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Effects of tillage and time of sowing on bread wheat, chickpea, barley and lentil grown in rotation in rainfed systems in Syria

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ABSTRACT

Cropping systems in the drylands of west Asia are characterized by grazing, burning or harvesting of stubbles, multiple cultivations and late sowing, which can limit yields and lead to soil erosion and degradation. There is a lack of information on more conservation-based technologies developed in other countries to address some of these problems, particularly manipulations of tillage and time of sowing. This long-term field experiment was conducted under rainfed conditions at ICARDA near Aleppo in northern Syria to investigate the effects of conventional tillage (CT) and zero tillage (ZT) in combination with early and late times of sowing on the performance (production and profitability) of bread wheat, chickpea, barley and lentil grown in rotation over six years (2006–07 to 2011–12). As expected, the amount and pattern of rainfall was a major driver of crop performance, varying from 222 to 453 mm among the growing seasons. The grain yield of crops was often similar under ZT and CT (≈70% of year–crop–time of sowing combinations) and with early and late sowing (≈80% of year–tillage–crop combinations), but there were also many instances when ZT yielded significantly better than CT (≈25%) and early sowing yielded better than late sowing (≈13%). Importantly, over the four years from 2008–09 to 2011–12, the improved crop management system of ZT and early sowing gave higher grain yields than the conventional farmer system of CT sown late in two (13%) of the 16 year × crop combinations, similar yields in 13 (81%) combinations and lower yields for ZT early in one (6%) combination. During this time, the average grain yield increases with ZT and early sowing when compared to CT and late sowing were a significant 332 kg ha^{-1} (18%) for wheat, 127 kg ha^{-1} (20%) for chickpea and 135 kg ha^{-1} (15%) for lentil, and a non-significant 295 kg ha^{-1} (12%) for barley. Corresponding increases in gross margins ($US) were 162, 147, 89 and 176 $ ha^{-1} for wheat, chickpea, barley and lentil, respectively. In chickpea, the most profitable treatment was ZT sown late, producing an extra 281 kg ha^{-1} and 271 $ ha^{-1} compared to CT sown late. Early sowing improved crop establishment with increased plant densities of 30%, 48% and 29% for wheat, barley and lentil respectively, while ZT increased densities by 19%, 22% and 12% for chickpea, barley and lentil, respectively, when sown early. Other yield components reflected the grain yield responses. The increased grain yields achieved in this study, in combination with lower costs and greater profits, suggest ZT plus early sowing should be evaluated and promoted more widely as an attractive cropping technology for farmers in the Middle East.

1. Introduction

The production of cereal and legume crops in West Asia, including Syria, is characterized by heavy grazing, burning or harvesting of stubbles, multiple cultivations, and delayed or late sowing. Crop production is dominated by cereals, with legumes making up a small proportion of the land cropped, and a weedy fallow is a common part of the rotation in low rainfall regions. The conventional tillage (CT) practices in this region often include three or four tillage operations with different types of ploughs and harrows (moldboard, disc, duck-foot or chisel points) before sowing, which often leads to a delay in sowing of four to six weeks after the first effective rains in autumn. Grain yields for wheat in this Mediterranean region, where a generally low and variable rainfall of about 250–350 mm falls from September–October to April–May, with almost no rain outside this period, are often less than 1.0 t ha^{-1}, well below the water-limited potential or attainable yields of

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4.2–6.4 t ha^{-1} (Sadras and Angus, 2006). In contrast, wheat yields have increased steadily over the past century in other countries such as Australia with many farmers approaching attainable yields through the use of improved crop varieties and better crop management (Anderson et al., 2005; Sadras and Angus, 2006; Anderson, 2010; Passioura and Angus, 2010; Richards et al., 2014). A key component of better crop management has been zero tillage (ZT), where crops are sown early with minimal soil disturbance and retention of stubbles.

Worldwide, ZT has been adopted over 120 million hectares in the last 30 years, mainly in the USA, Brazil, Argentina, Canada and Australia (Derpsch and Friedrich, 2009; Derpsch et al., 2010). In Australia, Llewellyn et al. (2012) reported that no-tillage – defined as "seeding with low soil disturbance (points or discs) and no prior cultivation" – has been adopted by nearly 90% of Australian farmers over the same period, with most (88%) using narrow points. Whilst ZT benefits crop production, profitability and resource sustainability, and reduces demands on labor and time, it also facilitates use of other improved crop management technologies. The elimination of ploughing and the availability of effective non-residual herbicides open the way for earlier sowing, which can have a strong positive effect on crop production (Coventry et al., 1993; Hobbs et al., 2008). A key to the success of ZT in Australia is where crops are sown before or immediately after the first autumn rains using minimal soil disturbance to utilize and store rainfall, assisted by the retention of stubbles from previous crops. Early sowing usually results in rapid and vigorous crop establishment under warm autumn conditions, and if the phenology of the crop genotype is matched to the early sowing, then grain filling usually occurs earlier during cool weather in early spring, resulting in higher grain yield and water-use efficiency (Loss and Siddique, 1994; Kirkegaard et al., 2014b; Richards et al., 2014). Until recently, ZT and early sowing have been little researched by scientists and little known or used by farmers in the Middle East. Giller et al. (2011) considered that because early planting is a main advantage of alternative land preparation methods, conservation agriculture (CA) and current practice need to be compared over a range of sowing dates.

Several long-term studies of maize and soybean in the USA, maize and wheat in Europe (Cannell and Hawes, 1994) and wheat in Mexico (Fischer et al., 2002) have shown that yields are often similar in ZT and cultivated systems. On the other hand, a 14-year study on soybean in Australia (So et al., 2009) showed grain yields under no-till (NT) were similar to or less than CT at the start of the experiment (1982–85), but CT was unable to sustain yields and from 1987 to 1994 yields were higher for NT (2.14 t ha^{-1}) than CT (1.67 t ha^{-1}). In a 14-year study of barley commenced in 1997 in Spain, Morell et al. (2011) found that mean yields for the 2006–09 cropping seasons were highest (2062 kg ha^{-1}) under NT, lower (1791 kg ha^{-1}) under minimum tillage (MT) and lowest (1155 kg ha^{-1}) under CT, with NT double that of CT in dry years and equal in wet years.

There have been few studies comparing ZT and CT in West Asia. In a two-year study in Lebanon, Yau et al. (2010) showed that tillage effects varied with years and crops, with grain yields under ZT compared to CT higher for safflower in 2005–06, similar with chickpea in 2005–06 and barley and safflower in 2006–07, and less with chickpea in 2006–07. In a three-year study in nearby Iran, Hemmat and Eskandari (2004) found yields were 27–31% higher under NT and MT than CT for wheat and 24–57% higher under NT than reduced, minimum and CT for chickpea. Numerous experiments in Morocco, some lasting 19 years, demonstrated superior yields (up to 146% greater) with wheat in rotation with chickpea and lentil under NT compared to CT (Mrabet et al., 2012).

Although ZT and early sowing are very compatible components for cropping systems in Mediterranean-type environments, there seem to be few studies published on the interactions between tillage and time of sowing (TOS). Given the limited awareness and use of ZT in the West Asia region, we wanted to determine if it was effective and whether, in conjunction with early sowing, it could improve the performance (productivity and profitability) of cropping. Of particular interest was whether the "improved" system of ZT with early sowing gave similar or better production and profit than the "conventional" farmer system of CT with late sowing. Our null hypothesis was that tillage and TOS have no effect on crop production or profitability.

The paper reports on results from the first six years (2006–07 to 2011–12) of a long-term experiment evaluating the effects of tillage and TOS on the production and profitability of bread wheat, chickpea, barley and lentil grown in rotation under rainfed conditions in northern Syria.

2. Materials and methods

2.1. Location

The experiment was conducted at the International Center for Agricultural Research in the Dry Areas (ICARDA), Tel Hadya, Aleppo, Syria (36.011°N 36.931°E, 285 m above sea level). The exact location of the trial, termed the B4 long-term trial, is shown in a satellite image in Sommer et al. (2014). The climate is typically Mediterranean with hot dry summers and cold wet winters, with the amount and pattern of rainfall and temperatures fluctuating widely from year to year. The average annual temperature is 17.8 °C and average annual rainfall (1980–2011) is 334 mm. The rainfed cropping season usually begins in September–November and extends to April–May. Wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), chickpea (*Cicer arietinum* L.) and lentil (*Lens culinaris* M.) are the main rainfed crops in the region.

The main soils of the region have been classified as vertisols, inceptisols, and aridisols, and are generally low in soil organic matter (SOM), nitrogen (N) and plant-available phosphorus (P), have a clay texture (60–70%), and are highly calcareous (~20% $CaCO_3$) with a pH around eight. The soil at Tel Hadya has been classified as a very fine, montmorillonitic, thermic, chromic calcixerert (Ryan et al., 1997). More details of the soils at the B4 experimental site are given in Sommer et al. (2012, 2014). The montmorillonite clay minerals expand when wet and shrink when dry and the alternate shrinking and swelling cause some moderate self-mulching. Soil water infiltration rates and saturated hydraulic conductivity are moderate to low when the soil is wet. Potentially available plant water between permanent wilting point and field capacity is between 100 and 150 mm in the upper meter of soil, with crop rooting depth to about 1.3 m.

2.2. Experimental design and management

Prior to commencement of the trial, the area had been cropped over many years with a range of cereal and legume crops under a conventional cultivation system. The aim of the trial, which commenced in 2006–07, was to evaluate the effects of tillage (CT vs ZT) and TOS (early vs late) on crop performance and profitability in a four-course rotation of wheat, chickpea, barley and lentil which was repeated four times so that each crop was present in the field each year. In the first two years (2006–07 and 2007–08) there were no TOS treatments, and the trial was a split plot design with tillage as main plots and crops as sub plots (32 in number) each measuring 24 m × 65 m (1560 m^2). In 2008–09 to 2011–12, the crop sub plots were further split into early and late time of sowing sub-sub plots (64 in number) measuring 12 m × 65 m (780 m^2). There were four replications. Tillage and TOS treatments remained on the same plots and the crops were rotated through these each year in a wheat–chickpea–barley–lentil sequence.

Table 1
Date of sowing of cereals and legumes during 2006–07 to 2011–12.

Year	Wheat and barley		Chickpea and lentil	
	Early	Late	Early	Late
2006–07	12–13 November		25–26 November	
2007–08	1–11 November		1–11 November	
2008–09	3–4 October	4 November	1 November	2 December
2009–10	8 November	3 December	8 November	3 December
2010–11	8–11 November	5–9 January	8–11 November	5–9 January
2011–12	2–4 November	1–3 December	2–4 November	1–3 December

The CT treatments, in accordance with local farmer practice to 'prepare a seedbed' and control weeds, involved mouldboard ploughing to about 20–25 cm after cereals or disk ploughing to about 10 cm after legumes soon after harvest in June or July, followed by one or two shallow cultivations with a tine cultivator before sowing in the autumn. There was no cultivation with ZT treatments, which were sown directly into the undisturbed soil; when weeds were present at sowing (usually only in late-sown ZT plots), these were killed with an application of glyphosate (1 L ha^{-1} of 360 g L^{-1} a.i.). For both ZT and CT, there was no removal of crop residues (straw, leaves, chaff, seed pods) from wheat, chickpea or barley plots during or after the machine harvesting operation. Lentils were harvested manually in accordance with local practice to reduce pod losses, with mature plants cut/pulled by hand at ground level and machine threshed with crop residues not returned to plots.

To avoid any inherent differences between ZT and CT seeders, all plots were sown with the same ZT seeder each year. From 2006–07 to 2010–11 the seeder was an Indian National Zero Till Ferti-Seed Drill (www.agroind.com) with 13 tines fitted with narrow (10 mm) openers (or points) and separate seed and fertilizer delivery, arranged in two ranks with a seed row spacing of 17.5 cm. In 2011–12 an ICARDA-made 'Norwood ZT seeder' with 12 tines, fitted with narrow (20 mm) openers and separate seed and fertilizer delivery, arranged in three ranks with a row spacing of 25 cm was used. A 20 cm chain ending in a 5 cm diameter metal disc was dragged behind each opener to cover the fertilizer/seed. Sowing speed was 6 km ha^{-1} and about 20% of soil was disturbed. The seed rates for all crops were 100 kg ha^{-1}. ICARDA varieties/lines used were Babagha 3 bread wheat, Reem barley, Ghab 4 chickpea and Idleb 3 lentil. Early planting treatments were sown after the first germinating rains (early October-mid November) and late planting about four weeks later (early November-mid December); ZT and CT treatments were sown at the same time. Planting dates for cereals and legumes are presented in Table 1.

Crops received a basal fertilizer of 150 kg ha^{-1} di-ammonium phosphate (18% N, 46% P_2O_5) for cereals and 150 kg ha^{-1} triple superphosphate (46% P_2O_5) for legumes. Cereals received an additional 40 kg ha^{-1} N (46% N urea) around mid-tillering, 2–3 months after sowing. Post-sowing weeds were controlled with selective herbicides and occasional hand weeding: pre-emergence Stomp (455 g L^{-1} pendimethalin) at 2 L ha^{-1} for dodder (*Cuscuta* spp.) in lentil and chickpea; post-emergence Express (750 g kg^{-1} tribenuron methyl) at 15 g ha^{-1} for broadleaf weeds plus Ralon Super (fenoxaprop-P-ethyl 69 + mefenpyr 75 g L^{-1}) at 650 ml ha^{-1} for grass weeds in wheat and barley; post-emergence Challenge (aclonifen 600 g L^{-1}) at 500 ml ha^{-1} for broadleaf weeds plus Super Verdict (haloxyfop 520 g L^{-1}) at 600 ml ha^{-1} for grass weeds in lentil and chickpea. Occasional outbreaks of Ascochyta Blight in chickpea were controlled with post-emergence Bravo (chlorothalonil 500 g L^{-1}) at 2 L ha^{-1}.

Plant density was measured on 10 linear meters of row per plot (an area of 1.75 m^2 with row spacing of 17.5 cm in the first five years or 2.5 m^2 with row spacing of 25 cm in the last year) at 2–4 weeks after emergence. Grain yield was measured by harvesting whole plots at maturity in May/June, using a large plot harvester for wheat, barley and chickpea or hand harvesting of plants and threshing with a stationary harvester for lentil. Moisture content of the grain which was air dried under the low-humidity, high-temperature summer conditions of Aleppo was 10%. Plant height at maturity (harvest) was measured as the height to the tip of the heads of most (≈80%) of the crop on the plot. To measure yield components, sub-samples of plants were cut at ground level in 20 m^2 (4 × 5 m^2 quadrats per plot) for lentil and chickpea and 1.75 m^2 in the first five years or 2.5 m^2 in the last year (10 m of row per plot with 17.5 or 25 cm spacing) for wheat and barley and threshed and separated to calculate biomass, grain yield, residue yield and harvest index (HI). Seed weight (g 200 $seeds^{-1}$) was measured on one 200-seed sample from each plot.

2.3. Weather

Daily rainfall (mm) and average daily maximum and minimum temperatures (°C) for 2006–07 to 2011–12 were recorded at the station and mean weekly data are presented in Fig. 1.

In 2006–07, the first effective autumn rain (break of the season) was early, commencing during 22–28 September (week 4). The relatively high total rainfall of 314 mm was spread evenly through to the last fall of 52 mm during 11–17 May (week 37). There was a prolonged cold period in winter with weekly mean minimum temperatures between −0.1 and −3.2 °C for eight of the 10 weeks from 24 November to 1 February (Fig. 1a).

In 2007–08, the break was later than the previous season, commencing during 20–26 October (week 8), with a total of only 223 mm rainfall spread evenly through to the last falls of 7 mm during 11–17 May (week 37). The winter was very cold with minimum temperatures between −1 and −7.5 °C for seven weeks between 22 December and 8 February (Fig. 1b).

In 2008–09, the break was early, commencing during 15–21 September (week 3). The relatively high total rainfall of 291 mm was spread evenly until an early finish with the last falls of 20 mm during 13–19 April (week 33). The winter was cool with minimum temperatures below zero (−1.2 to −2.3 °C) for only three weeks between 15 December and 18 January (Fig. 1c).

In 2009–10, the break was early, again commencing during 15–21 September (week 3), and the season was short with 268 mm of the total rainfall of 272 mm falling by 6–12 April (week 32). The winter was very mild, with the minimum temperature below zero (−0.3 °C) only for the week of 2–8 February (Fig. 1d).

In 2010–11, it was very dry in autumn with only 30 mm of rainfall during the first 14 weeks (Fig. 1e). The break of the season was very late commencing during 8–14 December (week 15), with 249 mm of the total of 259 mm falling by 27 April–3 May (week 35). The winter was mild, with the minimum falling below zero only twice, to −0.8 °C for 12–18 January and −1.2 °C for 2–8 February 11.

In 2011–12, rainfall was exceptionally heavy with the autumn break commencing during 13–19 October (week 7). Of the total

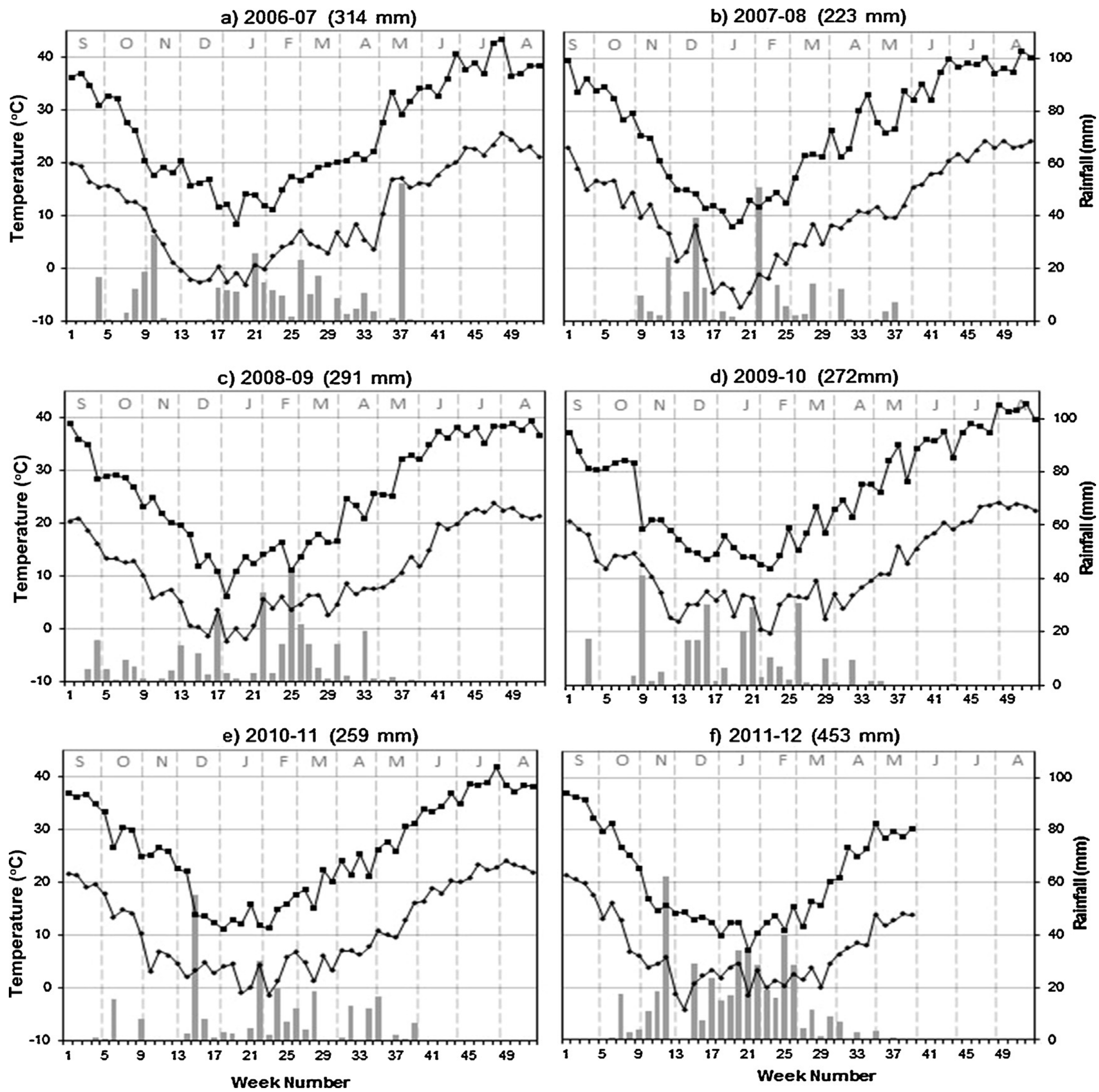

Fig. 1. Weekly rainfall (■) and average maximum (■-) and minimum (-♦-) temperatures at Tel Hadya Aleppo from 2006–07 to 2011–12. Total annual rainfall is presented in parentheses.

453 mm, 445 mm fell by the end of week 31 on 5 April (mid spring) with only 7.6 mm more up to 31 May (week 39). The winter was cool with minimum temperatures in late autumn and early-mid winter falling below zero for only three weeks, to −1.3 °C on 24–30 November, −4.2 °C on 1–7 December and -1.3 °C on 19–25 January (Fig. 1f). The recording of weather data after May was disrupted by the Syrian conflict.

In all years, weekly mean maximum temperatures did not rise above 35 °C until June, after crop maturity and harvest.

2.4. Data analysis

Data were analyzed with a general analysis of variance (Genstat 12), using a log10 transformation where residual plots indicated the data were not normally distributed. A first analysis of grain yield comparing ZT and CT when crops were sown early over six years (2006–07 to 2011–12) was conducted to incorporate the first two years (when there was only one sowing time) into the tillage comparisons. A second set of analyses looked at grain yield and a range of other crop performance parameters (plant density, plant height, grain yield, residue yield, harvest index, 200 seed weight) with the four crops over four years (2008–09 to 2011–12) comparing ZT versus CT and early versus late sowing and their interaction. Significant effects from all of these analyses are presented in Table 2. Where the transformed means are presented in parentheses in tables, the actual numbers were from collected data rather than re-transformations of these means.

A simple gross margin and benefit–cost ratio were calculated for each treatment using input and commodity costs and prices in northern Syria in 2011, before these were distorted following the outbreak of civil unrest. Kirkegaard et al. (2014a) used a similar 'simple economics' approach to effectively compare the profitability of two-year wheat-break crop sequences. The currency conversion rate used was 50 Syrian pounds per US dollar. The variable costs included all inputs and operations for tillage, sowing, fertilizer application, weed control, harvesting, transport of grain and transport of lentil residues. Tillage operations in the CT treatments were costed (US$) at 37 $ ha^{-1}. The ZT treatments sown early were generally planted before any significant weed germination, and application of glyphosate was only included in the ZT treatments sown late. The prices for wheat, barley, chickpea and lentil grain were 400, 200, 900 and 800 $ t^{-1} respectively, with seed costs 25% higher. Crop residue prices in Syria vary depending on the time of year and local availability. The lentil residues

Table 2
Analysis of variance of effects of year, tillage, crop and time of sowing for 6 traits during 4 years (2008–12) and of year, tillage and crop for grain yield during 6 years (2006–12).

Source of variation	d.f.	Plant density	Plant height	Crop residues	Harvest index	200 seed weight	Grain yield	Grain yield
	4/6 yr	2008–12[a]						2006–12[a]
		no m^{-2}	cm	log_{10} kg ha^{-1}	log_{10}	log_{10} g	log_{10} kg ha^{-1}	log_{10} kg ha^{-1}
Year·rep. stratum								
Year	3/5	**	**	**	**	**	**	**
Residual	12/18							
Year·rep·tillage stratum								
Tillage	1/1	**	**	ns	ns	*	**	**
Year·tillage	3/5	*	**	*	ns	ns	**	**
Residual	12/18							
Year·rep·tillage·crop stratum								
Crop	3/3	**	**	**	**	**	**	**
Year·crop	9/15	**	**	**	**	**	**	**
Tillage·crop	3/3	**	ns	**	ns	ns	**	*
Year·tillage·crop	9/15	ns	ns	*	ns	ns	**	*
Residual	72/108							
Year·rep·tillage·crop·timing stratum								
Timing	1/–	**	**	ns	*	ns	**	
Year·timing	3/–	**	**	ns	ns	ns	ns	
Tillage·timing	1/–	**	ns	ns	*	*	ns	
Crop·timing	3/–	**	**	ns	ns	ns	**	
Year·tillage·timing	3/–	**	ns	ns	ns	ns	ns	
Year·crop timing	9/-	**	**	ns	ns	ns	**	
Tillage·crop·timing	3/–	*	ns	ns	ns	ns	*	
Year·tillage·crop·timing	9/–	ns	ns	ns	ns	ns	*	
Residual	96/–							
Total	255/191							

[a] 2008–12; 4-year comparisons with early/late sowing: 2006–12; 6-year comparison with early sowing (see methodology).

removed in the hand harvesting operation were valued at 120 $ t^{-1}; the residues of wheat, chickpea and barley returned to plots in the machine-harvesting operation were not assigned an economic value.

3. Results

3.1. Grain yield response to tillage under early sowing over six years

For grain yield over six years, there was a three-way interaction due to different responses to tillage across crops and years (Table 2). Of the 24 year × crop comparisons of tillage, grain yield was higher for ZT than CT in 6 combinations (25%), similar for ZT and CT in 17 combinations (71%), with only one combination (4%) where yield was less with ZT than CT.

The two legumes were especially better adapted to ZT than CT: for chickpea there were three years where ZT was higher than CT (2007–08, 2008–09, 2010–11) and three where ZT and CT were similar; for lentil, there were two years where ZT was higher than CT (2007–08, 2010–11), three where ZT and CT were similar, and one where ZT was less than CT (2011–12). The cereals were less responsive to ZT, with only one year for wheat where ZT was higher than CT (2007–08) and eleven for wheat and barley where ZT was similar to CT (Table 3). On average over the six seasons, ZT grain yields compared to CT were 10.9% higher in wheat, 16.1% higher in chickpea, 2.5% lower in barley, and 6.2% higher in lentil (Table 3).

3.2. Crop performance in response to tillage and time of sowing over four years

For grain yield over the four years, there was a four-way interaction due to different effects of tillage and time of sowing (TOS) in the different crops and years (Table 2). Of the 32 year × crop × TOS comparisons of tillage, ZT and CT yields were similar in 23 combinations (72%) and ZT was higher than CT in 7 combinations (22%) of chickpea (2008–09 early and late sowing, 2009–10 late sowing, 2010–11 early and late sowing) and lentil (2010–11 early and late sowing). There were only two instances (6%) where ZT yielded less than CT, one each in wheat (2009–10 late sowing) and lentil (2011–12 early sowing). Of the 32 year × tillage × crop comparisons of TOS, early and late sowing gave similar yields in 27 combinations (84%) and early was higher than late sowing in four combinations (13%) of wheat (ZT 2009–10), barley (CT 2011–12) and lentil (CT and ZT 2010–11). There was only one instance (3%) where early sowing yielded less than late sowing, in chickpea ZT 2009–10 (Table 4). On average over the four years, grain yields were greater for ZT than CT by 2.8% for wheat, 26.3% for chickpea and 2.6% for lentil, and lower for ZT than CT by 0.5% for barley. Grain yields were greater for early than late sowing by 15.5% for wheat and 12.2% for barley and lentil, and lower for early than late sowing by 6.2% for chickpea. Over the four years, the average grain yield increase with ZT plus early sowing compared to CT and late sowing was a significant 332 kg ha^{-1} (17.9%) for wheat, 127 kg ha^{-1} (19.9%) for chickpea and 135 kg ha^{-1} (15.4%) for lentil, and a non-significant 295 kg ha^{-1} (11.8%) for barley (Table 4). Thirteen of the 16 highest yields for all crops were in the wettest year 2011–12; wheat and chickpea under all combinations of ZT and CT whether sown early or late; barley with CT and ZT sown early; and lentil under CT and ZT sown late and CT sown early. Eleven of the 13 lowest yields were in the driest year 2010–11; wheat and barley under ZT and CT sown early or late; chickpea under CT early and late; and lentil under CT late.

Plant density showed a significant tillage × crop × TOS interaction, where wheat, barley and lentil (but not chickpea) had a higher density with early than late sowing, and early-sown lentil and barley also showed a response to ZT. There was also a significant year × crop × TOS interaction, where the density of wheat and barley was higher for early than late sowing in all years except

Table 3
Year × tillage × crop interaction on grain yield (kg ha^{-1} and $\log_{10}$ kg ha^{-1}) of early sown crops during 6 years (2006–07 to 2011–12).

Year	Tillage	Crop			
		Wheat kg ha^{-1} ($\log_{10}$)	Chickpea kg ha^{-1} ($\log_{10}$)	Barley kg ha^{-1} ($\log_{10}$)	Lentil kg ha^{-1} ($\log_{10}$)
2006–07	CT	1305 (3.10)	554 (2.73)	1765 (3.24)	352 (2.52)
	ZT	1238 (3.08)	658 (2.82)	1700 (3.21)	431 (2.62)
		ZT = CT[a]	ZT = CT	ZT = CT	ZT = CT
2007–08	CT	474 (2.66)	385 (2.58)	1547 (3.18)	414 (2.61)
	ZT	732 (2.86)	599 (2.78)	1621 (3.21)	603 (2.77)
		ZT > CT	ZT > CT	ZT = CT	ZT > CT
2008–09	CT	1513 (3.18)	450 (2.65)	2372 (3.37)	1192 (3.08)
	ZT	1603 (3.20)	704 (2.85)	2532 (3.40)	1103 (3.04)
		ZT = CT	ZT > CT	ZT = CT	ZT = CT
2009–10	CT	1785 (3.25)	615 (2.78)	2154 (3.32)	899 (2.95)
	ZT	1890 (3.28)	556 (2.71)	2302 (3.35)	862 (2.93)
		ZT = CT	ZT = CT	ZT = CT	ZT = CT
2010–11	CT	556 (2.74)	449 (2.63)	1510 (3.18)	688 (2.84)
	ZT	652 (2.81)	586 (2.77)	1189 (3.07)	1247 (3.10)
		ZT = CT	ZT > CT	ZT = CT	ZT > CT
2011–12	CT	4024 (3.60)	1261 (3.08)	5495 (3.74)	1267 (3.09)
	ZT	4590 (3.66)	1209 (3.07)	5137 (3.71)	866 (2.93)
		ZT = CT	ZT = CT	ZT = CT	ZT < CT

[a] Indicates significance ($P \leq 0.05$) of differences between ZT and CT.
LSD (0.05) = (0.13); (0.12) for same year or same year × crop; (0.13) for same year × tillage.

Table 4
Year × tillage × crop × time of sowing interaction on grain yield (kg ha^{-1} and $\log_{10}$ kg ha^{-1}) of early and late sown crops during 4 years (2008–09 to 2011–12).

Year (rainfall)	Tillage	TOS	Wheat		Chickpea		Barley		Lentil	
			kg ha^{-1}	($\log_{10}$)	kg ha^{-1}	($\log_{10}$)	kg ha^{-1}	($\log_{10}$)	kg ha^{-1}	($\log_{10}$)
2008–09	CT	E	1513	(3.18)	450	(2.65)	2372	(3.37)	1192	(3.08)
(291 mm)		L	1333	(3.12)	377	(2.57)	2106	(3.32)	968	(2.98)
	ZT	E	1603	(3.20)	704	(2.85)	2532	(3.40)	1103	(3.04)
		L	1426	(3.15)	576	(2.75)	2365	(3.37)	1000	(2.99)
2009–10	CT	E	1785	(3.25)	615	(2.78)	2154	(3.32)	899	(2.95)
(272 mm)		L	1756	(3.23)	544	(2.73)	2421	(3.37)	702	(2.84)
	ZT	E	1890	(3.28)	556	(2.71)	2302	(3.35)	842	(2.92)
		L	1296	(3.09)	978	(2.99)	2467	(3.39)	769	(2.88)
2010–11	CT	E	556	(2.74)	449	(2.63)	1510	(3.18)	688	(2.84)
(259 mm)		L	536	(2.72)	491	(2.67)	1333	(3.12)	489	(2.67)
	ZT	E	652	(2.81)	585	(2.77)	1189	(3.07)	1247	(3.10)
		L	651	(2.81)	740	(2.86)	1317	(3.11)	747	(2.87)
2011–12	CT	E	4024	(3.60)	1261	(3.08)	5494	(3.74)	1267	(3.09)
(453 mm)		L	3782	(3.58)	1135	(3.05)	4121	(3.61)	1358	(3.13)
	ZT	E	4590	(3.66)	1209	(3.07)	5137	(3.71)	866	(2.93)
		L	3604	(3.56)	1374	(3.13)	4089	(3.61)	1189	(3.07)
LSD (0.05) = (0.12); (0.12) for same year, year × crop, year × timing, year × crop × timing; (0.12) for same year × tillage, year × tillage × timing; (0.11) for same year × tillage × crop										
Mean[a]	CT	E	1969	(3.29)	693	(2.84)	2882	(3.46)	1011	(3.00)
		L	1852	(3.27)	637	(2.80)	2495	(3.40)	879	(2.94)
	ZT	E	2184	(3.34)	764	(2.88)	2790	(3.44)	1014	(3.01)
		L	1744	(3.24)	917	(2.96)	2559	(3.41)	926	(2.97)
Tillage × crop × time of sowing interaction significant ($P < 0.01$). LSD (0.05) = (0.06); (0.06) for same tillage, tillage × timing; (0.05) for same tillage × crop										

[a] Mean of 2008–09 to 2011–12.

Table 5
Year × crop × time of sowing and tillage × crop × time of sowing interactions on plant density (plants m^{-2}) during 2008–09 to 2011–12.

	Wheat		Chickpea		Barley		Lentil	
	E	L	E	L	E	L	E	L
(a) Year × crop × timing								
2008–09	170	103	54	52	183	151	181	164
2009–10	134	138	45	48	146	135	182	164
2010–11	204	130	53	38	274	106	315	165
2011–12	180	158	32	37	171	131	178	170
LSD (0.05) = 23.4 (19.3 for same year and year × timing; 18.0 for same year × crop)								
(b) Tillage × crop × timing								
CT	176	133	42	43	174	126	202	167
ZT	168	132	50	44	212	136	226	164
LSD (0.05) = 13.3 (13.6 for same tillage and tillage × timing; 12.7 for same tillage × crop)								

Table 6
Year × tillage × crop interaction on residue yield ($kg\,ha^{-1}$ and $log_{10}\,kg\,ha^{-1}$) during 2008–09 to 2011–12.

Year	Tillage	Wheat		Chickpea		Barley		Lentil	
		$kg\,ha^{-1}$	(log_{10})	$kg\,ha^{-1}$	(log_{10})	$kg\,ha^{-1}$	(log_{10})	$kg\,ha^{-1}$	(log_{10})
2008–09	CT	3851	(3.57)	1413	(3.14)	2714	(3.43)	2078	(3.32)
	ZT	4015	(3.60)	1809	(3.25)	2875	(3.46)	2448	(3.38)
2009–10	CT	3827	(3.56)	1731	(3.22)	1538	(3.14)	1538	(3.19)
	ZT	3841	(3.57)	1048	(3.01)	1308	(3.08)	1809	(3.26)
2010–11	CT	2643	(3.42)	670	(2.80)	4386	(3.60)	921	(2.96)
	ZT	2572	(3.39)	656	(2.80)	3444	(3.53)	1213	(3.08)
2011–12	CT	7784	(3.87)	1656	(3.21)	5783	(3.75)	1683	(3.22)
	ZT	6599	(3.80)	1753	(3.24)	4206	(3.62)	1858	(3.27)

LSD (0.05) = (0.12); (0.10) for same year, year x crop; (0.11) for same year x tillage

2009–10. In contrast, TOS had little effect on legume density except in 2010–11 when lentil density was doubled with early planting (Table 5). On average over the four seasons, early sowing increased plant density by 30%, 48% and 29% for wheat, barley and lentil, while ZT increased densities by 19%, 22% and 12% for chickpea, barley and lentil, respectively, when sown early.

Plant height at maturity showed a significant year × crop × TOS effect with early-sown crops similar to or taller than later-sown crops (up to 15 cm taller in barley), except for barley in the first two years when late sowing was up to 5 cm taller than early sowing. The year × tillage interaction was also significant, with ZT taller than CT in 2008–09 and 2010–11 (up to 4 cm taller) but equal in the other years (data not shown).

Crop residue production was not affected by TOS (Table 6). It was also little affected by tillage although the year × tillage × crop interaction was significant because residue yield was higher for ZT than CT with lentil in 2010–11 but lower with chickpea in 2009–10 and barley in 2011–12. The interaction also showed that residue yield fluctuated from year to year largely reflecting total rainfall. For cereals, this ranged from 6 to 8 $t\,ha^{-1}$ in 2011–12 (ZT and CT wheat; CT barley), down to 1.3 to 2.6 $t\,ha^{-1}$ in 2010–11 (ZT and CT wheat) and 2009–10 (ZT and CT barley). Residue yields in legumes ranged from 1.4 to 2.4 $t\,ha^{-1}$ in 2011–12 (ZT and CT chickpea), 2009–10 (CT chickpea) and 2008–09 (ZT and CT chickpea and lentil), down to 0.7–0.9 $t\,ha^{-1}$ in 2010–11 (ZT and CT chickpea; CT lentil).

Harvest index showed a year × crop interaction, fluctuating very widely between years and crops (Table 7). It was high for legumes (chickpea 44%, lentil 48%) and low for cereals (barley 33%, wheat 20%) in the wet 2011–12 season and low for legumes (chickpea 26%, lentil 35%) and high for cereals (barley 49%, wheat 30%) in 2008–09. There was little effect of tillage or TOS on harvest index. We have no explanation why HI was so low for some crops/years.

The 200 seed weight varied with year for chickpea (56–70 g), wheat (4.6–6.2 g), barley (5.2–7.8 g) and lentil (5.5–6.2 g), tending to be higher in wetter years (2011–12 for wheat, chickpea, barley; 2008–09 for lentil) and with ZT (data not shown).

3.3. *Crop profitability in response to tillage and time of sowing over four years*

The estimated mean input costs, total income, gross margins and benefit–cost ratios for each treatment are presented in Table 8.

In all crops except chickpea the most profitable treatments were ZT sown early. Comparing CT sown late (the traditional farmer practice) with ZT sown early, the gross margin was increased from 505 to 667 $\$\,ha^{-1}$ in wheat, 251–398 $\$\,ha^{-1}$ in chickpea, 273–362 $\$\,ha^{-1}$ in barley, and 589–765 $\$\,ha^{-1}$ in lentil. Corresponding increases in benefit–cost ratios were 2.1–3.2 in wheat, 0.8–1.4 in chickpea, 1.2–1.8 in barley, and 2.0–2.9 in lentil. In chickpea, the most profitable treatment was ZT sown late, which had a gross margin of 522 $\$\,ha^{-1}$ and a benefit–cost ratio of 1.7. Lentil produced the greatest gross margins because of its reasonable yield, high grain price relative to the cereal crops and additional income from residue production, which on average over four years varied from a low of 1511 $kg\,ha^{-1}$ for CT late to a high of 1839 $kg\,ha^{-1}$ for ZT late, with a corresponding value of 181–220 $\$\,ha^{-1}$. Although lentil had a relatively high cost of production (265–298 $\$\,ha^{-1}$) because of high seed and hand harvest costs, it produced benefit–cost ratios similar to wheat and greater than chickpea and barley.

4. Discussion

Long term crop performance in response to tillage and time of sowing is of great importance and interest to farmers considering a shift from CT to ZT. As might be expected in our experiment with four different crops tested under rainfed conditions over six contrasting years, there was considerable interaction in the various crop parameters measured amongst the treatments of year, tillage, crop and TOS. The years varied greatly in terms of rainfall (distribution, total) and temperatures (maximums, minimums, extreme cold periods, extreme hot periods) and the crops were also contrasting (cereals, legumes). Similarly, Fischer et al. (2002) with wheat in Mexico and Yau et al. (2010) with barley, chickpea and safflower in Lebanon found the effects of various tillage treatments varied markedly with years and

Table 7
Year × crop interaction on harvest index (% and log_{10}%) during 2008–09 to 2011–12.

Year	Wheat		Chickpea		Barley		Lentil	
	%	(log_{10}%)	%	(log_{10}%)	%	(log_{10}%)	%	(log_{10}%)
(a) year × crop interaction								
2008–09	29.6	(1.47)	26.1	(1.41)	48.7	(1.69)	35.3	(1.56)
2009–10	31.2	(1.49)	38.9	(1.57)	50.8	(1.70)	30.0	(1.47)
2010–11	19.8	(1.27)	39.4	(1.59)	24.3	(1.38)	21.7	(1.33)
2011–12	19.8	(1.29)	47.8	(1.68)	33.0	(1.51)	44.2	(1.64)

LSD (0.05) = (0.06); (0.07) for same year

Table 8
Comparison of gross margins (US$) and benefit–cost ratios of wheat, chickpea, barley and lentil under different tillage and TOS averaged over 4 years (2008–09 to 2011–12).

Crop	Tillage	TOS	Total variable costs ha^{-1}	Total income ha^{-1}	Gross margin ha^{-1}	Benefit-cost ratio
Wheat	CT	E	239	788	549	2.3
		L	236	741	505	2.1
	ZT	E	207	874	667	3.2
		L	208	698	490	2.4
Chickpea	CT	E	323	624	301	0.9
		L	322	573	251	0.8
	ZT	E	290	688	398	1.4
		L	303	825	522	1.7
Barley	CT	E	235	576	341	1.5
		L	226	499	273	1.2
	ZT	E	196	558	362	1.8
		L	202	512	310	1.5
Lentil	CT	E	298	1001	703	2.4
		L	296	885	589	2.0
	ZT	E	265	1030	765	2.9
		L	275	961	687	2.5

crops. Morell et al. (2011) similarly reported that barley responses to tillage treatments over 14 seasons in Spain depended upon rainfall, with the greatest yield increases with NT in dry seasons.

Grain yield is a primary focus for crop producers because it is the main determinant of income and a good integrator and indicator of best crop management practices. Cannell and Hawes (1994) in a review of long-term (≥10 years) tillage experiments in North America, Europe and New Zealand, considered "crop yields from long-term experiments, as integrators of the effects of soil quality and climatic factors on crop growth, are the best estimates of the expected effects of different tillage practices." This study has shown that, as in southern Australia and other Mediterranean-type environments (Anderson et al., 2005; Sadras and Angus, 2006; Anderson, 2010; Passioura and Angus, 2010; Kirkegaard et al., 2014a), ZT and early sowing are robust technologies across variable years and a range of crops in northern Syria. This is consistent with the study reported by Sommer et al. (2012), which applied the crop–soil model CropSyst to the 2009–10 wheat crop from another long-term trial at ICARDA comparing tillage (ZT, CT), TOS (early, late) and residue retention (partial, full), and found in a 30-year (1980–2010) simulation that wheat yields were significantly higher for early than late TOS, mostly higher (but not significantly so) for ZT than CT, and little affected by residue management. They concluded that planting wheat immediately after the first significant rains in autumn bears little risk of crop failure due to early-season droughts. The clear messages from the trial reported here are that, firstly, crops often yielded similarly under ZT and CT (≈70% of the year–crop–TOS combinations) and with early and late sowing (≈80% of year–crop–tillage combinations), and, secondly, there were enough instances when ZT yielded significantly more than CT (≈25%) and early yielded more than late sowing (≈13%) to attract Middle East farmers to these technology options. Yields of crop residues, a valuable commodity for grazing or feed in the Middle East, varied between years and crops but were predominantly similar under the different tillage and TOS treatments.

Fischer et al. (2002), in a four-year study of wheat grown in rotation with wheat, maize, vetch or pasture in Mexico, found that ZT treatments gave wheat grain yields at least equal to those of cultivation treatments, concluding that even equal yields was an important result, which agreed with many studies in temperate regions as reported by Lal (1989). Equal residue yields are also an important result from our study, indicating little risk of reduced animal feed under early sown ZT systems.

It is most relevant for farmers to compare the improved crop production system of ZT which allows early sowing with the traditional system (CT and sowing delayed by four to six weeks after the first autumn rains). As long as yields are not reduced under ZT, farmers will be keen to eliminate ploughing because it saves time and expenditure, brings longer term sustainability and environmental benefits, and reduces the level of investment and risk. In our study, ZT sown early gave higher yields than CT sown late in 13 of the 16 year × crop combinations (although only two were significant at $P \leq 0.05$) and a significantly lower yield only with lentil in 2011–12 (Table 4). We cannot explain why ZT early lentil had such a low yield (866 kg ha^{-1}) compared to ZT sown late or CT sown early or late in 2011–12; the data across four replicates were consistent. Over the four years 2008–09 to 2011–12, the average grain yield increase of ZT with early sowing compared to CT with late sowing was a significant 332 kg ha^{-1} (18%) for wheat, 127 kg ha^{-1} (20%) for chickpea and 135 kg ha^{-1} (15%) for lentil, and a non-significant 295 kg ha^{-1} (12%) for barley. Such increased yields in combination with lower costs make ZT plus early sowing highly attractive to farmers. Similar yield increases were recorded by most of the ≈500 Syrian farmers who, as a result of this experiment and other project research and participatory extension, adopted ZT and early sowing on over 30,000 ha during 2008–12 (Piggin et al., 2011; Loss et al., 2015; Yigezu et al., 2015). These yield increases were evident even though most farmers did not adopt the other two principles of conservation agriculture (CA) – they did not retain crop residues which were usually heavily grazed, and did not change from cereal-dominated to mixed crop sequences. In contrast to these Syrian research results and farmer experiences, Pittelkow et al. (2014) found, in a global meta-analysis of hundreds of field trials across 48 crops in 63 countries, that yields in dry rainfed areas were decreased by 11.9% when no-till was implemented without residue retention and crop rotation and only increased (by 7.3%) when no-till was implemented together with the other two CA principles. It remains to be seen if relatively high yield increases such as those achieved in our trial, which involved cereal–legume rotation and retention of most residues, or by Syrian farmers without residue retention and rotations, can be maintained. In Australia, limited rotations and considerable removal of residues as hay or by grazing livestock are commonplace in many high-productivity ZT systems (Kirkegaard et al., 2014a).

The cost saving and income enhancement with ZT when combined with early sowing were clearly evident in our gross margin analysis, undertaken with a simple economics approach similar to that used by Kirkegaard et al. (2014a) to show two-year wheat–legume (field pea, lupin) rotations are much less profitable in southern Australia than wheat–canola or continuous wheat and explain why many farmers are attracted to high wheat and low legume frequencies in their rotations. When comparing ZT

treatments sown early with the traditional farmer practice, the estimated gross margin was increased by 162, 147, 89 and 176 $\$\,ha^{-1}$ for wheat, chickpea, barley and lentil, respectively. In chickpea, the most profitable treatment was ZT sown late, producing an extra 271 $\$\,ha^{-1}$ profit compared to CT sown late. From a survey of 621 wheat producers in Syria in 2011, Yigezu et al. (2015) estimated the net income of farmers using ZT and early sowing was increased by 194 $\$\,ha^{-1}$, which is in close agreement with the increases estimated from our experiment. It is recognized that cereal residues have a value; Syrian farmers were selling wheat and barley residues for about 50 and 70 $\$\,t^{-1}$, respectively, immediately after harvest in 2011. In our trial, the four-year average residue production was 3.8–4.7 $t\,ha^{-1}$ for wheat and 2.8–3.6 $t\,ha^{-1}$ for barley. If the value of these cereal residues was factored into the economic analysis this would boost their gross margins and benefit–cost ratios considerably. The fact that crop residues are a valuable commodity, sometimes worth more than the grain harvested (Magnan et al., 2012), helps explain why farmers are reluctant to retain crop residues for soil conservation purposes.

Our gross margin analysis did not take into account the capital cost of purchasing a ZT seeder. In 2011, seven machinery workshops in Syria were manufacturing and marketing effective small ZT seeders developed in collaboration with the project for $3000–5000 (Piggin et al., 2011; Loss et al., 2015). Using the mean increased income for all crops of 144 $\$\,ha^{-1}$ with ZT plus early sowing in the current study, a farmer might expect to recoup the cost of a $5000 ZT seeder after using it to plant 35 ha of crop, a potentially quick return on investment. For small farmers, this might require two or three years, with many reducing costs and increasing returns through sharing or contracting seeders to maximize their utilization.

Although there were interactions and exceptions with year and crop, the responses of the various crop traits to tillage and time of sowing reflected trends in grain yields, and there were considerable responses in plant density. Early sowing resulted in improved establishment in wheat, barley and lentil with 30–47% greater plant density, and ZT also improved plant establishment in early-sown barley and lentil, but not wheat or chickpea. This may have been a result of increased soil moisture and warmer soil temperatures in ZT, where crop residues were retained on the surface, compared to CT, creating a more favorable seed bed environment. Greater seedling vigor and early crop growth were often observed (although not formally measured) in early sown ZT treatments but this early advantage often did not translate into greater total biomass at the end of the season.

Our results suggested legumes were better adapted to ZT than cereals under the experimental conditions. In the four-year comparisons, grain production under ZT was higher than CT in seven of 32 (22%) year–crop–TOS combinations, and all cases were legumes (five for chickpea and two for lentil). Yau et al. (2010) suggested that the fibrous root system of cereals may not do as well in ZT as in CT systems, in contrast to legumes which have a tap root. In a study in Spain, however, Munoz-Romero et al. (2012) found that chickpea roots grew better with conventional than no tillage. Different responses might be expected under contrasting soil types.

Grain production under early sowing was similar to or higher than late sowing in 31 of 32 (97%) year–crop–tillage combinations, with only chickpea yielding significantly less for early than late sowing, under ZT in 2009–10. Chickpea grain yield was similarly (but not significantly) poorer with early than late sowing under ZT in 2010–11 and 2011–12. This may have been because early sown chickpea was sometimes limited by greater weed and Ascochyta Blight disease pressures than late sown treatments, and/or because chickpea is more sensitive to cold winter temperatures that restrict establishment and pod set (Croser et al., 2003) compared to lentil and the cereal crops. Hence, it is common practice in northern Syria and other cold parts of the Middle East that chickpea sowing is delayed to minimize these potential issues. In our study, chickpea under ZT sown late yielded significantly more (917 $kg\,ha^{-1}$) than under ZT sown early (764 $kg\,ha^{-1}$) or CT sown early (693 $kg\,ha^{-1}$) and late (637 $kg\,ha^{-1}$). Apart from yield advantages, ZT late planting with chickpea enhances opportunities to spread operations and workloads amongst other crop types with different optimal sowing dates. The introduction of slow-maturing chickpea varieties with improved cold tolerance and diseases resistance, along with enhanced weed management options, could also provide more flexibility and allow chickpeas to benefit more from early sowing with ZT, in much the same way as slow-maturing wheat varieties are used to allow earlier sowing in southern Australia (Kirkegaard et al., 2014b).

As expected in dryland Mediterranean environments, the amount and pattern of rainfall was a major driver of crop performance in our study. In the four-year comparisons, the highest yields for all crops were predominantly in 2011–12, reflecting the high and well distributed 453 mm rainfall. Of the 16 highest yields, there were eight under ZT and eight under CT and 10 sown early and six sown late. This suggests that, when moisture conditions are favorable as in 2011–12, all crops are able to produce well under both tillage systems and both times of sowing. The lowest yields were predominantly in 2010–11 which was the driest year with only 259 mm of rain, and also the seasonal break was very late (1–7 December). In this year, the early sowing on 8–11 November did not germinate or emerge until mid-December when it was already cold, reducing the possible discrimination with the late sowing on 5–9 January. Of the 13 lowest yields, there were nine under CT and four under ZT and six sown early and seven sown late. This suggests that poor crop yields occur more frequently with CT than ZT but similarly with early and late sowing, when moisture supply is constrained.

The adoption of ZT, retention of crop residues and rotations are reported to maintain or gradually improve various soil quality and fertility characteristics. Heenan et al. (2004) found in a 22-year study in Australia that soil organic carbon (SOC) and total nitrogen (TN) were maintained with direct drilling, stubble retention and wheat–lupin rotations, gradually increased if the legume rotation was subterranean pasture, and declined with cultivation (three passes), burning of stubble, and continuous wheat.

The crop responses to ZT measured in our study of tillage and TOS effects on a wheat–chickpea–barley–lentil rotation may also be linked to the dynamics of various soil parameters. Soil and water observations on this and several other long-term tillage trials at ICARDA in northern Syria during 2008–12 were reported by Sommer et al. (2014), who considered that increases in crop yield under ZT with crop residue retention could be linked to improvements in a range of soil fertility and quality indicators including higher SOM and microbial biomass contents, increased levels of extractable phosphate, sometimes (but not always) higher amounts of larger water-stable soil aggregates, and increased water infiltration capacity and soil water retention. The buildup of SOM and associated carbon sequestration was in the range of a modest 0.29 Mg C/ha/yr. High amounts of surface residues delayed the desiccation of the topsoil during the summer fallow period, but could not diminish the overall longer-term drying of the topsoil. They concluded that the small but positive changes observed in soil quality over six years, in combination with economic savings, mean that ZT provides an attractive option for farmers, from the standpoints of economy and ecological efficiency, especially in the long term.

The known cost savings and resource sustainability benefits from elimination of ploughing, in combination with the improved performance of crops under ZT and early sowing evident in this study, provide a clear message to researchers, extension specialists, policy makers and farmers and should encourage a move away from

traditional crop management practices based on heavy cultivation and the associated late sowing, and promote more development and adoption of ZT and early sowing to increase production, profitability and sustainability of crop production systems. It is also clear that ZT is not a crop-specific technology but can be used across crops and seasons. Wherever farmers are growing these temperate crops with CT and late sowing, they should be able to use ZT and early sowing to enhance production and profitability, and sustain the soil and environmental resource base. There will be a need to understand and locally address various issues and challenges (e.g., matching genotypes and optimal flowering time, weed management and herbicide resistance, pest and disease management, soil and nutrient management, retention/utilization of residues, integration of livestock, etc.), which will inevitably arise with a change from CT to ZT systems; that this can be done through on-going research and development is evidenced by the on-going refinement and enduring attractiveness and sustainability of ZT in countries such as Brazil, Canada and Australia (Kirkegaard et al., 2014a,b).

5. Conclusions

This study covering six seasons and four crops showed that ZT and early sowing were highly compatible cropping technologies for wheat, barley, chickpea and lentil, giving similar or better yields for ZT compared to CT and for early compared to late sowing in more than 90% of the relevant year, crop and tillage/TOS combinations. Comparing ZT treatments sown early with the traditional farmer practice of CT with delayed sowing, the gross margins were increased by 162, 147, 89 and 176 $\$\,ha^{-1}$ for wheat, chickpea, barley and lentil, respectively. The null hypothesis that tillage and TOS have no effect on crop performance or profitability was not supported by our study, which rather showed that ZT and early sowing are agronomically and economically attractive crop management options with little risk for farmers. These improved practices (eliminating ploughing, using ZT, sowing early) are not difficult to implement, provide flexibility and save costs in the cropping operation, and maximize the chances of achieving high yields and profits across variable seasons. They can be used wherever farmers are growing crops and have access to a ZT seeder, especially if they also have access to advice and support from researchers, extension officers and neighboring farmers already familiar and experienced with ZT. With the assurance brought by the widespread use and success of ZT and early sowing around the world, and the impressive performance of the technology in Syria, it can be recommended that farmers across the Middle East, where the technology has been little known or used, should consider eliminating ploughing and adopting ZT with early sowing in their cropping operations.

The experiment, set up on large plots with each of the main crops represented each year, was also used to raise awareness of and demonstrate the ZT system to the thousands of scientists, extension officers, farm machinery manufacturers and farmers who visited ICARDA each year, and was instrumental in promoting considerable adoption and impact of ZT in Syria and Iraq as described by Piggin et al. (2011), Loss et al. (2015) and Yigezu et al. (2015). Shortly after the outbreak of civil unrest, it was estimated that more than 500 farmers in Syria were using ZT and early sowing on 30,000 ha in the 2011–12 cropping season, having started from a zero base in 2006–07.

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