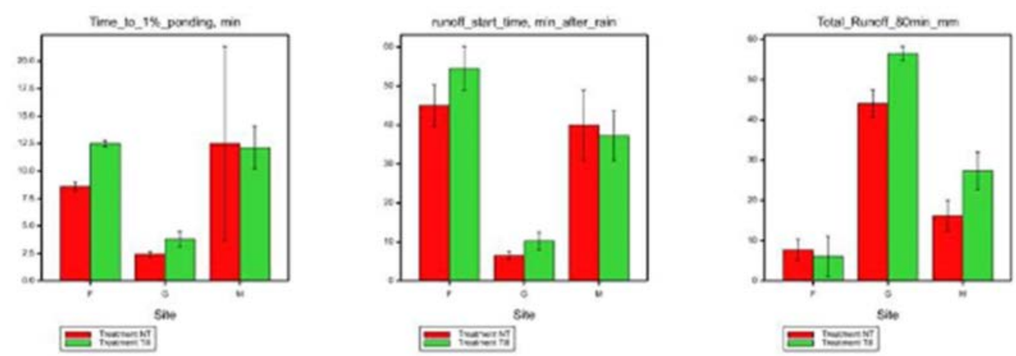


Figure 32: Time to ponding initiation (left), time to runoff initiation (centre), and total runoff after 80 minutes (right) of rainfall at Felton (F), Billa Billa (G) and Moonie (M). Values are indicated in mm.

Final rainfall infiltration rates of NT plots were the same across all sites (mean 33 mm/h) but after tillage were higher at Felton (53 mm/h) than at Moonie (22 mm/h) or Billa Billa (18 mm/h). There was high variability in the final infiltrations rates at Felton, particularly on the ST plots, such that there was no difference between NT and ST mean final infiltration rates. In contrast, tillage decreased final infiltration rates at Moonie and Billa Billa (Figure 33). There was no tillage treatment effect on rates of infiltration after 5, 10 or 20 hours of ponded infiltration predicted from single-ring infiltrometer measurements. Differences in ponded infiltration rates between sites were more exaggerated than differences in infiltration measured under rainfall simulation with infiltration rates highest at Felton and lowest at Billa Billa.

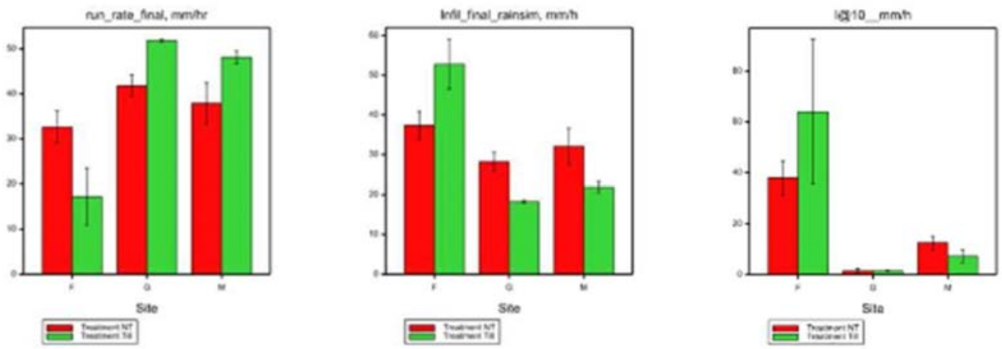


Figure 33. Final runoff rates during rainfall simulation (left), final infiltration rates during rainfall simulation (centre), and infiltration rate after 10 hours of ponding predicted from single-ring infiltrometer measurements at Felton (F), Billa Billa (G) and Moonie (M). All measurements are indicated in mm/h.

Runoff tended to increase with decreasing groundcover at Moonie and Billa Billa but not at Felton (Figure 34).

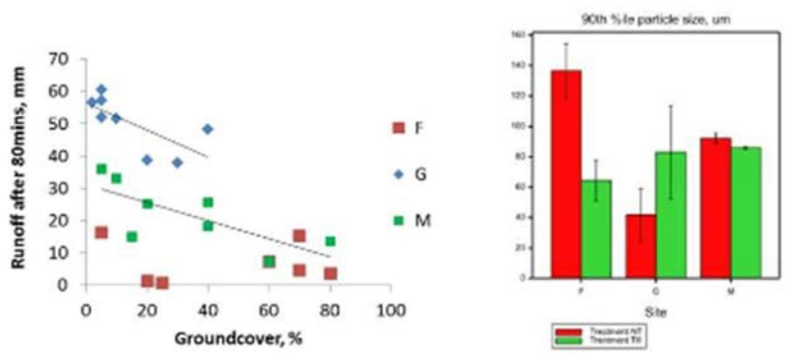


Figure 34: Left) Relationship between total runoff and groundcover across plots at Felton (F), Billa Billa (G) and Moonie (M) and right) runoff steady state 90th percentile particle size with no laboratory dispersion (right), µm.

Runoff concentrations and loads: Sediment and nutrient loads were not able to be calculated from the one plot where the runoff rate was not accurately sampled or measured, however, the samples collected were flow-weighted and therefore concentration measurements were deemed reliable.

Between 82 and 94% of suspended sediment in runoff at the end of the measured hydrograph was in the clay and silt particle size fraction (i.e. less than 62.5µm in size) and there were no differences between sites or treatments. Suspended sediment from all the treatments therefore had a high potential for transport and a low potential for deposition downslope, similar to findings by Freebairn and Wockner (1986) in Vertosol catchment runoff studies in south-east Queensland. Ninety percent of the particles were less than 42 to 137 µm across sites and treatments. Whilst there was insufficient replication to identify treatment or site differences, there was a non-significant trend for the 90th percentile size to be more similar between site after tillage than from NT plots and for the 90th percentile particle size from NT plots to decrease in the order Felton > Moonie > Bill Billa (Figure 34). These trends warrant further investigation. Following mechanical dispersion of the suspended sediments in the laboratory, the percentage of particles in the clay and silt size fraction remained the same and increased to 95-98% after ultrasound dispersion for all sites and treatments. After ultrasound dispersion the 90th percentile particle size decreased to 25 to 49 µm across sites and treatments (data not shown).

Runoff EMCs (Event mean concentration) were higher from ST than from NT for TSS (total suspended solid), TKN (total Kjeldahl nitrogen) (Figure 35), NH_4-N, TKP (total Kjeldahl phosphorus) (Figure 36), DKN (dissolved Kjeldahl nitrogen) and DKP (dissolved Kjeldahl phosphorus) (Figure 37) at Moonie and Billa Billa, EMCs were lower from ST than from NT for EC at Felton only. There were no treatment differences for the remaining chemistries tested; pH, DKN, NO x-N, DIN (Figure 36) and PO 4-P.

Runoff EMC were significantly lower at Moonie for TSS, TKN and TKP than the other two sites. At Felton, runoff EMC concentrations were lower for DKN, DKP (after tillage only) and NO x-N (after tillage only) than the other two sites and higher for EC, pH, TKN, NH 4-N, TKP, PO 4-P (NT only) and PP (data not shown).

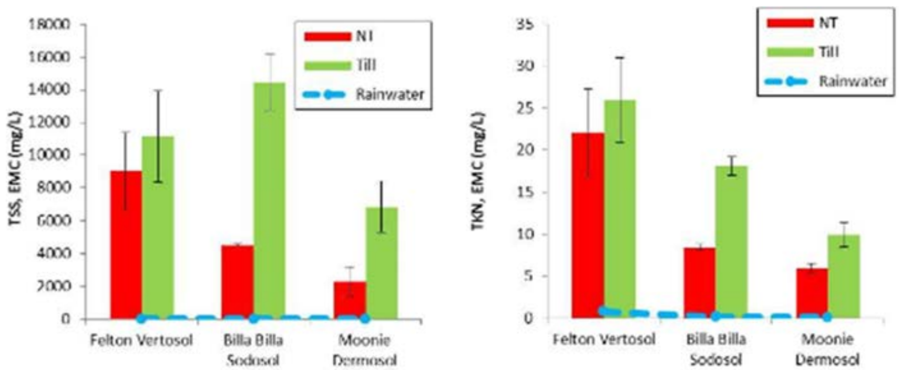


Figure 35. Runoff EMC and applied rainwater TSS (left) and runoff EMC and applied rainwater TKN (right) at Felton (F), Billa Billa (G) and Moonie (M), mg/L.

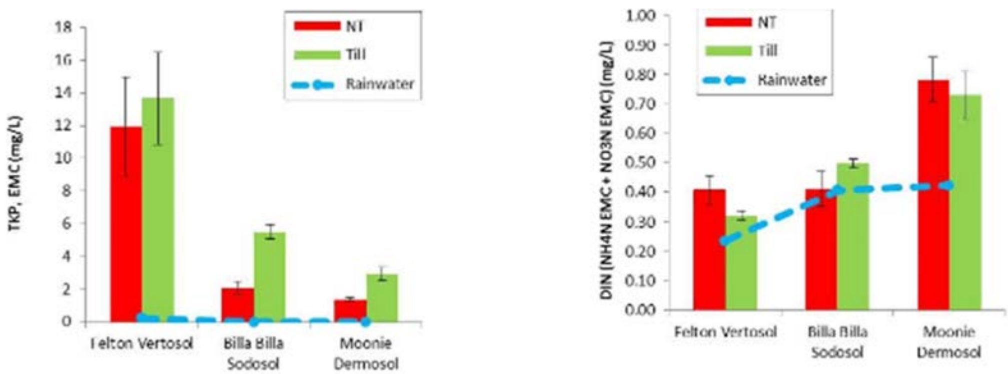
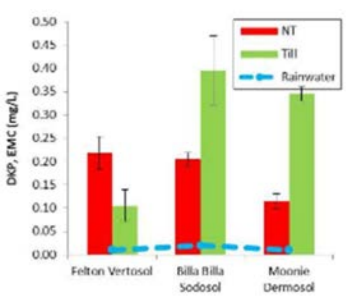


Figure 36. Runoff EMC and applied rainwater TKP (left) and runoff EMC and applied rainwater DIN (NH 4-N + NO 3 N) (right) at Felton (F), Billa Billa (G) and Moonie (M), mg/L.



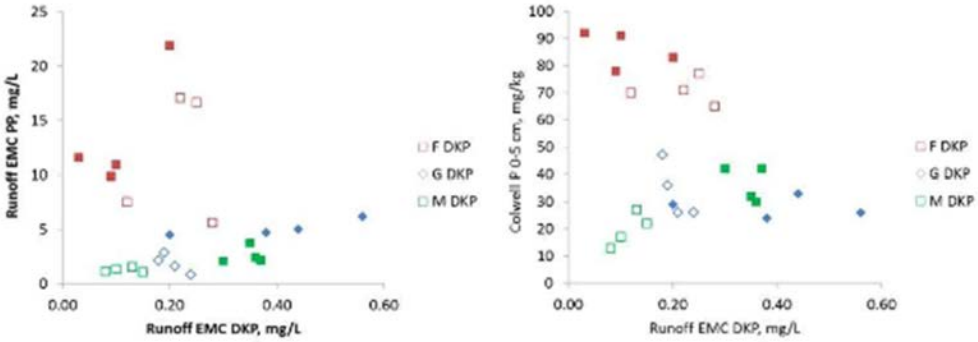


Figure 37: Runoff EMC and applied rainwater DKP (mg/L) (top); relationship between runoff EMC particulate P and dissolved P (bottom, left) (mg/L) and relationships between soil Colwell P 0-5 cm, mg/kg) and runoff EMC dissolved P (bottom, right) (mg/L) at Felton (F), Billa Billa (G) and Moonie (M) where open symbols are NT plots and closed symbols are ST plots.

The fraction of TKP in dissolved form (DKP) was 12% or less and the concentration tended to increase as particulate P increased (Figure 37). Runoff DKP concentrations were more highly buffered against partitioning from the particulate to dissolved phases at Felton (PBI unadjusted 124) than at Billa Billa (PBI unadjusted 31) or Moonie (PBI unadjusted 60). This was demonstrated by higher runoff particulate P concentrations and soil Colwell P (Figure 37) content for relatively low DKP concentrations in runoff at Felton compared with the other two sites.

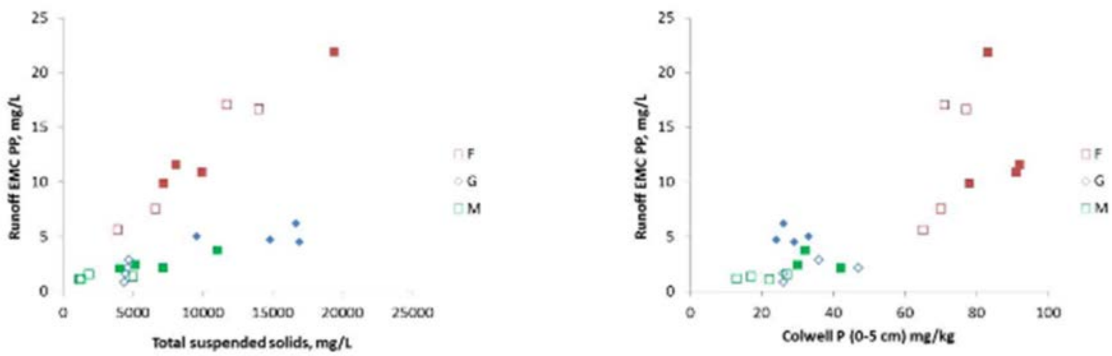


Figure 38: Runoff EMC particulate P vs runoff total suspended solids EMC relationships (left) and runoff EMC particulate P vs soil Colwell P relationships at Felton (F), Billa Billa (G) and Moonie (M) with open symbols for NT plots and closed symbols for ST plots.

Particulate and total P, EMCs in runoff were positively related to both runoff suspended solids concentrations (Figure 38) and soil plant available P (Figure 38). The fraction of TKN as DIN was 13% or less with NH_4-N tending to increase as TKN increased but NO_x-N tending to decrease as TKN increased (Figure 39). Nitrate-N, which was the largest DIN component, tended to increase with increasing soil nitrate-N (Figure 39).

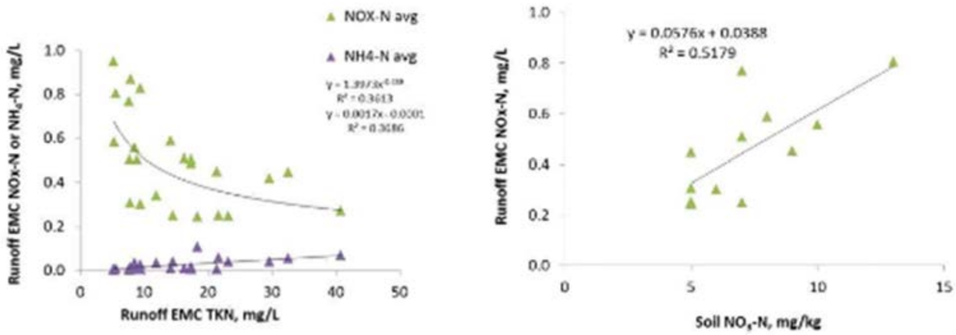


Figure 39: Relationships between runoff EMC NO x-N (mg/L) or NH 4-N and runoff EMC TKN (mg/L) across all sites combined (left) and relationships between runoff EMC NO x-N (mg/L) and soil nitrate-N (mg/kg) across all sites combined (right).

The TSS and total N loads in runoff were high from the strategic tillage at Billa Billa (8.3 t/ha TSS and 10.2 kg/ha TKN) and were lower and not different across other sites and treatments (Figure 40) According to within-site t-tests, total P loads were lower from NT than ST treatments at Billa Billa and Moonie but were similar between treatments at Felton. The highest measured total P load of 3.1 kg/ha was again from the ST treatment at Billa Billa.

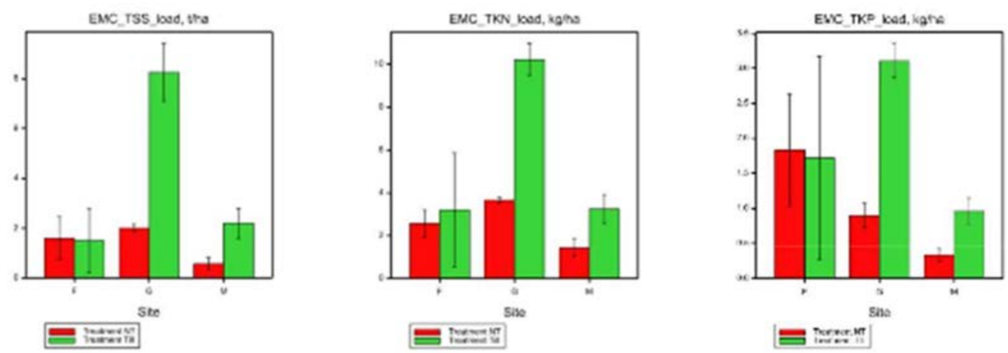


Figure 40: Loads in runoff of TSS (t/ha), TKN (kg/ha) and TKP (kg/ha) at Felton (F), Billa Billa (G) and Moonie (M).

Discussions

Soil physical properties

One of the key aspects of tillage is the impact it will have on the structure of the soil. Soil structure has been proven to be very important with respect to moisture holding capacity and root penetration. One of the key drivers of no-till has been the improved soil moisture status and reliability of planting.

Strategic tillage has the potential to affect plant available water in the short term. This in one of the key drivers of adoption of NT, as it is one of the major determinants of crop production in northern cereal growing region of Australia. As indicated by this study, a single tillage can result in moisture loss; however, this is limited, and typically confined to the surface soil. Sufficient precipitation would replenish soil water loss, and in this study recovery of soils to pre-till moisture status typically occurred within 3 months. For the few sites which did not recover in that time, by 12 months' post tillage soils were equivalent to the NT control. Plant establishment did not appear to be affected so immediate soil moisture was not a limiting factor. Similarly yield stability, even with tillage, at most sites would suggest that, if time appropriately, the moisture loss is not detrimental. Single pass tillage does not appear to reverse the improvements of long term NT with respect to soil moisture holding capacity. In a number of cases there did appear to be a loss of aggregate structural stability, and although statistically significant, may not be practically significant enough to result in loss of water retention, as indicated by soil volumetric moisture status. The aggregate breakdown may lead to increased erosion, or reduced infiltration, particularly in soils characteristic of having weaker structures in the surface soil. The loss of soil moisture appears to be quite rapid, as indicated by the study conducted at Felton, and recovery is a longer process, however in the space of weeks, rather than months, recovery occurred.

Vertosols appear to be resistant to the impacts of strategic tillage, and recover much more quickly than certain other soil types. Texture contrast soils and weakly structured hard setting soils are likely to be more affected by the application of tillage. One of the major factors to consider when tilling is the response of the soil, particularly in poorly structured soils. These soils are prone to aggregate breakdown and if tilled they may form hard surface crusts which will significantly reduce water infiltration. In addition, these soils will be more prone to compaction. Even in more versatile soils, tillage close to the soil plastic point may result in a smear layer which will affect infiltration; however, this did not appear evident in these trials however growers need to be mindful of the consequences. Long term, there did appear to be recovery of these soils within the study period.

Soil chemical properties

Strategic tillage, as with any major soil disturbance is likely to results in a decline of SOC for short period through the initial fluxes of CO_2 emission. This was evident at several sites implied by reduced particulate or total organic carbon, however recovery was rapid, with majority of sites recovering to the extent that there was no difference between tilled and untilled treatments at 12 months after tillage. As indicated at some sites, where POC was tested, this will lead to the majority of the initial breakdown, as it is known to be the most labile carbon source. Long term, the study did not find evidence that strategic tillage, in any of the forms tested, would result in drastic loss of soil organic carbon, and undo the build-up associated with NT.

Soil organic carbon (SOC) decreased slightly after 12 months of tillage imposition at all sites however no statistical differences were observed. Differences between different tillage implements were not significant. 24 months after tillage there appeared to be no residual effects of tillage on soil organic carbon. Sites set up in 2013 (Jimbour and Biloela) showed non-significant reductions in SOC; however, there was no significant impact due to the timing or frequency of tillage after 3 months and no statistically significant residual effects were evident 12 months after tillage.

Available P in sites set up in 2012 & 2013 showed non-significant reductions in surface soil and slight increase in subsoil, indicating possible top soil mixing. There were no significant impacts due to the timing or frequency of tillage and no significant impact observed 12 months after tillage imposition, similarly no significant impacts were evident after 24 months at the Condamine, Moonie, Warwick or Biloela (Site A) sites. 12 months after tillage, at the Jimbour and Biloela (B) sites there was no significant changes in the levels or depth distributions on soil Colwell P. At this stage, occasional tillage does not appear sufficient to ameliorate the heavily stratified nutrient build up associated with long term NT systems, however does not indicate any major negative effects which would point to off-site movement, based on increased runoff particulate P from strategically tilled sites. In the short term, there may potentially be a small, short lived, increase in available P immediately after tillage.

Soil nutrient stratification is one of the major issues associated with NT. Stratification, particularly of available P, was evident at the majority of sites, consistent with expectations. Micronutrient stratification was also evident at most sites. This, however, was not ameliorated by tillage, and another approach may be required to rectify this, such as deep placement of nutrients. The study of deep nutrient placement indicates that this may be an effective means to deliver nutrients to the root zone, without disturbing large areas of soil, and retaining the majority of benefits of NT, particularly if sufficient application for several seasons is applied, limiting tillage frequency. Although this trial did not show differences, the proximity of treatments was likely the cause. There is sufficient evidence indicating that deep nutrient placement is highly beneficial. Coupling this with the knowledge that ST does not appear detrimental when utilised responsibly, it appears that strip tillage can be highly beneficial when integrated into a no-till farming system.

Alterations in pH and EC were evident at the Moree site, however not at the Biloela and Jimbour sites. The two sites which did not show changes were heavier clay soils which again, may contribute to improved resilience. Changes in pH and EC can affect nutrient availability, potentially microbial activity and plant growth. The causes of these changes were not completely elucidated however may be due to increased mineralisation or loss of cations exchange surfaces with organic matter breakdown. It may be beneficial for land holders to collect pre- and post-tillage soil samples for analysis to gain an understanding of how tillage affects the chemical status of their individual property or paddock. Gaining this extra knowledge will further the predictability of future tillage outcomes.

Soil biological properties

Strategic tillage at Jimbour did little to ameliorate the noted levels of crown rot. It may be the case that a higher stubble incorporation technique is required to reduce disease incidence. In addition, small plot trials in close proximity to each other may not be ideal for determining the effects of ST on such stubble and soil borne diseases.

Tillage effects on soil microbial biomass carbon (MBC) and nitrogen (MBN) were minimal. At the Moonie site, the main effect of tillage was not statistically significant; however, there was a significant interaction between tillage and sampling depth. This interaction was attributed to a slight increase in microbial biomass carbon by chisel tillage compared with the NT at 0-10 cm depth. At 10-20 cm depth, however, chisel tillage did not influence MBC relative to the NT. Offset disc tillage did not influence microbial biomass carbon at either depth compared with the NT. No tillage effects on MBC/MBN were evident at Condamine or Moree. The result suggests that there is little detriment to the overall microbial biomass with a strategic tillage.

The type of implement utilised plays a pivotal role in determining the effects of occasional tillage on the soil microbial biomass. Generally, tilling with an offset disc or chisel is reported to cause less soil disturbance than that of inversion type tillage, such as is used in European/US (Conant et al., 2007, Dang et al., 2015a). According to previous reports, tillage with MP typically decreases soil microbial biomass (-13.70% ~ -40.63%) in shallow soils ((López-Garrido et al., 2011, Melero et al., 2011, Wortmann et al., 2008, Wortmann et al., 2010). Consistent with the results of Moonie site, Melero *et al.* (2011) also reported that soil microbial biomass carbon was increased by 46.59% at 0-5 cm depth in a clay loam soil eight months after chisel tillage, sampling the soil after harvesting a wheat crop. Strategic tillage, in most cases showed little to no impact on soil microbiological communities, with a few exceptions. The application of tillage is unlikely to significantly disturb the microbial communities that have been established over the course of long term no-till management. Some alterations are community substrate usage may suggest a slight shift in metabolic processes or community structure caused by increased aeration, or nutrient availability.

Percent mycorrhizal colonisation of plants was not affected by the application of tillage, however tillage did appear to reduce the length of AM roots per plant with tine tillage in the short term. The results indicate that there may be minor effects on AM associations with tillage. The follow up assessments showed no significant differences which suggest that recovery occurs within approximately four weeks, and is of minimal detriment to the cropping system.

Nematode populations were not affected by the application of strategic tillage at the Hermitage site. *P. thornei* populations were not reduced, however beneficial or neutral nematodes were also not affected.

Strategic tillage does not appear to be a management option to treat soils with *P. thornei.* It appears that single tillage events are not aggressive enough to significantly affect the nematode community profile.

Agronomic measurements

The implementation of occasional strategic tillage appears to be an effective tool to use for the management of hard to kill weeds such as herbicide-resistant barnyards grass, and feather topped Rhodes grass. At the majority of sites in short-term, there appeared to be a reduction in the weed density following tillage as compared to continuous no-till. In long term, effects varied significantly. Sites were shown to have maintained weed reductions, unchanged weed population, or increased weed populations 12 months following tillage, depending on the site. These variable responses indicted that it is imperative to know the weed history of the paddock in which a strategic tillage is being undertaken. Tillage has the capacity to activate seed banks that have been dormant for many years, and result in a shift on the type of weeds present. On the Brown Sodosol at Condamine, there was an increase in weed population, in particular of African turnip weed (*Sisymbrium thellungii*), 12 months' post-tillage. These results were significantly different between chisel 2-pass and NT treatments; with a high variance also recorded. Shallow germinating weeds such as these may pose an additional problem, as was seen at the Condamine site. If these weeds are easily treated with herbicides, preparations can be made to manage them at emergence to prevent moisture losses and the need for additional tillage. Furthermore, timing of tillage appears to be important. Again, knowledge of the type of seeds likely to germinate at the time of tillage, that may have historical presence in a field, will equip farmers with the ability to manage and reduce these populations. Chauhan *et al.* (2006) stated that seedling recruitment of wild radish was higher under minimum tillage than under NT, whereas recruitment of annual sowthistle and turnip weed was higher under the NT system.

From timing and frequency trials, it was indicated that incidence of weeds was decreased, however not significantly. In addition, it was not shown that more tillage passes reduce the weed populations more than a single pass. These results are promising, indicating that the lower financial and risk costs of a single tillage perform just as well as multiple investments in time, labor, and soil risks associated with multiple tillage.

Although the type of tillage did not appear to significantly change the effectiveness of weed management at most sites, some consideration may be required. Surface tillage may be useful for shallow germinating weeds at an early stage of development, and for more established hard-to-kill weeds the use of wide cutting cultivator feet may damage the well-developed root systems sufficiently to kill the plants. Disc cultivation results in some inversion of soil and knowledge of the weed seed bank in this instance is critical. Inversion will favor shallow germinating seeds that require warmer soils and exposure to sunlight.

Grain yields overall showed non-significant changes to tillage treatments. Slight yield increases were observed at Biloela, Moonie and Warwick in the first crop after tillage. The influence of tillage on weed populations may be one of the influencing factors for the increase in yield seen on the Black Vertosol at Biloela, the Grey Dermosol at Moonie and the Black Vertosol at Warwick. Condamine recorded a decrease in yield, a result likely caused by a significant increase in weed populations. Yields 24 months after tillage showed no change in relation to strategic tillage at Condamine, Moonie, Biloela, or Warwick. The indication is that impacts on yield are short lived and are likely reliant on other factors such as moisture loss and weed populations. This result reflects that of Kettler *et al.* (2000) where reduced weed pressure caused by tillage resulted higher grain yields in the succeeding three crops compared with the undisturbed NT.

Sites established in 2013 had non-significant increases in yield; there were overall positive impacts to yield due to the timing or frequency of tillage treatments observed at Biloela, Moree and Jimbour. Comparison between the years and sites suggest a likely trend for increase in yield with one or two cycles of tillage before a chickpea crop. At Biloela, where a repeat tillage occurred, there was a net gain due to increased yield and high chickpea prices. At Moree and Jimbour, the profitability of tillage had an overall negative net return on wheat. Moree depicted mixed results where Jimbour was largely negative. At Biloela, the increase in chickpea yield increased the profitability. 12 months after tillage there was no impact on chickpea yield, or sorghum yield. There appeared to be a residual impact on wheat yield at the Biloela site (B), with a significantly increased yield in the TF3, and TF1/TT2 against NT. Although there was reduced topsoil moisture in these plots it did not affect yield negatively. The majority of current literature suggests 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*. 2015). The results from our trial sites reflect this, with the exception of the Brown Sodosol at Condamine where weed pressure increased and resulted in decreased yield at and 12, 24 and 36 months.

Soil type is likely to play a major role in predicting yield outcomes. Texture contrast soils and soils with a weakly structured A- horizon are highly likely to demonstrate negative impacts on soil health due to imposition of tillage. Well-structured and resilient soils are unlikely to result in decreased yields long term. Over a 5-year period, Wortmann *et al*. (2010) observed no differences in productivity on a silty clay loam when utilising chisel, disc and mouldboard tillage. On loam–clay and loam soils, Baan *et al*. (2009) also observed no effects on crop productivity after one cycle of tillage at three levels of tillage intensity.

Typically effects on nutrients, moisture, and physical characteristics trend toward returning to a NT situation within 12 months and further return to normal after 24 months' post tillage. These results suggest that given all other factors do not differ from NT practice, yield is unlikely to suffer. In the right circumstances ST can potentially result in improved yield and hence profitability.

Long term data analysis may be highly useful in predicting the outcomes of strategic tillage, when coupled with long term predicted rainfalls. Overall the long term simulation results indicated that timing of tillage had only minor impacts on soil moisture, with variable effects on yield under wheat. In low rainfall years the risk of yield loss due to tillage increased at Moree, the earlier tillage was done relative to sowing. No effect at Biloela or Dalby was noted based on predictive modelling. Conversely in wet years, tillage closer to sowing had lower yield losses at Moree, and Dalby. No effects were seen at Biloela. These outcomes suggest that depending on the location effects can vary. Several factors are consistent with tillage resulting in lowered water and predicted yield. Reduction of surface residues results in increased evaporation which is the driver of reduced soil moisture with tillage application (Diaz-Zorita et al., 2004).

The NGR tends toward a higher summer rainfall and tillage prior to summer crops appears to be less risky, as indicated by the crop rotation APSIM models. Soil moisture loss was the major driver of reduced yield in these simulations. This was particularly pronounced in the low rainfall years. Higher rainfall years have been shown to produce similar yields between NT and CT (Freebairn et al., 1993), hence strategic tillage will be of minimal consequence and provide opportunity to manage issues such as weeds (Baan et al., 2009).

Tillage and erosion/nutrient loss

The rainfall intensity of 70 mm/h applied in this experiment has a 1/100 year return interval over 1 hour so 80 minute storms are likely to be highly infrequent in these environments and the study therefore tested a worst case scenario of a heavy storm soon after strategic tillage. Whilst the soil was rougher under ST than NT, runoff volumes after 80 minutes of rainfall were lower from the NT treatments than from the ST treatments on the Dermosol and Sodosol and similar on the Vertosol. There was also no difference in time for runoff to initiate between treatments. The hypothesis that runoff volumes would be lower under ST due to increased detention of the short term rainfall because of increased surface roughness was therefore rejected. There was no treatment effect on the final runoff rate between ST and NT treatments, which further rejects the hypothesis. This finding is consistent with literature describing benefits of long term no till over continuous cultivation in terms of runoff reduction (Mathers and Nash, 2009). Elsewhere, once-off tillage did delay runoff initiation from rain soon after tillage but the effect was predicted to diminish over time due to surface sealing (Smith, 2015). Given the cropping systems in this study had a long history of no tillage, it was notable that even a single pass of cultivation was sufficient to induce higher runoff volumes at these sites. Whilst the surface was rougher after tillage, there was also almost a five-fold reduction in groundcover. Lower groundcover played an important role in increasing runoff volumes at the Dermosol and Sodosol sites as it does for soil with a history of cultivation (Freebairn and Wockner, 1986).

The only evidence that suggested runoff could be lower under ST than NT was the non-significantly higher final infiltration rate from ST treatment at Felton compared with NT at that site. Higher final infiltration rates after ST may have been due to the relatively deep tillage to approximately 150 mm, and non-significantly longer time to ponding than NT creating transient hydrological connectivity subsurface macropores which were likely to be prevalent in the Vertosol. High variance and non-significantly higher steady-state infiltration rates predicted using the single ring infiltrometers also suggested connectivity with soil macropore or matrix pore volumes was enhanced by the tillage at Felton compared with the NT treatment.

Suspended sediment and particulate P, EMCs were higher for ST compared with NT and so, whilst at Felton the treatment differences were not significant, the hypothesis was accepted. Sediment and particulate P concentrations and loads were also increased by once-off vertical tillage of a previously no-till loam soil subjected to 75 mm/h rainfall in Indiana, USA (Smith and Warnemuende, 2015). Reflecting the small treatment differences on the Vertosol soil, McGarry (1987) also found that dry tillage of cracking clay soils in north-eastern Australia had minimal impact on soil surface aggregation relative to an uncultivated soil. Particulate P concentrations were almost ten times higher at Felton relative to the other two sites, however, reflecting the 8-fold higher total P content of the surface 0-10 cm of soil. The high PBI at Felton, however, resulted in lower dissolved P concentrations in runoff than from the other sites under ST, and the lower runoff volumes resulted in total P loads in runoff being similar across sites.

The suspended sediment concentrations were higher at Felton and Billa Billa than at Moonie. The higher concentrations at Felton might be explained by the higher clay content and the simulations at Felton being conducted on a higher slope and on what was observed as a partially eroded mid-slope landscape position where the surface soil was shallow and therefore potentially at higher risk of erosion. The higher concentrations at Billa Billa Sodosol might be due to the higher fine sand content and the potential for structural decline during rainfall because of the low soil EC (0.08 dS/m) and moderate ESP (5.4%) of the surface soil. The combination of high TSS concentrations in runoff (14.5 mg/L) and more than twice as much runoff resulted in strategic tillage on the Billa Billa Sodosol being the riskiest for losses of sediment and N in runoff, despite the low slope (0.75 %) at this site.

In terms of overall contribution to nutrient loss, dissolved P and N were less than 10% of the total P or N in runoff. Particulate P was over ten times higher by concentration, and higher by fraction, of total P than the 67-83% found by Mathers and Nash (2009) in runoff generated under low intensity rainfall (25 mm/h) from conventional (stubble burnt) and no-till (stubble retained) cropped soils in north-eastern Victoria. In their study nitrate dominated the total N loss in runoff which was in direct contrast to the particulate-dominated losses in this high-intensity rainfall study. Total DKP concentrations were similar across sites from the NT treatments (0.12-0.22 mg/L) and under ST were lower at Felton (0.11 mg/L) than the other two sites (0.35-0.40 mg/L). The site mean DIN concentration was higher at Moonie (0.75 mg/L) than at Billa Billa (0.45 mg/L) or Felton (0.36 mg/L).

At Moonie, the higher Colwell P in the top 5 cm after tillage was reflected by higher dissolved P concentrations (as EMC) in the runoff after tillage whereas at Felton there was no significant difference between DKP concentrations in runoff from NT and ST treatments, and at Billa Billa DKP concentrations were higher under ST despite no differences in Colwell P in the top 5 cm between tillage treatments. The hypothesis of ST increasing DKP concentrations in runoff relative to NT was therefore supported at two sites, although for potentially different reasons.

Instances of higher plant available P under ST compared with NT were attributed to tillage spreading and mixing soil from bands within the cultivated depth that were fertilised at planting throughout the plot area. In some studies, tillage has reduced stratification of plant available P in the surface relative to no-till soil ((Morrison and Chichester, 1994), albeit sometimes only marginally or not at all (Mathers and Nash, 2009). In this study, tillage did homogenise the surface soil relative to the NT treatment but simultaneously increased the plant available P. The increase in Colwell P due to ST needs to be treated with caution, however, as the co-location of sampling points with fertilised bands in either the NT or ST treatment would heavily influence the result.

The hypothesis for DIN was also supported because there were no differences in runoff DIN EMC between ST and NT treatments and neither were there any significant differences in soil nitrate in the top 10 cm between treatments. Nitrate was expected to be generated in the zone of highest organic C (presumably the top 10 cm) and the zone of highest exposure to legume N fixation (i.e. the root zone) or N fertiliser application (i.e. banded at 50-75 mm depth or broadcast, Table 1). Once generated, nitrate was expected to be redistributed throughout the root zone by rain and root activity or removed by denitrification. Redistribution or homogenisation of soil layers during strategic tillage was therefore expected to have little effect on the potential for nitrate to be mobilised into surface runoff. Whilst soil nitrate can accumulate in the surface 50 mm after long-term no tillage (Morrison Jnr and Chichester, 1994), in systems that have not been recently fertilised, others have similarly found no difference in DIN concentrations in runoff between no-tillage and either long-term conventional tillage (Mathers and Nash, 2009) or once-off tillage of previously no-till cropping soils (Smith et al., 2007)

Whilst soil Colwell P was inversely related to soil nitrate-N (R 2 0.47, Figure 12) and runoff nitrate-N concentration, soil nitrate N was positively linearly related to runoff nitrate-N concentration and tillage increased Colwell P at Felton and Moonie, there was no tillage effect on runoff nitrate concentrations. This might be explained by the curvi-linear relationship between Colwell P and soil nitrate whereby there was a larger (approximately 5-fold) variation in Colwell P (22-92 mg/kg) than in soil nitrate (5-13 mg/kg, approximately 3-fold) across all plots. Whilst stratification of soil N was not directly measured in this study, this supports the expectation that soil nitrate was less vertically or horizontally stratified than soil P and was therefore less affected by the disturbance of the top 100-150 mm of soil by the strategic tillage.

Conclusion

Overall, the impact of occasional strategic tillage on productivity, profitability, soil health, and environment is summarised in Table 33.

15 sites in total were established: 5 sites in winter 2012 (Biloela, Condamine, Moonie, Warwick and Wee Waa), 3 core sites in winter 2013 (Biloela, Jimbour and Moree) and 4 sites in summer 2013 (Felton, Yelarbon, Emerald and Goondiwindi with different types of tillage implements. Soil samples were obtained prior to sowing of crops from both 2012 and 2013 sites and analysed for soil's physical, chemical and biological properties. In general, one-time tillage slightly lowered bulk density, soil moisture prior to seeding, and the quantity of SOC and available P (Colwell-P) in the surface 0-10 cm soil depth 3, 12 and 24 months after tillage (Table 33). Negative effects 12 months after one-time tillage were seen at Condamine with a significant decrease in bulk density, increase in weed density and reduced yield. The bulk density increased at Moonie. Overall, there was non-significant increases in the yield at most sites.

Table 33: Summary of impact of one-time tine-tillage in otherwise long-term no-till farming systems

	Biloela (Vertosol)			Condamine (Sodosol)			Moonie (Dermosol)			Warwick (Vertosol)			Wee Waa (Vertosol	Moree (Vertosol)		Jimbour (Vertosol)	
	3m	12m	24m	3m	12m	24m	3m	12m	24m	3m	12m	24m	3m	3m	12m	3m	12m
Weeds	↓	↓	-	↓	↑	-	↓	+	-	+	+	-	↓	+	-	+	-
BD (0-10)	-	-	~	-	↓	~	-	+	~	-	-	~	-	-	~	-	~
SW (0-10)	-	+	~	-	+	~	-	+	~	↓	+	~	-	-	~	-	~
OC(0-10)	-	-	~	-	-	~	-	-	~	-	-	~	-	-	~	-	~
POC (0-5)	~	↓		~	-		~	-		~	+		~	~		~	
P (0-10)	↓	-	~	-	-	~	-	-	~	-	-	~	-	-	~	-	~
TMA (0-10)	+	-		-	+		-	-		-	-		~	+		-	
MCB(0-10)	~	~		~	+		~	+		~	~		~	+		+	
Yield	+	+	~	↑	-	~	+	+	~	+	+	~	↑	+	~	+	~
Net return	-	+		+	+		+	+		+	+		+	-		-	

(↑) significant increase; (↓) significant decrease; (+) increase; (-) 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/hour)*; MCB, microbial biomass (μg C g^{-1} soil); BD, bulk density (g/cc); SW, soil water (mm); OC, organic carbon (t/ha); POC, particulate organic carbon (t/ha); P, available (Colwell-P) mg/kg.

A number of risks have been identified with the use of strategic tillage, in addition to several benefits. The research indicates that the incorporation of strategic tillage in a farming management system is sustainable, however prior consideration of all of risks and potential rewards are required. All properties associated with soil health should be taken into account when considering a tillage operation, in addition to the financial costs, and the predicted effectiveness of the process. Weather forecasts will also determine the application of a strategic tillage, as heavy rainfall after tillage risks erosion and other detrimental impacts.

No till has provided a sustainable system to maintain soil health, and significantly improve the reliability and yields. The improved soil structure has been critical to improve water movement in soil, root penetration, and water holding capacity. Knowledge of soil structure appears to be key in making tillage decisions. Structure, texture, bulk density and soil moisture may be impacted by tillage and these parameters must be well understood for each soil before tilling. The results indicate that well-structured cracking clays, when tilled at an appropriate moisture contents will not result in significantly adverse long term effects that will affect the following crop. Tillage in soils that are too wet may lead to smearing and impact future crop yield. Furthermore, this study indicates that tillage of weakly structure soils such as Dermosols and hard setting Sodosols are likely to require longer periods for recovery and the negative impacts are more pronounced that in better structured soils. Understanding of the likelihood of rainfall between tillage and the next crop sowing will assist in ensuring that the soil moisture status of the soils is not adversely affected. Initially groundcover is depleted with tillage, and this may affect infiltration, in addition to wind erosion. Although follow up rainfall is imperative, heavy rainfalls after tillage were shown to have potentially negative outcomes.

Runoff has the potential to have a higher nutrient load, particularly on poorly structured soils. The slope of the land will affect the risk or erosion and topsoil loss if tillage is carried out. Experimentally there appears to be no significant effect or increased runoff compared with no tillage, which can be considered a neutral or negative result. There was increased erosion potential, in terms of suspended sediment concentrations at two sites and load at one site, which is also a neutral or negative result. Increased sediment concentrations after tillage were found in the Dermosol and Sodosol, both of which have weakly structured surface layers. Runoff after tillage also had higher or equivalent soluble P and N concentrations in runoff, which is also a neutral or negative result.

Landscape features such as topography, contour banks, downslope groundcover and vegetation, wetness and soil types, would control whether any runoff and mobilised suspended and dissolved sediment and nutrients would be retained within, or lost from, the farming system. However, the potential for short term increased risk of runoff, erosion and soluble nutrient loss should be included in considerations about strategically cultivating a previously no till soil.

The major chemical factor that appeared affected by tillage was the presence of soil carbon. Soil carbon, in the form of organic matter has a significant impact on soil health. It directly influences soils moisture holding capacity, structure, and nutrient status. The results indicate that tillage is likely to be at the detriment of soil organic carbon. Initially there is likely to be oxidation of the organic matter, resulting is loss via carbon dioxide. If damage to the carbon status does occur, it appears that recovery is rapid, generally requiring less than 24 months as indicated in this study. Another mode of potential loss is in surface run-off if intense rain occurs. Particularly in in situations where carbon stratification occurs, this may be an issue. The loss of organic matter due to off farm transport caused by a poor tillage operation will impact on the overall soil health and productivity. Strategic tillage, delivered in the form of this study did not remediate nutrient stratification sufficiently to deliver nutrients to the root zone. Assessing this issue will require more aggressive strategies such as deep nutrient placement. Considering this as strategic tillage, there are likely to be minimal detriments seen to the soil and subsequent crops, as indicated in the trials carried out at Goondiwindi. Any detriment is likely to be outweighed by ensuring that there is adequate nutrition for crops for several seasons to come.

The biology of the soils studied was diverse. Strategic tillage did not appear to be of use in treating the presence of pathogenic nematodes such as *P. thornei,* however it also did not negatively affect beneficial or neutral nematodes. The study at Jimbour indicated that tillage is likely to reduce the AM associations, however recovery is rapid. The initial reduction is likely due to longer establishment times which may be cause by disruption of hyphal networks or loss of spores. Further to this there did not appear to be any benefit by strategic tillage to the reduction of crown rot incidence.

The complete diversity and interactions of the soil microbial community are yet to be fully understood, especially with respect to the microbial population. The microbes present are critical in soil structure formation, plant growth promotion, nutrient cycling, and potentially pathogen suppression. Soil microbes respond rapidly to changes in the environment, such as those that occur with ST. The results appear to have minor effects on the microbial populations, potentially shifting the substrate utilization patterns of the community.

Implications

Generally, the negative effects associated with a strategic tillage were on bulk density, soil moisture, and soil carbon stocks. In general, these rarely reached statistical significance even in the immediate time period after tillage (3 months). In the 12 months after tillage the majority of impacts were minimal, indicating a relatively quick recovery in most soils (with some exceptions). Exceptions are poorly structured soils where impacts on these parameters are more significant and longer lasting. Even in poorer structured soils, most effects do not seem to last greater than 24 months. Negative impacts 12 months after tillage were seen on a Sodosol at Condamine with a significant decrease in bulk density, increase in weed density and reduced yield. At this site, a large number of African turnip weeds (*Sysibrium thellungii*) were recorded. Strategic tillage had a negative impact on weed control 12 months after its imposition at this site. At other sites, 12 months after tillage, there were minimal impacts on soil properties and at most sites there was a return to pre-till conditions within 12-24 months.

Provided tillage is not overly aggressive or on-going, the recovery is relatively rapid and unlikely to undo the long term beneficial changes associated with NT systems. Additionally, strategic tillage has the potential to support conservation or NT farming systems to remediate some of the problems of NT, provide appropriate approaches and preparations are addressed. One major benefit of ST is the addition of another method for the control of herbicide resistant and hard to kill weeds. Knowledge of the weed history and potential seed bank is imperative to ensure preparations can be made to prevent the emergence of other weed species. Considerations must also be made to ensure the moisture profile is replenished prior to planting. Furthermore, there must be consideration of the nature of the soil to properly assess risks of smearing (reducing infiltration), compaction, and aggregate breakdown.

The results indicate that ST has a place in conservation farming provided appropriate consideration and implementation is achieved. Single tillage events appear insufficient to significantly alter the long term benefits of NT in the vast majority of cases. In some circumstances strategic tillage will assist in overcoming certain issues associated with NT, thus improving the productivity of fields. Examples could 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.

Despite these benefits from ST, caution must be exercised. In particular, it is important to know the weed history of the paddock as tillage can stimulate emergence of previously dormant seed banks. There is a fine balance between burial for seed persistence and emergence which varies with all weed species, and for that reason it is highlighted that tillage must be used wisely and in combination with other control methods. Soil structure and texture are also very important when considering tillage; soils with moderate to strong structure were not significantly impacted by a strategic tillage whereas poorly structured and texture contrast soils demonstrated detrimental effects on soil health and crop productivity. Timing to ensure adequate rainfall to replenish soil moisture rainfall, yet also avoid extreme rainfall causing erosion, are also imperative.

Recommendations

If tillage is necessary, the most important question to address is the best timing, frequency and implement for such tillage operation. Timing of ST has the major implications for the success or failure of such operation. Limited research on the ST timing in continuous NT suggest that farmers should analyse long-term historical rainfall data and risk-management tools that have been developed. These tools are based around rainfall probabilities and seasonal forecasts using southern 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 ploughs is rare in Queensland and NNSW. Most growers use non-inversion tillage based on tine 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. Use of ST operations in soils that exhibit texture contrast properties (Sodosols) and weakly structured A-horizons (Dermosols) are likely to suffer negative soil health impacts and should be treated with caution. Further it is recommended that ST operation should occur after legume crop to increase the capacity of soil microbes to release nitrogen and for the ease of handling small stubble quantities.

One of the main objectives of inclusion of ST in NT farming systems is to manage herbicide resistant weeds, soil- and stubble-borne diseases and insects that have a below-ground pupal stage, as advocated in Integrated Weed Management and Integrated Diseases and Pest Management strategies. However, it is difficult to determine how long one-time ST operation would be effective in keeping otherwise NT fields below the economic thresholds of weed, disease and insect populations. Tillage could also potentially move buried seed to the soil surface and thus into a more favourable environment for weed seed germination.

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 strategic tillage 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.

In north-eastern Australia, most growers use non-inversion cultivation based on tine and disc implements. Tines lift and shatter the soil removing shallow compacted layers with effective in-crop weed management, deep placement of nutrients and alleviating soil physical constraints. Disc cultivation cuts and mixes stubble and breaks soil clods to leave a fine tilth for effective disease and pest management and fallow period weed management.

Appendix A: Supplementary Information

The Project team

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CSIRO: Jeremy Whish

RPS: David Freebairn

GRDC: Gus Manatsa, Martin Blumenthal, Rob Taylor

Land Holders & Agronomists: “Callitris” Condamine - Rod & Margaret Hamilton; “Killaloe” Moonie - Nev & Penny Boland; “Yallambee” Wee Waa – Ken Stump; “Grandview” Biloela – Darren Jensen; “Waverley” Felton - Paul & Samantha Fulbohm; “Luellen” Moree – Geoff Manchee; “Wyobi” Jimbour West – Warakirri Farming Co.; “Wondalli” Yelarbon – Paul McNaulty & Paul Caster (Agronomist); “Kolora” Emerald – Brian & Val Gregg; Goondiwindi – Agronomist Stuart Thorn.

Extension Activities

Field day was organised to demonstrate relative performance of long-term no-till and strategic occasional tillage applied on long-term no-till soil at Wee Waa, 13th September 2012.

Field walk at Biloela, GRDC Roadshow 2013, presentation to ~50 growers and agronomists.

Extension to GQ growers through presentation at the GRDC Roadshow (Biloela 9th September 2014).

Presentations at GRDC updates at Coonabarabran, Goondiwindi and Dalby February 2013.

Presentation by Yash Dang at the Condamine field day in 2013 to demonstrate the use of strategic tillage

Presentation at Grain and Graze meeting at Goondiwindi 2013.

Field days were organised to demonstrate relative performance of long-term no-till and strategic occasional tillage applied on long-term no-till soil at Moree (May 3rd 2013), Condamine (26 June 2013) and Tulloona (01 March 2013).

Grains Research Update – Northern Region. Summer 2014, Issue 74. Strategic tillage Project – Results from two years of trials.

Field day; Jimbour (21st October 2014) included presentation of both the key findings from the northern and southern region - in conjunction with Mark Conyers (Southern Region). The field day included ~20 growers and advisors in addition to ~20 students from Dalby State High School.

Strategic tillage field day; presentation to growers and agronomists by Mark Crawford, Biloela.

A field day; Yelarbon (14th April 2014) with ~20 growers and advisors attending.

Field site demonstration at Moree.

Field day, Yelarbon 2014. Presentation by Mark Crawford.

Resources produced

GRDC - Strategic Tillage Fact Sheet produced July 2014. The fact sheet provided growers and agronomists information on some of the key issues which had been raised with long term no-till management. The fact sheet also provided information on the optimal way that occasional strategic tillage could be introduced into the system to best manage the specific issues. It detailed the results of the trials to date, the successes of strategic tillage and the precautionary way in which strategic tillage could be used to benefit the system.

http://www.grdc.com.au/GRDC-FS-StrategicTillage


JULY 2014

STRATEGIC TILLAGE
FACT SHEET

GRDC
Grains Research & Development Corporation

NORTHERN AND SOUTHERN REGIONS

IS THERE ROOM FOR STRATEGIC TILLAGE IN A NO-TILL SYSTEM?

No-till has brought benefits in moisture retention and soil structure, but has also contributed to increased incidence of soil and stubble-borne diseases, herbicide resistant hard-to-kill weeds and stratification of immobile nutrients near the soil surface. Growers are asking the question: How much damage is done to soil by occasional tillage, strategically applied, in an otherwise no-till system?

KEY POINTS

- Conservation farming involves reduced tillage, stubble retention and good rotations. This underpins sustainable grain production systems worldwide.
- Current advice on soil tillage management contains apparent contradictions. Some flexibility may be required in the application of conservation farming practices.
- No-till has revolutionised cropping, but has resulted in an increased reliance on herbicides, leading to herbicide-resistant weeds.
- A lack of tillage can cause nutrient stratification and favour diseases such as crown rot, Rhizoctonia and Pseudomonas.
- Conventional tillage can suppress plant parasitic nematode populations, lower the number of snails and slugs prior to canola crops, and lower mice numbers in affected fields.

Introduction

Farming practices have been evolving to make best use of new technologies as they become available.

No-till farming with stubble retention is one such practice. It allows better infiltration of water and water retention, less erosion, and reduced labour, machinery and input costs by removing some operations from the cropping program.

However, conventional tillage was effective in managing weeds, and the move to no-till

Ground Cover TV – Episode 11 of GRDC was distributed with Issue 106 of Ground Cover, and was also made available on YouTube via GRDC TV. The episode detailed the trials being carried out at "Callitris" in Condamine, at the property of Rodney and Margaret Hamilton. The episode outlined the underlying causes that strategic tillage was being researched, and the potential for its integration into farming systems. The episode also detailed the outcomes of the research to that point, and showed that tillage, when applied appropriately, could be a useful farming tool.


Could strategic tillage enhance no-till systems

ABC Rural Cassie Hough

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Posted 27 Jun 2013, 2:02pm

Could an occasional cultivation be an option for farmers who are looking to balance the soil benefits often associated with no-till farming methods with the problem of increasing herbicide-resistance?

No-till farming is a way of growing crops without disturbing the soil by ploughing.

However a three year project in the northern cropping zone is looking at whether introducing a strategic tillage might enhance the system.

Strategic tillage is the use of opportunistic tillage for desired outcome, at the right time with the right implement to address some of the specific issues related to no-till farming.

Soil scientist with the Queensland Department of Science, Information Technology, Innovation and the Arts, Dr Yash Dang says there are a number of elements to look at when evaluating strategic tillage.

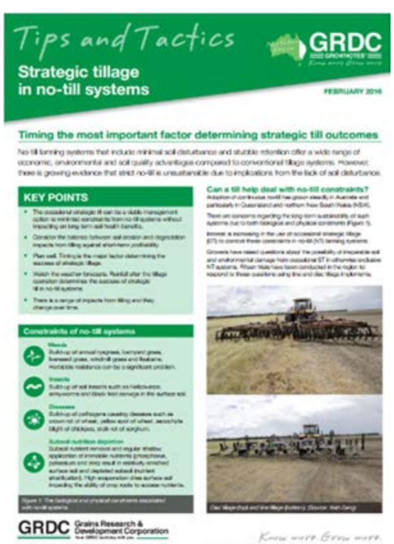
PHOTO: Strategic tillage trial continues (Tara De Landgrafft)

00:01 04:28

AUDIO: No-till benefits in tillage trial (ABC Rural)

MAP: Condamine 4416

At a similar time, an ABC radio interview, broadcast during the ABC Southern Queensland's "Country Hour", was released detailing the drivers for the strategic tillage research project, in conjunction with the outcomes to date and the way in which strategic tillage could be implemented for maximum effectiveness.


Tips and Tactics

GRDC

Strategic tillage in no-till systems

FEBRUARY 2016

Timing the most important factor determining strategic till outcomes

KEY POINTS

Can a till help deal with no-till constraints?

Constraints of no-till systems

GRDC Grains Research & Development Corporation

A decision support fact sheet (Tips and Tactics) was produced in 2016. This compiled the work carried out over the course of the research project and was aimed at delivering a comprehensive decision tool to farmers and agronomist who were considering the use of tillage. The decision support tool has outlined the most appropriate timing, implements choice, cautions and considerations, and expected outcomes when carrying out a tillage operation to deal with specific problems.

http://www.grdc.com.au/Resources/Factsheets/2016/03/Strategic-tillage-in-no-till-systems

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Dang Y, Crawford M, Balzer A, Rincon-Florez V, Ng C, Bell M, Dalal R, Moody P, Schenk P, Argent S, Carvalhais L (2014) Strategic tillage impacts in long-term no-till. Nineteenth Australasian Weeds Conference http://www.caws.org.au/awc/2014/awc201413161.pdf (oral presentation)

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Strategic tillage targets feathertop Rhodes grass. (05 November 2012). Queensland Country Life

Tillage findings help herbicide resistance fight (17 May 2013), Farmonline. http://www.farmingahead.com.au/articles/1/8354/20130517/new/tillagefindingshelpherbicideresistancefight


18 FARMING SYSTEMS

Trials study impact of strategic tillage

Trials in northern New South Wales and Queensland have been exploring whether strategic tillage will undo long-term soil improvement that has been built up under no-till


Tillage findings help herbicide resistance fight

RESEARCH results have indicated that one-time tillage may be able to improve grain yields and profitability without losing the benefits of no-till.

RESEARCH results have indicated that one-time tillage may be able to improve grain yields and profitability without losing the benefits of no-till.

Queensland Department of Science senior soil and nutrient management scientist Dr


Strategic tillage in the north

Author: Tom Dixon

No-till farming has been practised in the northern grains region for more than 30 years, but new research shows that its time may be running out.

No till has many advantages for soil health including increased moisture-holding capability and fewer problems with soil erosion. However, an increase in herbicide-resistant weeds could make no till unviable within a few years unless new methods of weed control are found. One option is a return to occasional strategic tillage.

Strategic tillage

"The key to successful no-till farming into the future is likely to be flexibility and the introduction of strategic tillage," says Dr Yash Dang, a GRDC-funded researcher at the Queensland Department of Science, Information Technology, Innovation and the Arts (DSITIA) in Toowoomba.


Condamine growers, Rodney (left) and Sam Hamilton, are looking to the results of strategic tillage trials on their property for a cost-effective alternative to herbicide spraying.

PHOTOS: CLARISSA COLLIS

Strategic cultivation shows on-farm profit potential

On-farm research in southern Queensland is showing that an occasional cultivation for weed control could lift the efficacy of an otherwise no-till system


Strategic tillage bears results

NEIL LYON

28 May, 2014 04:00 AM

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Strategic tillage targets feathertop Rhodes grass

Nov. 5, 2012, 7:30 a.m. Cropping

Biloela grain grower Darren Jensen is hoping a new series of trials will answer the question of what impact tillage control of feathertop Rhodes (FTR) grass will have on his soil health.

http://www.farmonline.com.au/news/agriculture/ cropping/general-news/strategic-tillage-bears-results/2698618.aspx

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Glossary and Acronyms

NT	No Till
ST	Strategic Tillage
NNSW	Northern New South Wales
NGR	Northern Grains Region
SOC	Soil organic carbon
GRDC	Grains Research and Development Corporation
SPSS	Statistical Package for the Social Sciences
EM	Electromagnetic
CT	Conventional Tillage
ZT	Zero Till
TOC	Total organic carbon
POC	Particulate organic carbon
APSIM	Agricultural Production Systems Simulator
ASC	Australian Soil Classification
Ch	Chisel
KCh	Kelly Chain
OD	Offset Disc
BD	Bulk density
VM	Volumetric Moisture
EC	Electrical Conductivity
MAP	Mono-ammonium phosphate
ICP	Ion Coupled Plasma (Spectroscopy)
TMA	Total Microbial Activity
DNA	Deoxyribonucleic acid
T-RFLP	Terminal Restriction Length Polymorphism
FDA	Fluorescein Diacetate
SD	Standard deviation
CN	Curve Number
PCA	Principal Component Analysis
dS/m	deci-Seimens/metre
rRNA	ribosomal ribonucleic acid
AM	Arbuscular Mycorrhizae
DIN	Dissolved inorganic nitrogen
AGRF	Australian Genome Research Facility
DKN	Dissolved Kjehdal Nitrogen
DKP	Dissolved Kjehdal Phosphorous
LSD	Least Significant Difference
EMC	Event mean concentration
MBC	Microbial Biomass Carbon
MBN	Microbial Biomass Nitrogen
TKN	Total Kjehdal Nitrogen
TKP	Total Kjehdal Phosphorous
TSS	Total Suspended Solids
ANOVA	Analysis of Variance
MWD	Mean weight distribution
mbs	months before sowing

SW	Soil Water
NR	Northern Region
DISTI	Department of Science, Innovation, Technology and IT.
CSIRO	Commonwealth Science Industrial Research Organisation
USQ	University of Southern Queensland

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    For more information on how best to implement strategic tillage into your farming system, please follow this link: http://www.grdc.com.au/Resources/Factsheets/2016/03/Strategic-tillage-in-no-till-systems

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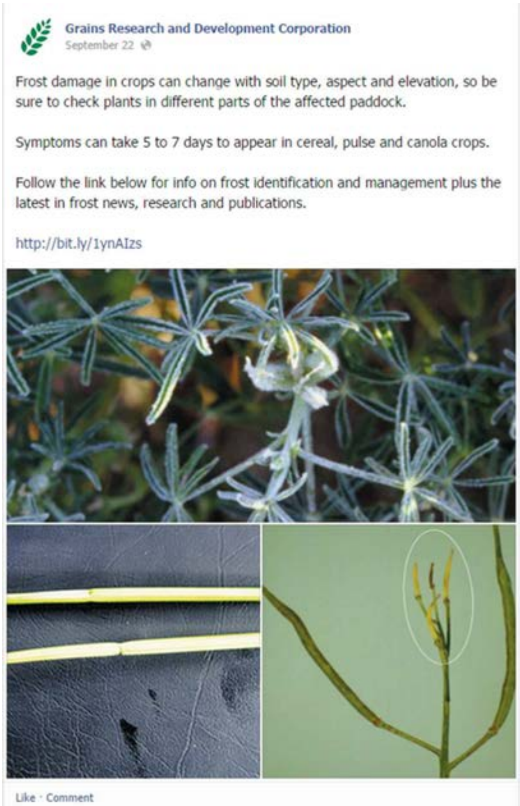

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