Renewable Agriculture and Food Systems: 27(1); 21–30 doi:10.1017/S1742170511000494

Conservation tillage for organic agriculture: Evolution toward hybrid systems in the western USA

John M. Luna[1]*, Jeffrey P. Mitchell[2], and Anil Shrestha[3]

[1]Luna and Associates, Agro-Ecological Consulting, 24663 Ervin Road, Philomath, OR 97370, USA.
[2]Department of Plant Sciences, University of California, Davis, CA 95616, USA.
[3]Department of Plant Science, California State University, Fresno, CA 93740, USA.
*Corresponding author: lunaj@peak.org

Accepted 26 October 2011 **Preliminary Report**

Abstract

Organic farming has been historically dependent on conventional tillage operations to convert perennial pasture leys to annual crop rotations, incorporate crop residues, compost and cover crops, as well as to mechanically kill existing vegetation. Conventional tillage, however, has long been known to lead to soil degradation and erosion. A recently developed no-till organic production system that uses a roller–crimper technology to mechanically kill cover crops was evaluated in two states in the western United States. In Washington, pumpkins (*Cucurbita* spp.) grown in a no-till roller–crimper (NT-RC) system produced yields 80% of conventional tillage, but with fewer weeds. However, in California on-farm research trials in organic cotton (*Gossypium barbadense* L.), tomato (*Lycopersicon esculentum* Mill.), eggplant (*Solanum melongena* L.) and cowpea (*Vigna unguiculata* (L.) Walp.), the no-till system produced virtual crop failure, or yields less than 20% of the standard production method. The major problems associated with rolled cover crops in California included reduced crop seedling emergence, planter impediment with excessive residue, lack of moisture and delay in transplanting of vegetable crops due to continued growth of cover crops, in-season crop competition from cover crop regrowth and impracticability of using cultivators. Further, excessive dry residue during summer in California can present the risk of fire. In both California and Oregon, considerable success has been demonstrated with zone tillage (strip tillage) in conventionally produced field and vegetable crops. In a replicated Oregon trial, the organic strip tillage treatment produced 85% of the broccoli (*Brassica oleracea* L.) yield compared to a conventional tillage treatment. Our studies suggest that the zone tillage concept may offer opportunities to overcome many of the agronomic challenges facing no-till.

Keywords: no-till, strip-till, zone tillage, conservation tillage, roller crimper, organic weed management, cover crops, *Secale cereale* L., *Phacelia tanacetifolia* Benth

Introduction

Conserving and enhancing soil quality has long been a philosophical cornerstone of the worldwide organic agriculture movement. With the creation of the US National Organic Program (NOP) in 2002, this philosophy became part of the federal laws regulating organic farming. Section 205.203 of the NOP[1] requires that 'The producer must select and implement tillage and cultivation practices that maintain or improve the physical, chemical, and biological condition of soil and minimize soil erosion'. Similarly, the International Federation of Organic Agriculture Movements standards[2] also require minimum tillage and other practices to prevent soil erosion and degradation.

Organic farming has been historically dependent on conventional tillage operations to convert perennial pasture leys to annual crop rotations, incorporate crop residues, compost and cover crops, as well as to mechanically kill existing vegetation. Preparing a relatively smooth, residue-free seedbed is essential for precision mechanical weed control in many organically grown crops. Conventional tillage, however, leaves the soil exposed to wind and water erosion, and has been shown to reduce soil aggregate size and accelerate the oxidation of soil organic matter[3,4]. The multiple passes over a field with conventional tillage are labor and energy intensive[5], contribute to soil compaction and generate airborne particulate matter[6].

Direct seeding of a crop into herbicide-killed crop residue, also known as no-till, has been documented in conventional agricultural systems to dramatically reduce soil erosion, and improve several key components of soil quality, as well as reduce machinery, labor and fuel costs[7,8]. In a 28-year comparison of no-till and conventional tillage in Ohio, for example, no-till systems had higher levels of organic carbon, aggregate diameter and water-holding capacity than conventional tillage systems[9]. In numerous studies, no-till systems have produced comparable or improved yields to conventional tillage, although yield response frequently depends on the crop and climatic region[10–12].

Some authors have suggested that because of the intensive tillage requirements of organic systems, conventional no-till agriculture may provide superior economic, agronomic and environmental benefits compared with organic farming[13]. There has been, however, widespread interest in no-till and reduced tillage systems among organic farmers and researchers, as demonstrated by numerous workshops and conferences in the United States and Europe in recent years. Much of the focus in the United States has been on an organic no-till planting system that uses a 'roller–crimper' to suppress a cover crop[14–16]. Although cereal rye (*Secale cereale* L.) is commonly used as a cover crop, various cover crop species and mixtures have been used in this system. A traditional no-till planter is used to plant the crop through the 'rolled down' cover crop mulch. The mulch serves to suppress weeds and conserve soil moisture. In this paper, we will refer to this system as the no-till roller–crimper (NT-RC) system.

Although this approach has shown potential for organic soybean (*Glycine max* L.) production in the mid-Atlantic region[17], and to some extent for no-till soybean production in the Midwestern US[18], it has shown limited success for field corn[19]. In this paper, we present preliminary evaluation of the NT-RC system in Washington and California, and discuss fundamental agronomic constraints and risks facing no-till organic farming. We also present work in Oregon on zone tillage systems for organic vegetable crops.

2009 Washington On-farm No-till Pumpkin Research

An on-farm experiment was conducted near Woodinville, WA to compare two tillage treatments: (1) standard tillage with a rototiller and (2) rolling/crimping the cover crop[20]. All plots were tilled and planted to cereal rye in September 2008, and the tillage treatments were implemented when approximately 75% of the cover crop was at full flower. Cover crop was incorporated into the rototilled plots on May 31, 2009 and no-till plots were rolled/crimped on June 2, 2009. The cover crop regrew in the rolled/crimped plots within 2 weeks, so these plots were rolled/crimped again on June 16, 2009. Tilled plots were rototilled again prior to transplanting pumpkins on June 27, 2009. Pumpkin yields in the no-till plots (7.2 $\mathrm{Mg\,ha^{-1}}$) were 20% less than the rototilled plots (9.8 $\mathrm{Mg\,ha^{-1}}$); however, yields were not statistically different at a 0.05 level of significance[20].

In the Washington trial, soil quality parameters measured in mid-August indicated that the tilled plots had significantly lower bulk density (i.e., 'lighter' soil) and more rapid infiltration than in the no-till plots. According to the authors, 'these short-term improvements in soil quality from rototilling may have resulted in more immediate vigorous pumpkin growth (observed visually) and yield, although this was not significantly different between treatments.' The authors point out that improvement in soil quality through tillage reduction and unincorporated cover crop residue occur over the longer term, and are rarely measured within one growing season.

Organic No-till Experiences in California

Several experimental trials and farm demonstration evaluations of the NT-RC system have been conducted at various sites in California's Central Valley during the past 5 years. These studies have evaluated cover crop termination using a 5 m-wide roller–crimper for production of Pima cotton, tomato, eggplant and cowpea. This work was initiated in 2006 at four sites: Five Points, Madera, Capay and Parlier, CA.

Cotton

At Five Points, an experiment was established to compare conventional tillage with NT-RC systems for conventional cotton production. Treatments included: (1) conventional tillage (beds prepared in winter, trifluralin applied pre-emergence in fall, spring cultivation, and re-shaping and preparation of beds); (2) stale seedbed (beds prepared in winter, spring burndown with paraquat with no further cultivation or bed shaping); (3) NT-RC system using cereal cover crop mixture of cereal rye (cv. Merced) and triticale (x *Triticosecale*) cv.Trios 102; and (4) NT-RC system using a legume cover crop mixture of Balansa clover (*Trifolium michelanium* L.), Persian clover (*Trifolium resupinatum* L.) and Austrian winter pea (*Pisum sativum* spp. *arvense* L.). No herbicides were used in the NT-RC treatments 3 and 4. The experimental design was a randomized complete block with four replications. Each treatment plot was 5 m wide and 100 m long. Cover crop mixtures of cereals or legumes were planted in October 2005 and rolled/crimped at an appropriate maturity stage[21] on April 24, 2006 using the front-mounted roller–crimper. Pima cotton was planted directly behind the roller–crimper with a John Deere 1730 no-till seeder in the same operation. The same planter was used to plant the conventional tillage and the stale seedbed plots.

Results. Although the roller–crimper appeared to kill the cover crop, the crop seedlings took nearly 3 weeks to emerge following the rolling operation due perhaps to cooler temperatures under the cover crop mulch, and continued growth of the cover crop during this time resulted in the soil surface becoming quite dry. This likely reduced the cotton crop germination and emergence. The cover crop plots were then flood irrigated to enhance crop emergence but the stand count was still 90% less than that in the conventionally planted or the stale seedbed cotton plots. Aboveground biomass samples taken on May 31 showed that the cotton dry mass in the conventional and stale seedbed plots was 30 times more than that in either of the cover crop treatments. There was no significant ($P<0.05$) difference in cotton stands or biomass between the cereal and legume cover crop treatments (data not shown). While these plants eventually grew, they did not mature early enough to be harvested. Thus, there was no marketable yield from the rolled/crimped cover crop plots at this site. Weed density samples taken on May 31 showed that the cover crops had similar weed densities as the conventional plots, ranging from 2 to 3 plants m^{-2}. The stale seedbeds, however, had greater ($P<0.05$) weed densities (13–16 plants m^{-2}) than the cover crop or the conventional plots. The cover crop plots demonstrated that these treatments could provide as much weed suppression without herbicides as the conventionally tilled plots with herbicides. However, acceptable crop stand establishment was not achieved. Therefore, if such a cover crop system were to be adapted for cotton in California, earlier and complete termination of the cover crops is needed, or perhaps zone tillage may be more appropriate than no-till and necessary measures have to be taken to prevent continued cover crop regrowth.

Eggplant

At the Madera organic farm site (36.96°N 120.07°W), similar mixes of cover crops were rolled with the roller–crimper before hand transplanting eggplant, and this system compared with the organic farmer's traditional system of plasticulture eggplant production. As in the Five Points experiment, the cover crop was easily rolled down; however, it took 3 weeks for the cover crops to eventually die. This resulted in a 4-week delay in transplanting the eggplant in the cover crop plots compared to the traditional plastic culture system. The rolled cover crop plots yielded about 20% of the eggplant production of the plastic system.

Tomatoes

At another organic farm site near Capay (38.71°N 122.05°W) the same cover crop mixes were compared with a farmer's customary hairy vetch (*Vicia villosa* Roth.) cover crop within a tomato transplant system. Data were collected for cover crop growth and percent cover crop kill following rolling. Similar observations were made at this site as at each of the two other sites. It took about 3 weeks more for the rolled cover crops to fully die compared to the farmer's customary system. This in turn delayed the transplanting and eventually the study was abandoned due to a poor crop stand.

Cowpeas

In 2007–2008, a study was conducted in cowpea at Parlier (36.6°N 119.53°W). Treatments included conventional tillage with or without herbicide and no-till rolled cover crops with or without herbicide. The experimental design was a split-plot, with tillage as the main plot and presence or absence of herbicide as the sub plot. The treatments were replicated four times; each main plot was 61 m long and 18.3 m wide. The plots were split into 30×18.3 m subplots. A cover crop mixture of oats (*Avena sativa* L.), wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) was planted in October 2007 and irrigated as needed. On April 15, 2008 when the cover crop mixture had reached an optimal level of maturity, it was rolled using the roller–crimper. Beds 75-cm wide were then prepared as is customarily done in the conventional tillage plots. Beds were not made in the cover crop plots. On May 29, cowpea seeds were planted in the conventional tillage beds using a John Deere Flex planter. In the no-till plots, cowpea was drill-seeded into the rolled cover crop plots using a Sunflower 1540 no-till drill at 18-cm row spacing. Seeding rate was 67 kg ha^{-1}. Crop seedling emergence was poor in the no-till plots because of 'hair pinning' of the cover crop, which is the pressing of cover crop residue into the slot created by the disk openers on the no-till planter. This produces poor seed-to-soil contact for the crop seeds. The cowpeas were re-planted using a John Deere 1530 no-till seeder on June 10. During this no-till seeding operation, hair pinning occurred again and the planter's residue managers were used to push away the cover crop from the seed row in front of the planter disk. Better cowpea stand was achieved when the residue manager was used. Bentazon herbicide was applied at the first trifoliate stage of the crop at 1.6 liter ha^{-1} and incorporated with sprinklers immediately after application. Cowpea and weed dry biomass were determined on July 21. Plants were cut on September 24 and harvested on October 16.

Results. The conventional tillage treatments with herbicide had almost no weeds, whereas weed biomass in the plots without herbicides ranged from 12 to 20 g m^{-2}. Weed biomass in the no-till plots with or without herbicides was significantly ($P<0.05$) greater than in the conventional tillage plots, ranging from 55 to 96 g m^{-2} in the plots with herbicide and 154 to 331 g m^{-2} in the plots without herbicides. More than 90% of this weed biomass represented continued growth or regrowth of the cover crop. Cowpea dry biomass in the conventional tillage plots with or without herbicides was about 2.5 times greater than that over the rolled cover crop mulch. Cowpea yields were approximately 40% lower in the cover crop plots than in the conventional tillage plots (data not shown). Therefore, the cover crop not only impeded and delayed crop emergence but also served as a weed, resulting in cowpea yield loss. In summer, in a dry environment like California, excessive dry residues on the surface can also pose fire hazards, especially in organic production systems that rely on flame weed control.

The No-till Roller-crimper System: Constraints

From our experiences with the NT-RC system in the western United States, as well as in following the development of this system in other areas of the country, we believe this system has major agronomic constraints that limit its adoption by organic farmers. Understanding these constraints is critical for improving the performance of this system, or in knowing when to select other tillage systems when they are better suited.

The NT-RC approach is predicated on several components, including: (1) producing a 'high biomass' cover crop; (2) adequately killing the cover crop (and other weeds) with the roller–crimper prior to planting; (3) achieving a satisfactory cash crop stand by no-till drilling into the rolled cover crop residue; (4) providing adequate mineral nutrition to the cash crop; and (5) managing weeds and other pests in the cash crop.

Producing high cover crop biomass

Most of the work on the NT-RC approach has stressed the need for 'high biomass' of the cover crop before rolling to provide a sufficient level of mulch on the soil surface to control weeds. McLenaghen et al.[22] reported that weed suppression by cover crops was directly proportional to the amount of cover crop growth. Smith et al.[17] suggested that at least 9000 kg ha^{-1} of dry matter biomass is required for adequate weed control. In a factorial experiment examining the impact of N fertilizer rate (from poultry manure) and the seeding rate of the rye cover crop on cover crop biomass and weed suppression, Ryan et al.[23] found increasing rates of N increased rye biomass, but did not reduce weed biomass. Increasing seeding rates of rye did not increase rye biomass, but did reduce weed biomass. These authors suggest that the early spring ground cover obtained with the higher seeding rates was key in reducing weed levels.

Establishing a solid cover crop stand in the fall is necessary to smother winter annual weeds, as well as to have uniform ground cover in the spring for the roll down operation. Since the rolled-down, dead cover crop biomass is expected to provide weed control across the soil surface, any openings in the cover crop stand can allow weed growth. Also in regions where the cash crop is typically harvested late in the season, soils are frequently too wet for fall tillage. Cover crops are planted late or not at all. Usually late-planted cover crops do not produce adequate spring biomass for weed suppression in the NT-RC system[24].

Killing the cover crop with the roller–crimper

Effectiveness of the roller–crimper to kill the cereal rye cover crop is dependent on the stage of maturity of the rye. Rye must be at least at Zadoks growth stage 61 (anthesis) to obtain 'effective control' of at least 85% kill with the roller[24]. If the rye is rolled at earlier maturity stages, the rate of suppression falls quickly. This translates to rolling the cover crop fairly late in the growing season—late May or early June for Pennsylvania and other northern locations[19]. These late planting dates will necessarily result in lower crop yields than longer season varieties planted earlier. For farmers trying to produce crops for the fresh market, delays in planting are even more costly from loss of market share.

In work at Pennsylvania State University, Mirsky et al.[24] examined the effect of fall planting date of a cereal rye cover crop on the effectiveness of the roller–crimper to kill the rye in the following spring. Rye planted on August 25 was 79% killed by the roller–crimper; however, only 73% of the rye was killed in the spring following a September 15 planting, with rye suppression dropping to 63% following the fall planting date of October 5.

Although the roller–crimper usually achieves a uniform 'laying down' of the rye cover crop in the field, the cover crop usually does not die until several weeks after rolling. In California's production environments, for example, irrigation is typically needed to establish most cash crops. The timing and application method of this irrigation need to be refined in order to accommodate the cover crop rolling operations so as to allow the cover crop to quickly die and the subsequent crop to successfully emerge and establish.

Achieving a satisfactory crop stand

The no-till seeding of a cowpea crop into the rolled cover crop in California was not successful due to hair pinning of the rolled residue. Using a no-till planter with residue managers achieved some improvement in crop stands, but the movement of residues out of the drilled row also increased weed germination. Although rye was not used in this study in California, it has well-known allelopathic chemicals that can also suppress germination and growth of crops as well as weeds[25–28].

Providing adequate crop nutrition

Most organic fertilizer materials (composted manures and animal by-products) tend to be in solid form, and soil incorporation is typically used to increase N mineralization and crop uptake. Soil incorporation also reduces N loss to the atmosphere through ammonia volatilization. Soil incorporation of amendments is impossible in the NT-RC system, however, unless they are applied in the fall preceding cover crop seeding.

Although the NT-RC approach has promise for organic soybean production, success has been limited for corn (*Zea mays* L.) and other crops requiring relatively high levels of N input for maximum yield. This is likely explained by the immobilization of N by the cereal rye cover crop that will have a very high carbon to nitrogen (C:N) ratio in the tissue when it is flowering. In a North Carolina study[29], soil N was immobilized for 6 weeks following a rolled and crimped rye cover crop. These authors suggested that the 'induced low nitrogen environment' was also a key factor in the weed reduction under the rolled rye. Angustia[30] also showed that high C:N ratio cover crops suppressed weeds when tilled into the soil, but that this weed-suppressive effect was eliminated with application of N fertilizer.

A major constraint of the NT-RC system with a rye cover crop is the inability to include a legume cover crop into the mixture to supply biologically fixed N. Numerous authors have documented N contributions to the following cash crops following legume cover crop mixtures and ecological synergism that occurs in a cereal–legume mixture[31,32]. The cereal scavenges soluble nitrate from soil that would otherwise be lost through leaching from the soil, and serves as a physical trellis to hold up the legume as it grows. The legumes also provide a significant amount of N to the rye during the growing season.

The problem of including legumes with the rye in the NT-RC system is the differing crop phenologies, particularly the timing of the stage of growth necessary for killing the legumes using the roller–crimper. In work in Pennsylvania, Mischler et al.[33] examined the impact of the timing of roller crimping on regrowth of hairy vetch. Vetch needed to reach the early pod-set stage to achieve a complete kill, but in Pennsylvania this did not occur until the second or third week of June. According to the authors, this is approximately 4–6 weeks after recommended corn planting dates, and this delay is likely to limit corn yield potential due to a reduced length of growing season and smaller accumulation of heat units for the corn.

The delay of planting date for the NT-RC system eliminates many of the crops planted in California and the Pacific Northwest. With California's relative mild winters, growers are able to start cropping relatively early in the season (i.e., March–April) and waiting for a rye or rye/vetch cover crop to reach a stage where it can be killed by the roller–crimper means 4–6 weeks of lost crop growth and economic return. In the cool, wet Pacific Northwest (west of the Cascade Mountains), similar problems occur. Most annual vegetable crops must be planted much earlier than the NT-RC system allows if the cover crop is going to be killed with the roller.

The use of cover crops in annual cropping systems in California's Central Valley is not currently widespread due largely to concerns about additional costs associated with cover crop management and limitations of available water needed for successful cover crop establishment and production. Studies in Five Points, California in western Fresno County, however, have shown that when no irrigation water is used to establish cover crops, biomass production depends closely on the amount of winter rainfall that occurs from October to March. Thus, farmers who have integrated cover crops into their annual cropping systems in this region for crops such as tomatoes, now tend to expend 10–15 cm of fall irrigation water to establish the crops prior to the onset of winter rains[34].

Controlling weeds and other pests

Ironically one of the primary reasons for developing the NT-RC system was to use the rolled down mulch for weed control, however, one of the largest challenges to the NT-RC system is weed management. The rolled down mulch must be of sufficient biomass and uniformly distributed across the soil surface to achieve optimum weed suppression. Frequently the mulch will not suppress all of the weeds, and there are weed escapes. For example, Curren et al.[19] considered 85% weed suppression in the NT-RC system as 'acceptable.' Also the no-till planter opens up a small slot where weeds can emerge within the crop row. In the NT-RC system, however, there are no opportunities for mechanical weed control to provide 'rescue' control for these weed escapes. For example, field bindweed (*Convolvulus arvensis* L.) is a common weed in many annual crops in California, including tomatoes, beans and cotton. In many cases, cultivation is the most effective method of control of this prostrate, vining species. Hand hoeing through the cover crop residue is difficult, and hand weed pulling is frequently required.

In the Pacific Northwest, cover crops can provide an excellent habitat for slugs[35] and rodents such as the meadow vole (*Microtus* sp.). Both slugs and voles are major economic pests of a broad array of crops, and few effective control practices are available for organic growers. This can be a severe limitation to adoption of conservation tillage systems that leave more than 30% crop residue on the soil surface, including both the NT-RC system and the zone tillage systems that will be described. In California, there are no reports of vertebrate pest populations in rolled down cover. However, studies have shown vertebrate pests such as gophers (*Thomomys* sp.) were more abundant in orchards and vineyards that had cover crops[36,37].

Zone Tillage: A 'Hybrid' Tillage System

Zone tillage (also known as strip tillage) is a form of conservation tillage that clears a narrow zone of soil, loosening subsoil layers and preparing a seedbed, while areas between the tilled strips receive shallow or no tillage[38,39] (Fig. 1). Zone tillage has been used extensively in the Midwestern United States to overcome many of the

https://doi.org/10.1017/S1742170511000494 Published online by Cambridge University Press

Figure 1. Zone tillage involves separate tillage, weed control and fertilizer operations for the crop zone and the between-row zones. The shank/coulter strip tillage machine shown here tills strips approximately 25 cm wide and 30 cm deep.

yield-reducing impacts of no-till in conventional farming systems[40]. We consider zone tillage to be a hybrid tillage system, integrating aspects of conventional tillage and no-till.

In zone tillage, there are two distinct zones of tillage activity: (1) the crop zone, typically 20–30 cm wide, where tillage, fertilizer and weed management are intensified; and (2) the between-row zone that is managed less intensively, and with different objectives. In conventional tillage systems, the entire surface of a field receives multiple passes of various kinds of tillage equipment to prepare a uniform soil surface for planting and subsequent cultivation operations. In strip tillage systems, however, with a typical 75- to 90-cm row spacing, tillage occurs on only 35–40% of the soil surface. Crop residue is mixed with the soil in the tilled strip, accelerating a beneficial release of N through microbial mineralization of organic matter. The area between the tilled zones (between row) is managed independently, depending on the nature of the crop or cover crop residue. Surface residues remaining between rows are critical to reduce soil erosion.

Zone tillage decreases both the area and volume of soil that is disturbed on each tillage operation, reducing the amount of dust that is typically generated in intercrop tillage[41]. Fuel, labor and equipment costs are also reduced when compared to conventional tillage[42,43]. Soil compaction from tractor wheel traffic is confined in zone tillage, dramatically reducing compaction in the crop growth zone.

Oregon and California Experiences with Conventional Strip Tillage

In a replicated 4-year study in the Oregon Willamette Valley, 20 on-farm trials were conducted comparing strip-tillage systems with conventional tillage systems for sweet corn production. In the first 2 years of the trials a 4.5 m Northwest Tillers® rototiller, modified to till 6 rows 20 cm wide was used. In the later 2 years of the trials, a strip-till machine using a shallow shank and rolling coulters was used. Across an array of soils and crop residue situations, sweet corn yields from strip-tillage and conventional tillage systems were identical in each year of the 4-year trial. However, machinery and labor costs were reduced by nearly 50% by strip-tillage[38].

In California, a range of economic and natural resource conservation benefits have attracted dairy farmers, in particular, to strip tillage. This system uses fewer intercrop tillage passes or operations than traditional tillage systems thereby reducing ‘land preparation’ costs. In a 2002 farm evaluation of strip-tillage forage-corn production near Modesto, CA, the land preparation costs were about 54% lower than the costs of traditional preplant soil preparation[39]. The requirements for farm labor and the time required for tillage between crops was also lower and time between successive forage crops was reduced. This allowed more opportunities for ‘triple-cropping’, the sequential production of three crops within a given calendar year. However, these were not organic production systems.

Organic Strip Tillage Broccoli Production

To evaluate strip tillage for organic production systems, a randomized block experiment was established in 1998 at the Oregon State University (OSU) Vegetable Research Farm near Corvallis[44]. A conventional tillage treatment (using a Tortella® reciprocating spader and a Lely® roterra to prepare the seedbed) was compared with a strip–till system using a Northwest Farm Tillers® 3.7-m rototiller modified to till four 15 cm-wide strips approximately 15 cm deep on 75-cm row centers. Cereal/vetch cover crops, planted the previous October, were suppressed using a flail mower prior to imposing tillage treatments. Granular fish fertilizer was manually applied in 15-cm band over each crop row and incorporated using the strip tiller prior to planting in both tillage treatments. Broccoli (cv.= 'Arcadia') was transplanted on May 28 and irrigated as necessary through the season. Two weed management treatments for the between row areas in the strip tillage treatments were evaluated in a split-plot design. These included: (1) 'cultivated' with a Buffalo® high residue V-sweep cultivator (Fleischer Manufacturing, Columbus, NE); and (2) mowed with a walk-behind trimmer mower (DR Power Equipment, Vergennes, VT). Mowing was conducted on June 14 and June 27. The reduced tillage and the strip till plots were cultivated with the Buffalo cultivator on June 27. Weeds within the rows were controlled by hand hoeing on July 1 and 7.

Broccoli yield estimates were made by cutting, grading and weighing heads on August 10 and 16. Weed abundance was estimated on June 23 (25 days after transplanting broccoli and before the between-row cultivation in the strip-till, cultivated plots).

Results

The conventional tillage treatment produced significantly higher broccoli yield (11,500 kg ha^{-1}) than both the strip-till cultivated (9810 kg ha^{-1} and the strip-till mowed (9320 kg ha^{-1}) ($P < 0.05$). Densities of purslane (*Portulaca oleracea* L), hairy nightshade (*Solanum sarrachoides* Sendtner) and Persian speedwell (*Veronica persica* Poir) were all greater in the between-row areas of the conventional tillage plots than in between-row areas of the strip-till plots ($P < 0.05$)[44].

Discussion and Conclusions

Although the NT-RC system has shown potential for production of organic soybeans in the mid-Atlantic region of the USA, and for some late-planted crops in other regions, we believe there are major agronomic constraints that ultimately limit the application of this system in organic agriculture. There are significant risks of crop failure or economically significant yield loss associated with the NT-RC system because of these problems. Future research should address these constraints to improve the productivity and reliability of this system.

We suggest that the zone tillage concept offers opportunities to overcome many of the agronomic challenges faced with the NT-RC, as well as to reduce the risk of crop loss. We do not present any 'off the shelf, ready-to-go' zone tillage systems for organic agriculture. Numerous technical and agronomic challenges must be met before zone systems become operational. There are, however, obvious advantages to zone tillage compared to the no-till approach that may allow a broader adoption by organic farmers in multiple scales of production.

A variety of tillage implements can be used in the tilled 'crop' zone to achieve specific tillage objectives, including breaking of soil compaction layers, killing and incorporating existing vegetation into the soil, and preparing a fine seedbed for precision planting. For example, 'second-pass' zone tillage equipment can be used to perform minimum-tillage finishing operations in the tilled zone[45] (Fig. 2). Organic fertilizers can be band-applied and mechanically incorporated into the strip, and later side-banded based on crop needs. Precision flaming[46] (Fig. 3), stale seedbed techniques, and precision mechanical cultivation technologies can be used to manage weed populations in the crop zone[47]. Weeds and cover crop regrowth in the between-row zone can be managed by a combination of mowing, cultivating or other shallow tillage, depending on the crop and soil situation.

Clearly, there are challenges to the adoption of zone tillage systems by organic farmers. The need for new, specialized equipment is a formidable barrier, both in terms of availability and cost. A list of specialized equipment might include: (1) a primary strip tillage machine, such as the shank/coulter strip tiller described earlier; (2) a 'second-pass' finishing machine, often needed to prepare a seedbed suitable for planting; (3) a strip fertilizer and compost application machine, needed for zone fertilization; (4) strip flamers and thermal weed control technologies; (5) precision in-row cultivation equipment; and (6) strip-mowers, high-residue cultivators and undercutters to manage weeds and cover crop regrowth in the between-row areas. This can represent a significant investment in specialized equipment, and some of this equipment is not yet available commercially.

Additional research is needed on novel cover crops and cover crop mixtures to facilitate organic conservation tillage systems. For example, *Phacelia tanacetifolia* Benth., an annual native of the southwestern USA, has shown promise as a substitute for the cereal crops when grown with common vetch in Oregon (Luna, unpublished data). *Phacelia* is much easier to kill mechanically, and the residue and roots are easy to incorporate into the tilled zone. *Phacelia* is not adapted to cold winter temperatures, however, which limits its range of utility.

Curren et al.[19] emphasized that continuous no-tillage was not going to be possible in organic systems. Nor is zone tillage suggested here as a continuous system.

Figure 2. A second-pass strip tillage machine was developed by Hendricks Farms (Stayton, OR) and modified by Pearmine Farmers (Gervais, OR). Multiple gangs of parallel disks and a sprocket roller break up soil clods to prepare a seed bed within the tilled crop zones.

Figure 3. A strip flamer, developed by Charles Merfield and modified by Edward Peachey at Oregon State University, can be used in organic zone tillage systems to reduce weeds in the crop row.

Rather, no-till and zone tillage are conservation tillage options that could be used at specific points in the crop rotation cycle. As Peigné et al.[47] emphasized, the success of conservation tillage systems for organic farming depends on the choice of crop rotation to enhance pest and nutrient management.

Minimum or reduced tillage practices will continue to be needed in organic farming systems for a wide array of agronomic and economic reasons[48]. Research is needed to develop a more prescriptive approach to minimum tillage, which would integrate various tillage tools to address specific crop production and environmental goals. By focusing on the specific goals of each separate tillage operation (i.e., breaking up soil compaction, killing existing vegetation), a suite of equipment can be used to minimize detrimental impacts as well as tillage costs.

https://doi.org/10.1017/S1742170511000494 Published online by Cambridge University Press

There will be inexorable trade-offs between agronomic and economic imperatives, and the desires to conserve and improve soil quality. Such is the ongoing dialectic of developing sustainable agricultural systems. Conservation tillage for organic agriculture will require a more integrated, holistic approach to optimizing cover cropping and tillage systems for the specific crops, soils and climatic regions of the world.

References

1 USDA National Organic Program. 2011. Available at Web site http://www.ams.usda.gov/AMSv1.0/nop (accessed December 14, 2011).

2 IFOAM. 2002. IFOAM basic standards for organic production and processing. International Federation of Organic Farming Movements, Germany. p. 13–40.

3 Grandy, A.S., Robertson, G.P., and Thelen, K.D. 2006. Do productivity and environmental trade-offs justify periodically cultivating no-till cropping systems? Agronomy Journal 98:1377–1383.

4 Morris, D.R., Gilbert, R.A., Reicosky, D.C., and Gesch, R. W. 2004. Oxidation potentials of soil organic matter in histosols under different tillage methods. Soil Science Society of America Journal 68:817–826.

5 Mitchell, J.P., Klonsky, K.M., Miyao, E.M., and Hembree, K.J. 2009. Conservation tillage tomato production in California's San Joaquin Valley. Publication 8330. University of California Division of Agriculture and Natural Resources.

6 Baker, J.B., Southard, R.J., and Mitchell, J.P. 2005. Agricultural dust production in standard and conservation tillage systems in the San Joaquin Valley. Journal of Environmental Quality 34:1260–1269.

7 Blevins, R.L., Smith, M.S., and Frye, W.W. 1983. Changes in soil properties after 10 years of no-tillage and conventional tilled corn. Soil and Tillage Research 3:135–146.

8 Lal, R., Griffin, M., Apt, J., Lave, L., and Morgan, M.G. 2004. Managing soil carbon. Science 304–393.

9 Mahboubi, A.A., Lal, R., and Faussey, N.R. 1993. Twenty-eight years of tillage effects on two soils in Ohio. Soil Science Society of America Journal 57:506–512.

10 Dick, W.A., McCoy, E.L., Edwards, W.M., and Lal, R. 1991. Continuous application of no-tillage to Ohio soils. Agronomy Journal 83:65–73.

11 Grandy, A.S., Loecke, T.D., Parr, S., and Robertson, G.P. 2005. Long-term trends in nitrous oxide emissions, soil nitrogen, and crop yields of till and no-till cropping systems. Journal of Environmental Quality 35:1487–1495.

12 Vyn, T.J. and Raimbault, B.A. 1993. Long-term effect of five tillage systems on corn response and soil structure. Agronomy Journal 85:1074–1079.

13 Trewavas, A. 2004. A critical assessment of organic farming-and-food assertions with particular respect to the UK and the potential environmental benefits of no-till agriculture. Crop Protection 23:757–781.

14 Kornecki, T.S., Price, A.J., Raper, R.L., and Arriaga, F.J. 2009. New roller crimper concepts for mechanical termination of cover crops in conservation agriculture. Renewable Agriculture and Food Systems 24:165–173.

15 USDA Natural Resources Conservation Service. 2002. The knife roller (crimper): an alternative kill method for cover crops. Technical Note No. 13. September 2002.

16 Ashford, D.L. and Reeves, D.W. 2003. Use of a mechanical roller-crimper as an alternative kill method for cover crops. American Journal of Alternative Agriculture 18:37–45.

17 Smith, A.N., Reberg-Horton, S.C., Place, G.T., Meijer, A. D., Arellano, C., and Mueller, J.P. 2011. Rolled rye mulch for weed suppression in organic no-tillage soybeans. Weed Science 59:224–231.

18 Davis, A.S. 2010. Cover-crop roller–crimper contributes to weed management in no-till soybean. Weed Science 58:300–309.

19 Curren,, W., Mirsky, S., and Mason, W. 2011. The evolution, status, and future of organic no-till in the northeast US webinar. [Updated March 31, 2011; cited 2011 October 24, 2011]. Available at Web site http://www.extension.org/pages/33063/the-evolution-status-and-future-of-organic-no-till-in-the-northeast-us-webinar (accessed December 14, 2011).

20 Collins, D.P., Corbin, A., Benedict, C., Cogger, C., Bary, A., Burrows, C., and Miles, C. 2011. Reducing tillage with cover crops in western Washington organic vegetable production: early research progress and future direction. Tilth Producers Quarterly 21:15–19.

21 Creamer, N.G., Bennett, M.A., Stinner, B.R., Cardina, J., and Regnier, E.E. 1996. Mechanisms of weed suppression in cover crop-based production systems. HortScience 31:410–413.

22 McLenaghen, R.D., Cameron, K.C., Lampkin, N.H., Daly, M.L., and Deo, B. 1996. Nitrate leaching from ploughed pasture and the effectiveness of winter catch crops in reducing leaching losses. New Zealand Journal of Agricultural Research 39:413–420.

23 Ryan, M.R., Curran, W.S., Grantham, A.M., Hunsberger, L.K., Mirsky, S.B., Mortensen, D.A., Nord, E.A., and Wilson, D.O. 2011. Effects of seeding rate and poultry litter on weed suppression from a rolled cereal rye cover crop. Weed Science 59:438–444.

24 Mirsky, S.B., Curran, W.S., Mortensen, D.A., Ryan, M., and Shumway, D.L. 2009. Control of cereal rye with a roller/crimper as influenced by cover crop phenology. Agronomy Journal 101:1589–1596.

25 Barnes, J.P. and Putnam, A.R. 1983. Rye residues contribute weed suppression in no-tillage cropping systems. Journal of Chemical Ecology 9:1045–1057.

26 Barnes, J.P. and Putnam, A.R. 1986. Evidence for allelopathy by residues and aqueous extracts of rye (*Secale cereale*). Weed Science 34:384–390.

27 Perez, F.J. and Ormeno-Nunez, J. 1993. Weed growth interference from temperate cereals: the effect of a hydroxamic-acids-exuding rye (*Secale cereale* L.) cultivar. Weed Research 33:115–119.

28 Teasdale, J.R. and Mohler, C.L. 1993. Light transmittance, soil temperature, and soil moisture under residue of hairy vetch and rye. Agronomy Journal 85:673–680.

29 Wells, M.S., Reberg-Horton, S.C., and Smith, A.N. 2010. Nitrogen immobilization in a rye (*Secale cereale* L.) roll-killed system. In Proceedings of the International Annual

Meetings of the ASA-CSSA-SSSA, Long Beach, CA. Paper 60014. Available at Web site http://a-c-s.confex.com/crops/2010am/webprogram/Paper60044.html (accessed December 14, 2011).
30 Angustia, S.N. 1995. Impact of cover crops on weed abundance and nitrogen contribution in broccoli, *Brassica oleracea* var italica, production systems in the Maritime Pacific Northwest. MS Thesis, Oregon State University, Corvallis, OR. 92 p.
31 Sullivan, P.G., Parrish, D.J., and Luna, J.M. 1991. Cover crop contributions to N supply and water conservation in corn production. American Journal of Alternative Agriculture 6:106–113.
32 Sainju, U.M., Whitehead, W.F., and Singh, B.P. 2005. Biculture legume-cereal cover crops for enhanced biomass yield and carbon and nitrogen. Agronomy Journal 97:1403–1412.
33 Mischler, R., Duiker, S.W., Curran, W.S., and Wilson, D. 2010. Hairy vetch management for no-till organic corn production. Agronomy Journal 102:355–362.
34 Mitchell, J.P., Pettygrove, G.S., Upadhyaya, S., Shrestha, A., Fry, R., Roy, R., Hogan, P., Vargas, R., and Hembree, K. 2009. Classification of conservation tillage practices in California irrigated row crop systems. Publication 8364. University of California Division of Agriculture and Natural Resources, Davis, CA.
35 Krzic, M., Fortin, M., and Bomke, A.A. 2001. Sweet corn tillage-planting systems in a humid maritime climate of British Columbia. Journal of Sustainable Agriculture 19:25–39.
36 Ingels, C.A., Scow, K.M., Whisson, D.A., and Drenovsky, R.E. 2005. Effects of cover crops on grapevines, yield, juice composition, soil microbial ecology, and gopher activity. American Journal of Enology and Viticulture 56:1:19–29.
37 Smallwood, K.S. 1996. Managing vertebrates in cover crops: a first study. American Journal of Alternative Agriculture 11:155–160.
38 Luna, J.M. and Staben, M.L. 2002. Strip tillage for sweet corn production: yield and economic return. HortScience 37:1040–1044.
39 Mitchell, J., Shrestha, A., Campbell-Mathews, M., Giacomazzi, D., Goyal, S., Bryant, D., and Herrera, I. 2009. Strip-tillage in California's Central Valley. Publication 8361. University of California Division of Agriculture and Natural Resources, Davis, CA.
40 Janovicek, K.J., Deen, W., and Vyn, T.J. 2006. Soybean response to zone tillage, twin-row planting, and row spacing. Agronomy Journal 98:800–807.
41 Madden, N.M., Southard, R.J., and Mitchell, J.P. 2009. Conservation tillage reduces PM10 emissions in dairy forage rotations. Atmospheric Environment 42:3795–3808.
42 Nail, E.L., Young, D.L., and Schillinger, W.F. 2007. Diesel and glyphosate price changes benefit the economics of conservation tillage versus traditional tillage. Soil and Tillage Research 94:321–327.
43 Weersink, A., Walker, M., Swanton, C., and Shaw, J.E. 1992. Costs of conventional and conservation tillage systems. Journal of Soil and Water Conservation 47:328–334.
44 Luna, J.M. 2003. Conservation tillage systems for organic vegetable production. Organic Farming Research Foundation Information Bulletin 12:14–16.
45 Luna, J.M. and Staben, M.L. 2003. Strip tillage vegetable production systems for western Oregon. No. EM 8824. Oregon State University Extension Publication, Corvallis, OR, 12 p.
46 Merfield, C. 2011. Physical Weeding. Available at Web site http://www.physicalweeding.com/index.htm (accessed December 14, 2011).
47 Peigné, J., Ball, B.C., Roger-Estrade, J., and David, C. 2007. Is conservation tillage suitable for organic farming? A review. Soil Use and Management 23:129–144.
48 Berner, A., Hildermann, I., Fliessbach, A., Pfiffner, L., Niggli, U., and Mäder, P. 2008. Crop yield and soil quality response to reduced tillage under organic management. Soil and Tillage Research 101:89–96.