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Strategic tillage of a long-term, no-till soil has little impact on soil characteristics or crop growth over five years

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Abstract. Strategic tillage describes the occasional use of tillage in an otherwise no-till system. The practice can provide a pragmatic solution to emerging agronomic issues in no-till systems but raises concerns about prolonged or irreversible soil damage. We investigated the impact of a single tillage event at a long-term no-till experiment under treatments with retained or annually autumn-burned crop residues. One half of each residue-treatment plot received a single pass of a rotary hoe (ST) 4 weeks before sowing in 2011, the first year of the experiment; the other half of each plot remained unchanged (NT). Soil physical, chemical and biological fertility in the surface layers (0–20 cm), as well as crop growth and yield were monitored for 5 years (2011–15). Following the ST treatment, soil bulk density and strength were initially reduced to the depth of cultivation (~15 cm) irrespective of residue treatment. Water-stable macroaggregates in the surface 0–5 cm were also reduced but recovered to pre-tillage levels within 1–2 years after ST treatment. Soil pH, total carbon (C), total nitrogen (N), and fine-fraction C and N were all initially stratified in the surface layer (0–5 cm) of the NT treatment but were redistributed more evenly throughout the 0–10 cm layer of the ST treatment and remained so throughout the 5-year period. With ST, there was an initial loss in total C stocks in the 0–10 cm layer of 2.2 t/ha, which recovered within 2 years; however, total C stocks remained lower in plots with stubble retained than with stubble burnt after 5 years. Soil Colwell P levels were not stratified and not influenced by tillage treatment, presumably because of the annual additions in the starter fertiliser at sowing. ST had no impact on crop establishment or grain yield in any year but increased the early biomass of wheat at Z30 compared with NT in the first 2 years. Annual stubble retention reduced the early growth of crops in all years, and yield of wheat in the first 3 years, consistent with long-term effects of retained stubble at the site, but there was no interaction between stubble retention and tillage treatments on soil conditions or crop growth. Crop yields of long-term, annually cultivated treatments were also similar to those of ST and NT treatments during the 5 years of the experiment. Overall, the minor short-term negative impacts on soil physical conditions, the persistent and arguably beneficial effects on soil chemistry and biology, and absence of impacts on crop production suggest that strategic tillage can be a valuable agronomic tool in sustainable production in this region.

Keywords: acidity, aggregates, carbon sequestration, conservation agriculture, cultivation.

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Introduction

The three major principles of conservation agriculture are eliminating pre-sowing tillage operations and minimising disturbance at sowing in broadacre farming systems (i.e. no-till), retaining residue cover, and maintaining crop diversity. Conservation agriculture originally emerged in response to the 'dust bowl' years in the US and was facilitated in the 1960s by the development of herbicides, which could control weeds without soil disturbance. Currently conservation agriculture accounts for only 12.5% of global crop area (Kassam *et al*. 2019) but has been widely adopted in Australia (Llewellyn and Ouzman 2019) and North and South America (Fischer and Hobbs 2019), where broad-scale, mechanised, dryland agriculture in areas prone to wind and water erosion benefit significantly from the soil-protection and water-conservation elements of the system. According to the 2016 survey of Australian grain growers, 80–90% of the Australian cropped area received no pre-sowing cultivation to establish crops (Umbers 2017). Despite these high levels of adoption of no-till, this survey and others indicate that ~10% of growers still choose to cultivate some of their land before sowing, and that 15% of cropped area may be cultivated in any season, suggesting that Australian farmers have retained a pragmatic approach to tillage within a predominately no-till system (Kirkegaard *et al*. 2014).

The occasional use of tillage in an otherwise no-till system is termed strategic tillage, and has emerged from the need to deal with agronomic constraints that can develop under long-term no-till systems such as subsurface acidity (Conyers *et al*. 2003; Li *et al*. 2019), water-repellent surface soils (Chan 1992; Hall *et al*. 2010), nutrient stratification (Paul *et al*. 2003), some soil-borne pests and diseases such as slugs (Glen and Symondson 2003) or nematodes (Rahman *et al*. 2007), and herbicide-resistant weeds (Owen *et al*. 2007; Powles and Yu 2010). These agronomic issues can all be managed to some extent with appropriate strategic tillage (Kirkegaard *et al*. 2014; Dang *et al*. 2015*a*; Conyers *et al*. 2019*b*). However the appropriate level of soil disturbance in conservation agriculture systems remains contentious, driven principally by concerns that even a single cultivation of the soil can reverse the benefits of long-term, no-till systems on soil physical, chemical or biological fertility (Grandy *et al*. 2006). Evidence for this has been disputed (Baan *et al*. 2009; Wortmann *et al*. 2010) and the wisdom of complete removal of tillage as a tool in the sustainable agronomic management of crops has been questioned for some time (Pierce *et al*. 1994; Kirkegaard 1995; Dick 1997). The duration of long-term no-till experiments and commercial adoption now exceeds 20 years in areas of early adoption such as Australia, and consequently, more opportunities have emerged to investigate the impacts of strategic tillage on soil conditions and crop performance (Conyers *et al*. 2019; Dang *et al*. 2015). In areas of relatively low adoption such as sub-Saharan Africa, the fit for strict conservation agriculture with no soil disturbance in no-till systems has come under scrutiny (Giller *et al*. 2015), and in Australia, Kirkegaard and van Rees (2019) suggest that strategic tillage forms part of a maturing in the evolution of conservation agriculture systems from the necessary protective origins and recent prescriptive phase towards a more flexible and pragmatic future. Nevertheless, ongoing concern regarding impacts of tillage on soil health persist (Peixoto *et al*. 2020), particularly the impact of tillage on the loss of soil organic matter (SOM).

The historic losses of soil carbon (C) from cultivating agricultural land are vast (Sanderman *et al*. 2017), yet recent studies have called into question the role of no-till in sequestering soil C. In a recent review, Richardson *et al*. (2019) points out that although several studies support the proposition that no-till systems sequester more soil organic C than tilled systems, this often relates to the stratification of less stable forms of organic C in the surface, with lower levels at depth (Baker *et al*. 2007), whereas cultivation can increase organic C at depth, especially with residue incorporation (Alcántara *et al*. 2016). Incorporation of residue-C into microbial biomass has been facilitated by cultivation and soil mixing (Helgason *et al*. 2014), and with careful attention to the stoichiometric ratios of the C and stabilising nutrients nitrogen (N), phosphorus (P) and sulfur (S), incorporated residues can ultimately increase the levels of stable SOM (Kirkby *et al*. 2016; Coonan *et al*. 2020). The recent meta-analysis by Sun *et al*. (2020) also confirms the important role of climate in determining the likely effect of no-till on crop yield and soil C sequestration, with 'win–win' outcomes for increased yield and soil C most likely in the warm, arid regions of the world. Beyond C sequestration, the motives to maintain higher levels of SOM may also need reassessing, because recent studies suggest the contribution of SOM to crop yield is almost entirely due to the supply of nutrients and not to effects such as increased C, improved soil structure, or enhanced water-holding capacity as is often believed (Chen *et al*. 2018; Schjønning *et al*. 2018; Minasny and McBratney 2018; Celestina *et al*. 2019). These revelations reinforce the argument that no-till is best adopted with pragmatism, and according to the specific soil, climate and agronomic circumstances that can arise in specific farming systems.

The effects of long-term tillage and stubble management strategies have generally been investigated in long-term experiments, where the changes in soil and crop response to consistent management treatments can be carefully monitored over time. In this study, we utilised a long-term tillage and stubble-management experiment that had been established for 20 years and where soil biological, physical and chemical factors impacting crop growth had been investigated throughout the experiment since its commencement in 1990 (Kirkegaard *et al*. 1994; Kirkegaard 1995; Simpfendorfer *et al*. 2001; Watt *et al*. 2006; Kirkby *et al*. 2016). The design of the experiment facilitated the opportunity to introduce a one-off strategic tillage event to soil that had not been cultivated for 20 years, both with and without retained crop residue, and to monitor soil conditions and crop growth in the short and medium term (5 years) compared with ongoing no-till.

Materials and methods

Site and experimental design

The experiment was performed at a long-term field experimental site on a private farm ('Oxton Park') near Harden, in the wheatbelt of southern New South Wales, Australia (34°30′S, 148°17′E). The site is at an elevation of 497 m a.m.s.l. and sloping (3%); the soil is a Red Chromosol (Isbell 2002), well drained with a sandy-loam surface texture (clay 15%, silt 10%, sand 75%). The long-term experiment had been established in 1990 to assess the effects of different tillage and stubble-management treatments on soil fertility and crop performance in a continuous, annually cropped system, as first reported by Kirkegaard *et al*. (1994) and more recently by Kirkegaard *et al*. (2014). The seven soil management treatments, including various tillage and crop-residue treatments, were replicated four times in a randomised block design. Individual treatment plots (30 m by 6 m) comprised two paired sown subplots (30 m by 2 m), side by side, separated by a central 1-m buffer and with a 0.5m buffer on either side of the plot to allow controlled-traffic management (i.e. no wheel traffic on the plots). The characteristics of the soil at the site are shown in Table 1.

The experiment reported here utilised two of the long-term treatments, burn–no-till (B-NT) and retain–no-till (R-NT), neither of which had been cultivated for 20 years (since 1990) at the commencement of this experiment in 2011.

Table 1. Characteristics of the soil at the Harden long-term tillage site in 2010

Depth (cm)	pH ($CaCl_2$)	EC (mS/cm)	BD (g/cm^3)	Organic C (%)	Organic N (%)
0–10	6.4	0.098	1.36	0.87	0.08
10–20	5.8	0.054	1.62	0.51	0.05
20–30	6.2	0.047	1.61	0.32	0.03
30–60	6.5	0.062	1.66	0.23	0.03
60–90	6.4	0.076	1.76	0.15	0.02
90–120	6.5	0.065	1.78	0.11	0.02
120–150	6.2	0.060	1.82	0.08	0.02
150–180	6.0	0.051	1.86	0.05	0.01

Both treatments had the crop residues retained standing over summer each year between harvesting (November) and early April, with no livestock grazing. In early April each year, the residues were burnt before sowing in the B-NT plots, and retained on the R-NT plots. Generally, the crop sequence over the 20 years before the establishment of the strategic tillage experiment (i.e. 1990–2010) had been 1 year of wheat (*Triticum aestivum*) followed by 1 year of break crop (either lupin, *Lupinus angustifolius*, or canola, *Brassica napus*), although the crop sequence in the 4 years immediately preceding this experiment (2007–10) had been wheat–wheat–wheat–canola (Kirkby *et al*. 2016). Strategic tillage (ST) treatments were imposed in 2011, allocated randomly to one of the subplots (i.e. 30 m by 2 m) in both the B-NT and R-NT treatments; the other subplot remained unchanged. In this way, the impact of a one-off tillage event on a no-till system in terms of soil characteristics and plant growth could be monitored over the subsequent 5 years, with both retained and burnt residue.

The long-term experimental site also included burn–cultivate (B-C) and retain–cultivate (R-C) treatments, which were also established in 1990, and in which the soil was cultivated once with a scarifier (tines to a depth of 10 cm) annually 2–10 days before sowing. These treatments were maintained during the strategic tillage experimental period; and crop growth and yields on those plots were measured and are reported for comparison.

A long-term (5-year) perennial pasture comprising predominately phalaris (*Phalaris aquatica*) and lucerne (*Medicago sativa*) in an adjacent paddock was also sampled for some soil physical parameters, given the known capacity for pasture to improve soil physical conditions (Bell *et al*. 1997).

The ST treatments were imposed on 21 April 2011, using one pass of a tractor-driven rotary hoe (Howard Rotavator HR30), to a depth of 10–12 cm. Following the hoeing, the soil was immediately lightly re-consolidated with a rubber-tyre roller in order to provide more uniform sowing depth for the 2011 wheat crop. This effectively created the following four treatments, coded as follows:

(i) B-NT (1990–2015), no pre-sowing tillage, stubble burnt yearly in autumn (early April);
(ii) B-ST, as for B-NT, but rotary-hoed once on 21 April 2011;
(iii) R-NT (1990–2015), no pre-sowing tillage, stubble retained;
(iv) R-ST, as for R-NT, but rotary-hoed once on 21 April 2011.

The other treatments at the site for which comparative crop growth data were available during the same period were:

(i) B-C (1990–2015), one pre-sowing cultivation annually (tine), stubble burnt in autumn (early April);
(ii) R-C (1990–2015), one pre-sowing cultivation annually (tine), stubble retained.

Soil sampling and analyses

Soil physical, chemical and biological properties were measured on samples taken from the site following the implementation of the ST treatments on 21 April 2011, and before, on 11 April 2011. The sampling of soil was generally more intense in the first growing season (2011: samples taken immediately after implementation of ST treatments, then 7, 21 and 40 days later), to investigate the immediate changes in the soil characteristics following tillage, and then annually (in April–May) over the next 4 years to follow soil recovery. Sampling strategies and analytical methods for the various properties are described below.

Soil chemical properties

Sampling for determination of soil chemical properties was done at all sampling times listed above. Cores were taken to a depth of 20 cm, using a 5.6-cm-diameter corer, and divided into 5-cm increments (composite of five subsamples per plot). The methods of Rayment and Lyons (2011) were used for chemical analyses of the composite samples: soil pH (0.01 M $CaCl_2$; method 4B1), Colwell P (method 9B1), and total C and N percentages (LECO; method 6B2b). The change in total C stocks (t/ha) in the 0–10 cm layer was calculated by using bulk density and C percentage measures for the 0–5 and 5–10 cm layers.

Soil physical properties

Sampling for measurement of wet aggregate stability (WAS) was also done at all sampling times listed above. Samples were taken to a depth of 10 cm and divided into 5-cm increments (composite of five subsamples per plot). The soil was carefully broken into layers to minimise aggregate disruption and then oven-dried at 36°C. Macroaggregates are defined as >250 μm diameter and microaggregates as <50 μm diameter. Aggregates in each class were measured by an oscillating 3-cm pass through water for 10 min at 30 cycles per min on nested sieves (Yoder 1936).

Saturated hydraulic conductivity, *Ksat*, was measured on one occasion during 23–25 August 2011 (Day 124 after ST treatment). Ring infiltrometers (nominally 30 cm diameter, area 692–700 cm^2) were placed at three locations within each of four replicate plots per treatment. Readings of the water level in the Mariotte bottle were taken until a stable rate of infiltration was obtained, generally after ~30 min.

Soil bulk density and penetrometer readings were also taken during 23–25 August 2011 (Day 124 after ST), during early crop growth, when the profile was wet to field capacity. Penetrometer resistance was measured with a digital recording cone penetrometer (CP40, 12.7-mm tip diameter; RIMIK, Toowoomba, Qld) to a depth of 45 cm with five readings taken per plot. Bulk density was measured in 5-cm increments to 30 cm depth by removing intact cores with a 5.6-cm-diameter corer and separating soil into 5-cm increments before drying at 105°C to determine oven-dry weight. In addition, soil bulk density was monitored in the 0–20 cm layer over time, using the soil cores collected for soil chemical analyses.

The long-term perennial grass–legume pasture paddock adjacent to the experimental site was monitored for bulk density and WAS in 2011.

Soil biological properties

Samples for determination of microbial biomass and fine-fraction soil organic C (FFC) and N (FFN) (i.e. SOM) were taken at 7, 21 and 40 days after tillage in 2011, and then annually in April (July in 2013). Five soil cores were taken to a depth of 10 cm in each plot and divided into 5-cm increments. FFC and FFN were prepared for analysis by using the dry-sieving–winnowing procedure described in detail by Kirkby *et al*. (2011). Briefly, air-dried soils were sieved to 2 mm, and coarse (>0.4 mm) or light fraction organic material was removed by dry-sieving–winnowing, leaving only the more stable, slowly decomposing fine-fraction SOM. A 100-g subsample was pulverised to <50 μm and total C and N concentrations were determined with a dry-combustion analyser (Model 20-20; Europa Scientific, Crewe, UK). The microbial biomass was estimated as chloroform-labile C using the fumigation-extraction method (Vance *et al*. 1987). Two subsamples were taken from each replicate, making a total of eight samples for each treatment analysed for microbial biomass.

Crop growth, plant sampling and analysis

Crop establishment, growth and yield were monitored for each crop over 5 years following the strategic tillage in 2011. The sequence of crops grown over the period was wheat–wheat–wheat–lupin–canola; the agronomic management details are shown in Table 2. Weeds, diseases and insect pests were all successfully controlled throughout the experimental period. Established plant populations were measured each year during the early crop growth stage (2–3-leaf stage) by measuring the number of established plants along 10 randomly selected 0.5-m lengths of row. Biomass was measured at stem elongation in wheat crops (Z30; Zadoks *et al*. 1974), and at anthesis in wheat (Z69) and broadleaf crops (mid-flowering), by cutting the shoot material at ground level from two 0.4-m^2 quadrats and oven drying at 70°C. At physiological maturity the aboveground material was removed from two 1-m^2 quadrats in each plot for measurement of seed yield, harvest index and yield components after threshing, seed cleaning and oven drying. Yield components were calculated by counting the heads on a subsample and measuring 100-seed weights. The entire plots were harvested with a plot harvester, leaving standing residue on the plots, and the harvested yield and hand-cut yields were compared so as to ensure consistency in terms of treatment effects. The hand-harvested yields are presented here because the conditions at machine-harvest can influence levels of seed loss from the harvesters.

Data analyses

Soil data were analysed separately at each sampling time and depth using two-way analysis of variance in GENSTAT 20th edition (VSN International, Hemel Hempstead, UK) and SigmaPlot version 14 (Systat Software, San Jose, CA, USA), to test the main effect and interactions for tillage and residue. Where significant differences existed ($P < 0.05$), the treatment means were compared using least significant difference. In cases where there was no significant interaction between tillage and residue treatments, the tillage treatments were averaged across residue treatments for presentation. Crop growth and yield data were analysed in a similar way at each sampling date. In order to compare the crop growth data from the R-NT, B-NT, R-ST and B-ST treatments with the long-term cultivation treatments (B-C, R-C) over the 5 years following the ST treatment (2011–15), a separate analysis of variance was conducted with factorial combination of two residue-management treatments (R or B) and three tillage treatments (NT, ST and C).

Results

Seasonal conditions

Annual rainfall was close to or above the long-term average of 607 mm in all years of the experiment except 2013 (Table 2), when summer and spring rainfall were low but

Table 2. Details of crop agronomy and management during 2011–15 at the Harden long-term experimental site
Average long-term annual rainfall for Harden is 607 mm

	2011	2012	2013	2014	2015
Crop	Wheat	Wheat	Wheat	Lupin	Canola
Variety	Bolac	Elmore	Gauntlet	Mandelup	45Y25RR
Seeding rate (kg/ha)	60	70	70	93	3.2
Row spacing (cm)	18	18	18	30	30
Target density (plants/m^2)	150	150	160	50	60
Starter fertiliser (N : P : S, kg/ha)	16 : 13 : 12	15 : 12 : 11	8 : 17 : 1	0 : 7 : 9	8 : 15 : 1
Topdressed N as urea (kg N/ha)	90	173	150	0	0
Sowing date	5 May	8 May	16 May	14 April	25 May
Anthesis	18 Oct.	16 Oct.	10 Oct.	25 Aug.	15 Sept.
Physiological maturity	29 Nov.	4 Dec.	26 Nov.	20 Nov.	10 Nov.
In-crop rainfall (April–Oct, mm)	330	289	277	282	354
Annual rainfall (mm)	738	707	348	554	606

winter rainfall was close to average (Fig. 1). The 2011 and 2012 years featured high summer-fallow rainfall, and although most years had close-to-average winter rainfall, there were prolonged periods in spring of below-average rainfall in 2012, 2013 and 2014 (Fig. 1). There were no periods of extreme heat (>30°C) or significant frost damage during the critical period of yield formation (data not shown) and no disease or pest outbreaks, so crops could express water-limited yield potential.

Soil conditions

Soil chemical properties

In the long-term NT soil in 2011, the pH and C and N percentages were stratified with higher values in the top 5 cm of soil, decreasing with depth (Fig. 2*a–c*). Irrespective of the residue treatment, the ST treatment had significant effects on the redistribution of pH, C and N, all of which decreased in the 0–5 cm layer and increased in the 5–10 cm layer, and in some cases the 10–15 cm layer, following implementation of the ST treatment (Fig. 2*a–c*). These changes persisted throughout the experiment to 2015, especially for C and N percentages, which maintained similar overall levels throughout that time. For pH, the effects of the ST treatment tended to become less pronounced and declined over time throughout the profile (Fig. 2*a*, *e*, *i*). Colwell P concentration was less stratified than the pH in 2011 (Fig. 2*d*), and there was no significant impact of ST treatment on soil P levels at any depth or time (Fig. 2*d*, *h*, *l*), presumably because new fertiliser P was added each year to all treatments at the depth of sowing. Stubble-retained treatments had reduced pH at all depths irrespective of tillage (Fig. 2*a*, *e*, *i*), and increased P at some depths (Fig. 2 *d*, *h*, *l*), but there were no significant effects on soil C or N at any depth, and no interaction between stubble retention and the tillage effects.

Soil physical properties

Soil bulk density and penetrometer (soil strength) measurements in August 2011 showed a reduction in both parameters from 5 cm to the depth of cultivation (~15 cm) in the ST treatments (Fig. 3*a*, *b*), but no significant effect of stubble treatment, and no interaction. The similarity in measures at the very surface is likely to reflect soil disturbance to 5 cm by the sowing process, and greater depths than 15 cm were beyond the tillage zone. There was no evidence that the rotary hoe caused an increase in density or soil strength below the depth of disturbance. The surface-soil (0–5 cm) bulk density in the ST treatments reconsolidated quickly after the initial disturbance, and the annual disturbance by sowing in both ST and NT treatments meant few consistent differences existed after that point (Fig. 4*a*). In the 5–10 cm layer, lower bulk density in the ST treatments persisted until 2013, but there was no difference between tillage or stubble treatments after that point (Fig. 4*b*). By comparison, the NT treatments had bulk densities that approached those of the nearby undisturbed grazed pasture in both soil layers (Fig. 4), with the somewhat higher levels on the pasture presumably related to grazing livestock and lack of soil disturbance.

Total C stocks in the surface 0–10 cm layer were calculated from the bulk density and soil C data presented in Fig. 2*b*, *f*, *j* and Fig. 4*a*, *b* to determine whether the redistribution of soil C and reduction in bulk density in ST treatments resulted in a net loss of C stocks (Table 3). In 2011, there was a significant initial reduction in total C in the top 10 cm in the ST treatments, related to both reduced C concentration and

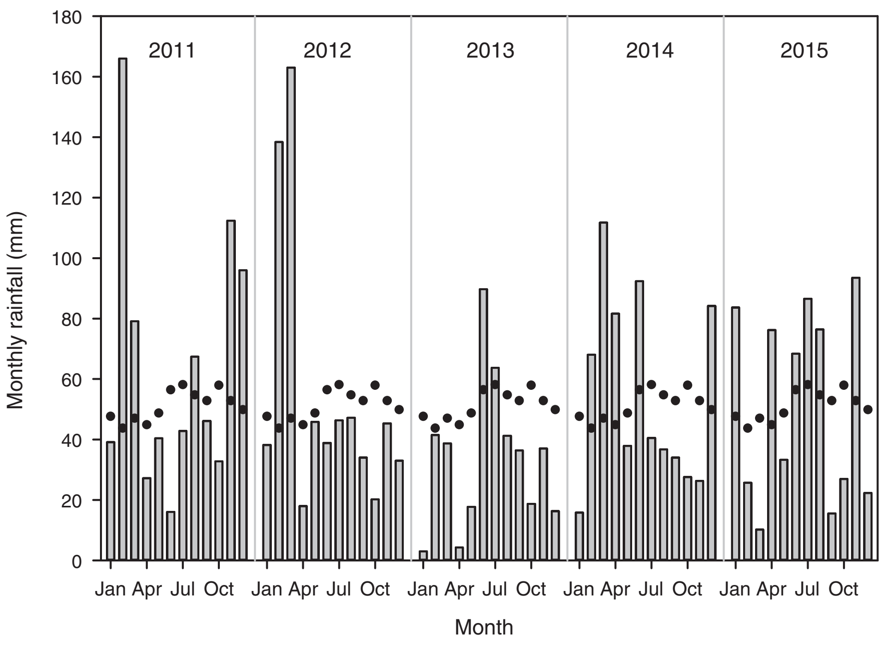

Fig. 1. Monthly rainfall for the experimental period (2011–15, bars) and average monthly rainfall (•) for the Harden long-term experimental site.

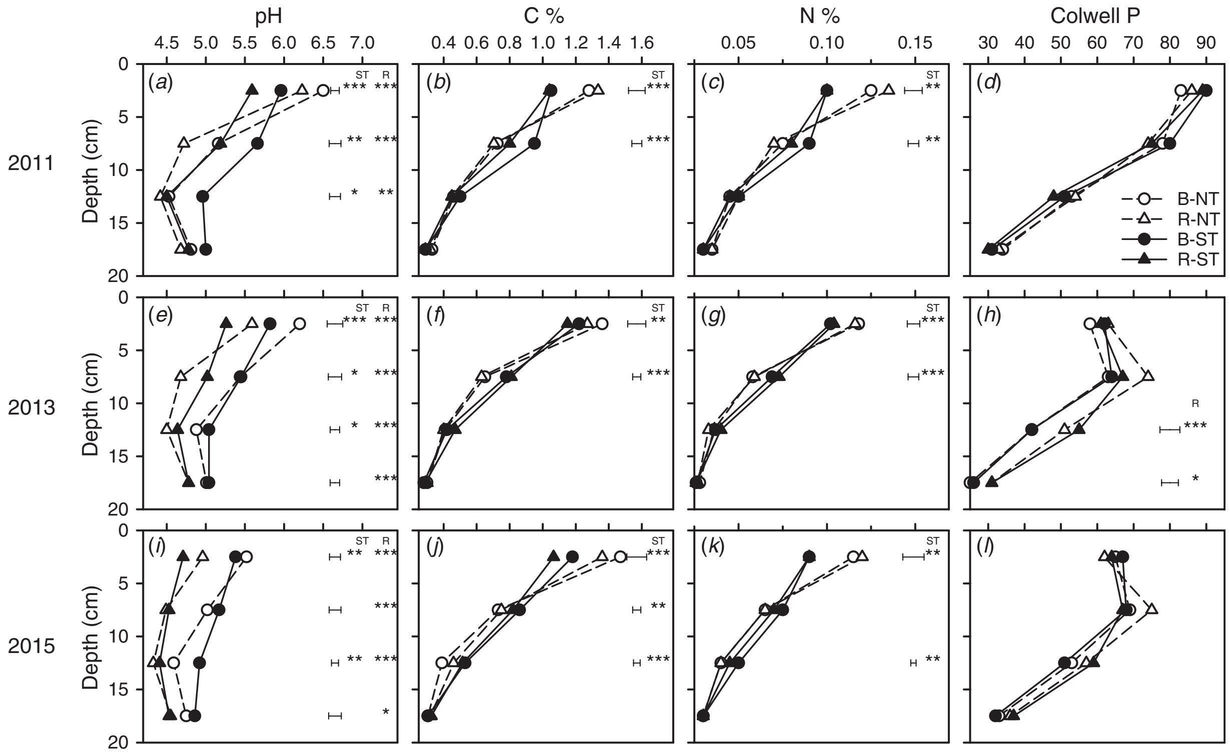

Fig. 2. Effect of tillage (ST, strategic till; NT, no-till) and residue (R, retained; B, burnt) treatments on soil chemical properties in the 0–20 cm layer on 28 April 2011, 22 May 2013 and 13 April 2015 at the Harden long-term experiment. Horizontal bars are l.s.d. ($P = 0.05$) for the strategic tillage and residue main effect, shown only where significant differences exist: *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

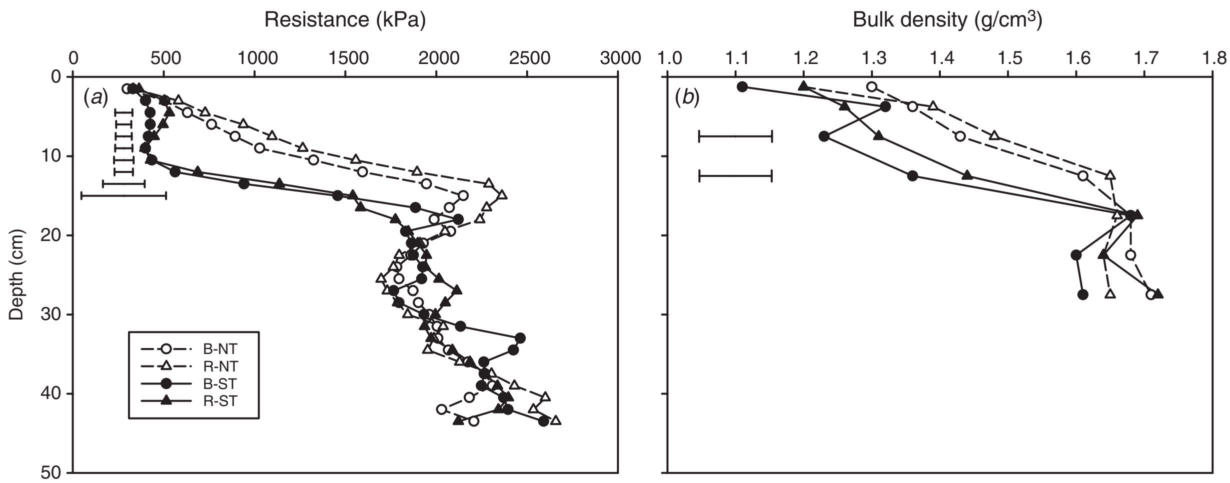

Fig. 3. Effect of tillage (ST, strategic tillage; NT, no-till) and residue (R, retained; B, burnt) treatments on (*a*) soil penetrometer resistance and (*b*) bulk density measured in August 2011 at the Harden long-term tillage experiment. Horizontal bars are l.s.d. ($P = 0.05$) for the strategic tillage and residue main effect, shown only where significant differences exist.

bulk density, which was apparently not compensated by the increase in C percentage in the 5–10 cm layer (Figs 2, 4). However, in 2013 and 2015, although the levels of total C were similar in the ST and NT treatments, levels were lower in the R than the B stubble treatment (Table 3).

There was no effect of the tillage and residue treatment on saturated hydraulic conductivity, but the data were variable across the site (Fig. 5). B-NT had consistently low values, possibly as a result of less surface variation due to the lack of both crop residue and surface roughness from tillage, but readings for the other treatments were highly variable. The generally high readings (450–800 mm/h) suggest a limited impact of the treatments on water infiltration given the relatively low rainfall intensity typical in the area (<50 mm/h).

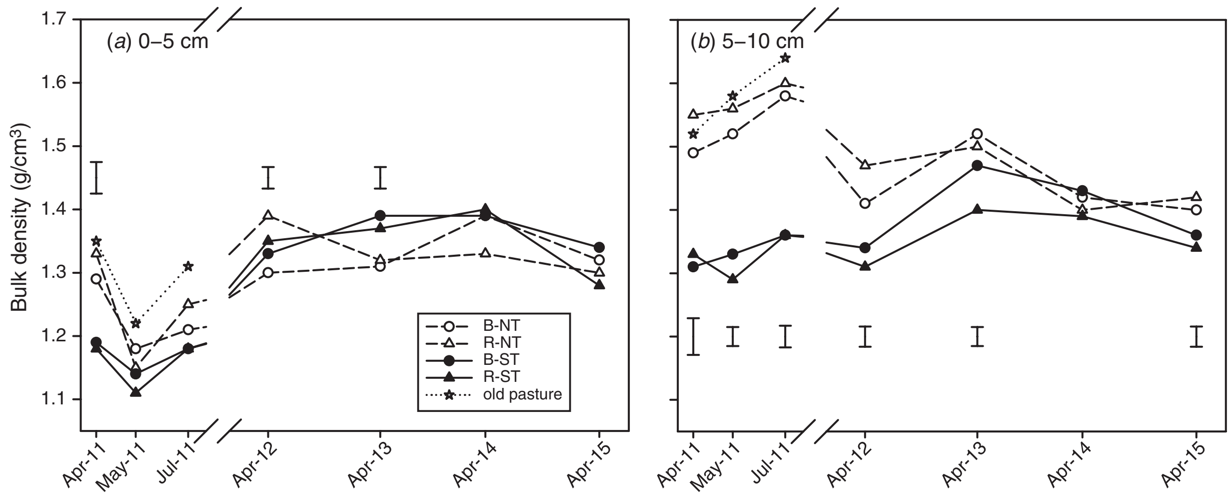

Fig. 4. Effect of tillage (ST, strategic till; NT, no-till) and residue (R, retained; B, burnt) treatments on bulk density in the (*a*) 0–5 cm layer and (*b*) 5–10 cm layer at the Harden long-term experiment. Vertical bars are l.s.d. ($P = 0.05$) for the strategic tillage and residue main effect, shown only where significant differences exist.

Table 3. Effect of tillage (ST, strategic tillage; NT, no-till) and residue (R, retained; B, burnt) treatments at the Harden long-term site on the total C stocks (t/ha) in the top 0–10 cm

Calculated using data on C percentage (Fig. 2) and bulk density (Fig. 4). *$P < 0.05$; **$P < 0.01$; n.s., not significant ($P > 0.05$)

	2011	2013	2015
B-NT	14.3	15.1	15.5
R-NT	14.3	13.1	14.0
B-ST	12.6	14.4	15.0
R-ST	11.6	13.9	12.2
l.s.d. ($P = 0.05$)			
Tillage	1.8**	n.s.	n.s.
Residue	n.s.	1.1*	1.8*
Tillage × residue	n.s.	n.s.	n.s.

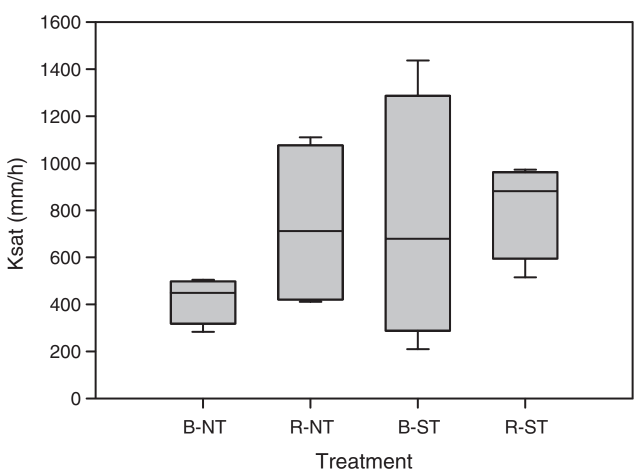

Fig. 5. Effect of tillage (ST, strategic till; NT, no-till) and residue (R, retained; B, burnt) treatments on saturated hydraulic conductivity (*Ksat*) at Harden in August 2011. Central line represents median, boxes 25% and 75% percentile, and bars 10th and 90th percentiles.

In the R-NT treatment on 11 April 2011 (before implementation of the ST treatment), ~70% of the surface soil (0–5 cm) was in stable macroaggregates, a similar level to that in long-term pasture measured adjacent to the site (Fig. 6*a*). B-NT had a somewhat lower level of stable macroaggregates at ~62%. Implementation of the ST treatment reduced the level of stable macroaggregates to ~60% in both R-ST and B-ST. R-NT maintained the highest macroaggregate stability in the 0–5 cm layer throughout the 5 years of the experiment, and although both ST and B treatments reduced aggregate stability, all treatment combinations tended to converge after 2 years, and all remained at >60% macroaggregates. By contrast, microaggregates in the 0–5 cm layer were lowest in R-NT and highest in B-ST, but the differences tended to be small and inconsistent (Fig. 6*a*). In the 5–10 cm layer, the macroaggregate stability of NT soil was less than that of ST soil (Fig. 6*b*), suggesting that some of the loss of macroaggregates in the 0–5 cm layer was simply due to mixing of the 0–5 cm and 5–10 cm layers of the soil by implementation of the ST treatment, rather than solely caused by the destruction of macroaggregates in the 0–5 cm layer. In common with the 0–5 cm layer, most of the differences in aggregate stability generated by implementation of the ST treatment had disappeared after 2 years.

Soil biological properties

There were no significant effects of stubble retention on microbial biomass, FFC or FFN at the site in the 0–5 cm or 5–10 cm depths, and no interactions between stubble and tillage treatments; therefore, tillage-treatment data have been averaged across stubble treatments for presentation (Fig. 7*a*, *b*). Immediately following implementation of the ST treatment on 21 April, there was significant stratification in C and N between the 0–5 and 5–10 cm layers but no difference was evident at that time between the ST and NT treatments.

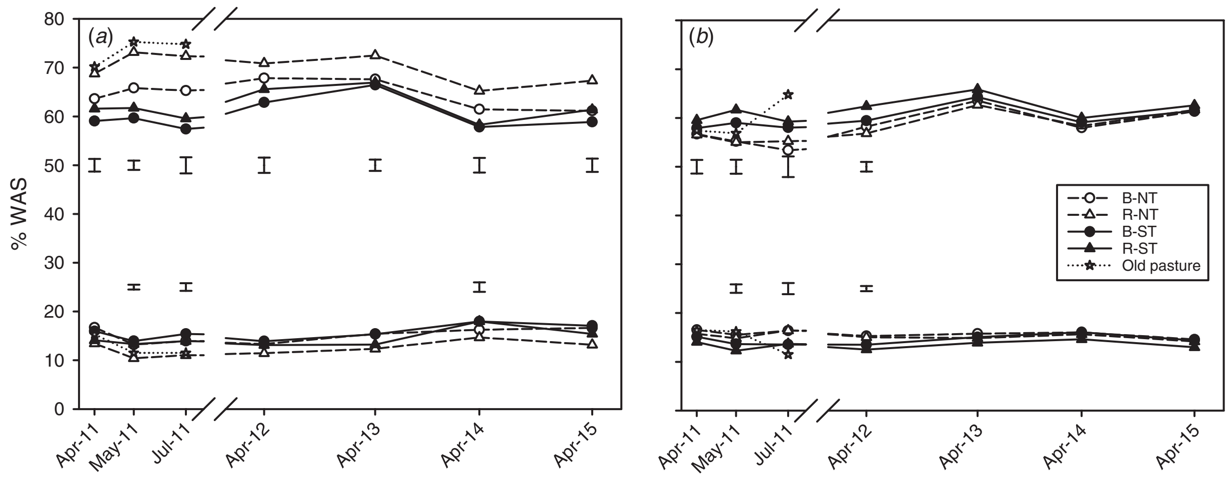

Fig. 6. Effect of tillage (ST, strategic till; NT, no-till) and residue (R, retained; B, burnt) treatments on wet aggregate stability (WAS) in the (*a*) 0–5 cm layer and (*b*) 5–10 cm layer at the Harden long-term experiment. In each graph, macroaggregates are the upper datasets and microaggregates the lower datasets. Vertical bars are l.s.d. (P = 0.05) for the strategic tillage and residue main effect, shown only where significant differences exist.

However, 7 days later, the FFC and FFN levels had significantly decreased in the 0–5 cm layer and increased in the 5–10 cm layer in the ST treatment, an effect that persisted throughout the entire experimental period. This represented an effective redistribution across the 0–10 cm layer. Differences were less distinct in the microbial biomass measured immediately after implementation of the ST treatment in 2011, but in 2012 and 2013, patterns of redistribution of microbial biomass similar to those of C and N in the ST treatment were evident although they did not persist (Fig. 7*c*).

Crop growth and yield

As a result of good autumn and winter conditions in all years (Fig. 1), the crops were successfully established in each year of the experiment and all intended crop measurements were completed. In general, only main effects of tillage and residue treatments were observed, with no significant interactions during the experiment (Table 4). Where significant main effects of tillage and residue treatments were observed, the ST treatment tended to increase crop growth but not yield, and this persisted for only 2 years after treatment (2011, 2012). By contrast, the R treatment (which re-occurred each year) tended to reduce the growth of all crops throughout the entire experiment and reduced the yield of wheat from 2011 to 2013, whereas the lupin (2014) and canola (2015) yields were not affected. There was no impact of any treatment on seed quality (seed protein or oil content) throughout the experiment (data not shown).

Comparison of strategic tillage with annually cultivated treatments

Crop growth and yield on the long-term NT plots, including the ST subplots from 2011 onwards, were compared with long-term annually cultivated plots with and without residue (Table 5). The overall performance of the R-NT, B-NT, R-C and B-C from 1990 to 2011 is summarised as the mean yield for the wheat crops harvested during those 11 seasons before implementation of the ST treatment. This provides background to the performance of these treatments in the 20 years before the 5-year period (2011–15) following the implementation of ST treatments and shows an overall yield penalty (0.3 t/ha) for wheat in R plots, but little penalty (<0.1 t/ha) under long-term NT compared with long-term annual tillage irrespective of the residue treatment. This trend is consistent with the impacts of similar treatments across southern Australia reviewed previously (Kirkegaard 1995). Over the course of the 5-year experiment, both the ST and NT treatments had similar yields to the long-term cultivated plots, both R and B, and the overall negative impact of the R treatment persisted. The data suggest that for crop growth at this site, even annual cultivation of the soil over 30 years had not diminished the productive potential of the soil compared with long-term no-till or strategically tilled soil irrespective of residue management, whereas residue retention created a small, but significant and persistent wheat yield penalty at the site.

Discussion

Irrespective of the residue retention treatment, application of a single intensive strategic tillage (i.e. rotary hoe) after 20 years of no-till at the Harden long-term site has had relatively minor and short-lived impacts on soil physical properties, arguably some beneficial impacts on soil chemistry and biology in reducing stratification, and no significant impacts on crop yield. Crop yield was unaffected over the 5-year period following a single strategic tillage event (Table 4) and no different from the yield in treatments cultivated annually during the trial and for 20 years prior (Table 5). This is consistent with previous reports that the overall impacts of tillage *per se* on crop yields at this site and other long-term sites in Australia are relatively minor (Kirkegaard 1995; Armstrong *et al*. 2019). Notwithstanding the need for

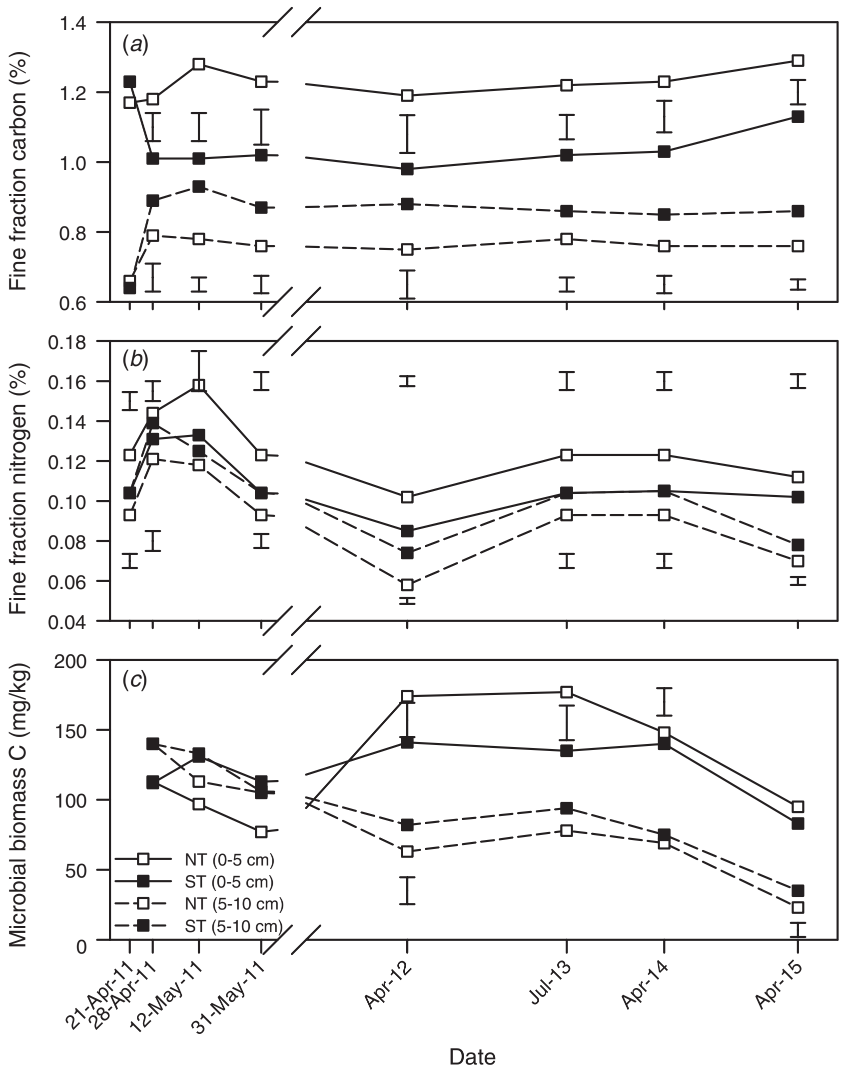

Fig. 7. Effect of strategic tillage on (*a*) fine fraction soil C, (*b*) fine fraction soil N, and (*c*) microbial biomass C in the 0–5 cm (—) and 5–10 cm (– – –) layers at the Harden long-term experiment. Vertical bars are l.s.d. ($P = 0.05$) for the strategic tillage main effect in each depth layer, shown where significant differences exist.

careful consideration of timing and implementation of strategic tillage owing to ongoing erosion risks of bare soil (Dang *et al*. 2015*b*; Melland *et al*. 2017; Conyers *et al*. 2019*b*), it appears that strategic tillage is a safe and useful tool to manage some of the agronomic challenges that may emerge under long-term no-till systems in the region.

The most significant and persistent impact of strategic tillage was the reduction in stable macroaggregates in the surface soil (0–5 cm) by ~8% (from 70% to 62%), which was partly accounted for by the mixing of some macroaggregates into the 5–10 cm layer, rather than entirely by the destruction of surface macroaggregates in the 0–5 cm layer. Most of the differences in aggregate stability generated by strategic tillage had disappeared after 2 years, although R-NT maintained the highest level of macroaggregates throughout the 5-year period and was similar to nearby undisturbed perennial pasture. Perennial pastures are known for the capacity to improve many soil structural parameters and typically have higher WAS than long-term cropped soil (Bell *et al*. 1997). Higher levels of stable aggregates in undisturbed cropped soil with high levels of retained residues are consistent with previous studies (Conyers *et al*. 2019*a*). In this case, the relatively small but significant changes in aggregate stability caused by strategic tillage appeared to have minimal impacts on water infiltration (*Ksat*), crop establishment or early crop growth, which were either unaffected or improved. Grandy *et al*. (2006) found a 36% decrease in the mean weight diameter of aggregates following a mouldboard ploughing of a grassland, but most subsequent studies on a range of different cropped soils found either no effect or short-term effects (<2 years) of a single tillage on the aggregates and aggregate stability at a range of sites (Quincke *et al*. 2007;

Table 4. Effect of strategic tillage (ST) in 2011 of long-term no-till (NT) soil on crop establishment, growth and yield over the subsequent 5 years in systems of burnt (B) and retained (R) crop residue at the Harden long-term site

l.s.d. (P = 0.05) of major effects presented for significant effects in bold; n.s., not significant (P > 0.05). HI, Harvest index

	Establishment (no. of plants/m^2)	Biomass (g/m^2) Z30	Biomass (g/m^2) Anthesis	Yield (g/m^2)	HI	100-grain weight (g)
			Wheat 2011			
B-NT	142	176	1306	575	0.39	3.01
B-ST	147	233	1316	561	0.37	2.94
R-NT	144	160	1068	490	0.39	2.85
R-ST	146	208	1220	509	0.38	2.92
Tillage	n.s.	**21**	n.s.	n.s.	n.s.	n.s.
Residue	n.s.	**21**	**107**	**30**	n.s.	n.s.
T × R	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
			Wheat 2012			
B-NT	109	86	1017	674	0.47	3.36
B-ST	105	113	1013	740	0.47	3.29
R-NT	108	63	964	639	0.47	3.38
R-ST	106	72	988	636	0.47	3.72
Tillage	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Residue	n.s.	n.s.	**91**	**60**	n.s.	n.s.
T × R	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
			Wheat 2013			
B-NT	167	206	1111	446	0.47	3.38
B-ST	145	196	1098	431	0.48	3.28
R-NT	118	119	967	385	0.50	3.32
R-ST	100	142	1028	378	0.48	3.18
Tillage	**10**	n.s.	n.s.	n.s.	n.s.	n.s.
Residue	**10**	**18**	n.s.	**39**	n.s.	n.s.
T × R	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
			Lupin 2014			
B-NT	62	–	612	260	0.32	–
B-ST	55	–	635	302	0.35	–
R-NT	46	–	392	317	0.35	–
R-ST	45	–	464	299	0.34	–
Tillage	n.s.	–	n.s.	n.s.	n.s.	–
Residue	**7**	–	**70**	n.s.	n.s.	–
T × R	n.s.	–	n.s.	n.s.	**0.03**	–
			Canola 2015			
B-NT	74	–	309	273	0.24	–
B-ST	70	–	–	286	0.23	–
R-NT	72	–	208	249	0.25	–
R-ST	71	–	–	256	0.24	–
Tillage	n.s.	–	–	n.s.	n.s.	–
Residue	n.s.	–	**32**	n.s.	n.s.	–
T × R	n.s.	–	–	n.s.	n.s.	–

Baan *et al*. 2009; Wortmann *et al*. 2010; Conyers *et al*. 2019*a*). Although the effects can be soil-specific (see Conyers *et al*. 2019*a*), the results at the Harden site are consistent with the conclusion of Conyers *et al*. (2019*b*) that a single tillage of long-term no-till cropping soils causes no damage or minimal damage to various measures of soil physical conditions, and these generally recover within one or two seasons after a return to no-till management.

After 20 years of no-till management, there was significant stratification of pH and SOM (C and N) at the Harden site, an issue that has been acknowledged in long-term no-till systems (Paul *et al*. 2003; Heenan *et al*. 2004; Conyers *et al*. 2015). Surprisingly, we did not find the same stratification for soil P; this has also been observed in no-till soils at some sites, caused by return of residues to the surface, fertilisation and lack of soil mixing (Vu *et al*. 2009; Conyers *et al*. 2019*a*). This was presumably due to the application of starter P fertiliser either with or below the seed at sowing each year and the practice of interrow sowing in alternate years, which would diminish the chances of significant surface stratification. The tillage with a rotary hoe clearly provided a thorough mixing of the 0–5 cm and 5–10 cm layers in which both the pH and the SOM were immediately more evenly distributed throughout the 0–10 cm depth, and unlike the soil physical changes, these changes persisted for the entire 5-year period of measurement. The pH levels also showed a decline at all depths and in all

Table 5. Effect of no-till (NT), strategic tillage (ST in 2011) and annual tillage (C) on crop yield (g/m²) with systems of annually burnt (B) and retained (R) residues over 5 years to 2015

l.s.d. ($P = 0.05$) presented where significant differences exist; n.s., not significant ($P > 0.05$). Average yield for the 11 wheat crops grown at the site from 1990 to 2010 (i.e. before the ST treatments in 2011) are also shown for comparison

Treatment	Wheat before 2011	Wheat 2011	Wheat 2012	Wheat 2013	Lupin 2014	Canola 2015
B-NT	426	575	674	446	260	273
B-ST	–	561	740	431	302	286
B-C	438	562	680	411	264	265
R-NT	397	490	639	385	317	249
R-ST	–	509	636	378	299	256
R-C	406	537	648	427	285	276
l.s.d. ($P = 0.05$)						
Tillage		n.s.	n.s.	n.s.	n.s.	n.s.
Residue		45	58	36	38	n.s.
Tillage × residue		n.s.	n.s.	n.s.	n.s.	n.s.

treatments across the 5 years, such that the pH in the 10–15 cm layer after 5 years in the stubble-retained treatments fell below the critical level of 4.5 at which aluminium is known to solubilise in soils (Norton *et al*. 2018), potentially reducing the growth of acid-sensitive crops. By mixing the higher pH soil in the 0–5 cm layer throughout the entire 0–10 cm layer, the strategic tillage maintained higher pH levels throughout the topsoil. Although no significant impacts of these pH changes on crop yield were observed, the canola, wheat and lupin crops are all relatively acid-tolerant, and more significant effects may be likely with acid-sensitive crops such as pulses and barley. These overall declines in soil pH that extend to some depth emphasise the need to maintain adequate and frequent lime input on these soils (Norton *et al*. 2018), and to incorporate the lime adequately to ensure that the deeper layers remain at acceptable pH (Conyers *et al*. 2003). The acidifying effect of stubble retention compared with stubble burning was also noteworthy at the site and has also been identified previously in long-term studies (Heenan and Taylor 1995; Conyers *et al*. 2012). This generally results from the longer term effect of the dissociation of acidic functional groups in the organic matter overriding the shorter term effect of organic matter addition contributing some alkalinity to the soil (Helyar and Porter 1989). The use of strategic tillage for lime incorporation may therefore be even more important in no-till systems where residues are retained on the surface without incorporation for long periods of time (Conyers *et al*. 2003; Azam and Gazey 2020).

In common with the observations of soil pH profiles, strategic tillage generally had the effect of redistributing SOM rather than simply reducing it, which is a relatively recent revelation from meta-analyses of long-term tillage experiments when sampling extended beyond the surface layers (Baker *et al*. 2007; Richardson *et al*. 2019). It is also evident that surface-retained SOM is often less decomposed (i.e. more particulate organic matter) and so is subject to decomposition and loss from the system over time (Wander and Bidart 2000). In the context of this experiment, the strategic tillage with a rotary hoe has had the effect of both mixing the stratified SOM throughout the top 10 cm, which would not only potentially expose the previously surface-retained particulate organic matter to more decomposition in deeper layers, but would also move more of the stable FFC into deeper soil layers with lower microbial populations where mineralisation may be slowed. In the short term, the strategic tillage also reduced the soil bulk density (this difference was largely in the 5–10 cm layer and had disappeared after 2 years), and both soil density and C concentrations will impact C stock. There was an initial loss of total carbon in the top 10 cm with strategic tillage, suggesting net loss of some soil C from the 0–5 cm layer that was not fully compensated by the increases in the 5–10 cm layer. Despite this initial reduction in total C (~2 t/ha), the differences had disappeared by 2013, and the overall C levels were largely maintained or increased during the 5-year experiment.

The more surprising observation of lower total C stocks persisting in the stubble-retained than stubble-burnt treatments over the 5-year period may have several explanations. First, stubble retention caused a reduction in growth and biomass in all years of the experiment (Table 4); in total, this meant that 3.98 t/ha less aboveground, non-grain biomass was returned to the soil over the 5 years in these treatments. Reduced net primary production is acknowledged to reduce C input and, in this case, was related to crop growth reductions caused by retained residues. Second, there are other long-term studies where no differences in soil C levels between burnt and retained treatments were reported (Rumpel 2008), which were shown to result from small amounts of highly resistant C being returned to the soil in the burnt ash, which maintained soil C levels in burnt treatments. Third, the timing of operations and the sampling processes in the experiment may have influenced the outcome. Both stubble-retained and stubble-burnt treatments retained the stubble over the whole summer so that soluble C and other decomposition would be similar in both treatments for the 4–5 months from harvest until burning occurred immediately before sowing. After burning, the remaining ash and unburnt finer residue material would be incorporated into the soil with the sowing process in those treatments, and likely mixed within the soil sampled for C analysis. By contrast, in stubble-retained treatments, the surface-retained residue would be moved aside during core sampling and larger stubble pieces removed in the sieving process. Accounting for the C contained in the coarser surface-retained residues could explain some of the apparent differences in total C reported. Irrespective of these effects of the stubble treatment, the overall C stocks have not been significantly reduced in the medium term following strategic tillage, an observation in common with other tillage studies (reviewed by Richardson *et al*. 2019).

The longer term overall decline in soil C at the Harden site in the 0–10 cm layer from ~1.3% in 1990 to 0.9% in 2012 (equivalent to a C stock loss of 5.8 t C/ha) has been previously reported (Conyers *et al*. 2015), but the differences between tillage and stubble treatments were relatively minor. This overall loss was more related to the climate-driven level of C-input from crop residues (Conyers *et al*. 2015) as well as limitation in the supply of supplementary nutrients, rather than the effects of tillage or stubble management *per se*. Kirkby *et al*. (2016) demonstrated that soil C could be increased by an almost equivalent amount (up to 5.5 t C/ha) over a 5-year period at the Harden site by using supplementary nutrients added to crop residues and incorporated with a rotary hoe. In this experiment on long-term no-till soil, it appears that despite some initial loss and redistribution of soil C after the strategic tillage in 2011, the level of C input from the relatively high-yielding cereal and broadleaf crops, together with robust fertiliser application (Table 2), meant that over the 5 years of the experiment, C levels were maintained or increased, and any short-term differences in soil C diminished over time. In the context of concerns regarding irreversible loss of soil C with occasional tillage, these results concur with those on other soils in this region and elsewhere that the impact of strategic tillage in long-term cropping soils is minor and short-lived (Conyers *et al*. 2019*a*, 2019*b*).

There were few interactions between residue retention and tillage treatments for any of the soil or crop parameters monitored during the 5-year period of this experiment. However, the persistent negative impact of retained residue on wheat growth and yield during the period continues a trend that has been observed at the site since it was first established (Kirkegaard 1995; Watt *et al*. 2006; Giller *et al*. 2015) and has continued at least in the wheat crops up to the present time (Table 5). A summary of the impact of seasonal rainfall on the wheat yield response to retained residue at the site was presented by Giller *et al*. (2015), and showed positive or neutral effects of retained residues in seasons of below-average rainfall and increasing yield penalties in wetter seasons. Recent studies using supplementary N or deep-placed N at sowing suggest this is likely caused by in-season N immobilisation, an effect that is missed when soil measurements are restricted to the pre-sowing period and close to the time of burning, because differences in soil mineral N have likely not developed (Kirkegaard *et al*. 2018). Although not the focus of this study, the results suggest that a closer consideration of in-season N-dynamics may uncover strategies to avoid these effects, and explain the observation that crops growing in no-till, stubble-retained systems (conservation agriculture) require a higher level of applied N to reach yield potential.

Conclusion

This study has demonstrated no persistent negative impacts of a single intensive tillage event on long-term no-till treatments in terms of soil conditions or crop performance over a 5-year period. The work demonstrates that strategic tillage to deal with specific agronomic issues can be compatible with productivity and sustainability though attention to timing in erosion-prone areas will be important. The short-term loss of soil C and aggregate stability had recovered within 2 years, whereas the positive effects of less stratification of pH and soil C and N persisted for the 5-year duration of the experiment. The work supports a growing literature on other soil types in different agroecological zones suggesting that occasional strategic tillage in an otherwise no-till system is compatible with the dual long-term objectives of soil protection and crop productivity.

Conflict of interest

There are no conflicts of interest related to this research

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