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Review

Organic Agriculture and the Quest for the Holy Grail in Water-Limited Ecosystems: Managing Weeds and Reducing Tillage Intensity

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Academic Editor: Patrick Carr
Received: 5 February 2017; Accepted: 29 March 2017; Published: 31 March 2017

Abstract: Organic agricultural production has become a major economic and cultural force. However, in water-limited environments the tools used for weed control and nutrient supply, namely tillage and cover crops, may not be environmentally or economically sustainable as tillage damages soil and cover crops use valuable water. Thus, a major challenge has been finding appropriate ways to minimize tillage and terminate cover crops while still controlling weeds and obtaining cover crop ecosystem services. One approach to achieve this is through the economically viable integration of crop and livestock enterprises to manage weeds and terminate cover crops. In this article we (1) review research needs and knowledge gaps in organic agriculture with special focus on water-limited environments; (2) summarize research aimed at developing no-till and reduced tillage in organic settings; (3) assess approaches to integrate crop and livestock production in organic systems; and (4) present initial results from a project assessing the agronomic and weed management challenges of integrated crop-livestock organic systems aimed at reducing tillage intensity in a water-limited environment. The goal of eliminating tillage in water-limited environments remains elusive, and more research is needed to successfully integrate tactics, such as cover crops and livestock grazing to increase organic farm sustainability.

Keywords: cover crops; crop-livestock integration; no-till; northern Great Plains; reduced tillage; weed management; zero till

1. Introduction

Organic agriculture is at the crossroads. Critics view organic production as an ideologically driven, environmentally-unsustainable, and ineffective approach to farming that does not allow humankind to respond to global challenges, such as population growth and climate change. Concerns associated with organic agriculture include yield reductions, lack of effective pest and nutrient management tactics, soil erosion due to excessive tillage, and the use of land to grow green manures and cover crops instead of crops or animals for direct human consumption [1–3]. Advocates of organic farming point to an environmentally-benign approach to farming with reported increased soil health and ecosystem services, as well as socio-economic benefits [4], growing consumer demand for organic products with yearly double-digit growth to US $43 billion in 2016 [5], and nationwide availability in nearly 20,000 natural food stores and in three out of four conventional retailers [6]. Regardless of these views, organic agriculture has become a major market and cultural force. However, are tillage-based organic systems, particularly in water-limited environments, able to sustainably maintain or increase productivity when confronted with nutrient deficiencies, the need for soil conservation, and pest management challenges? What knowledge breakthroughs will close the existing yield gap between conventional and organic cropping systems and ensure net profitability while maintaining the biological and environmental integrity of its production base? How sustainable is organic production in the face of surging consumer and market demands? What strategies can help organic farmers effectively reduce tillage intensity and frequency, while enhancing the system's resiliency to increased temperatures and shifting precipitation patterns? Answering these questions will provide critical knowledge that will allow organic agriculture to increase market share and enhance productivity and net returns, while maintaining environmental underpinning and economic viability. While each of these questions is important, this paper focuses on the complexities of reducing tillage in semi-arid organic systems.

For organic agriculture to meet the growing demand for food, while sustaining the environment's ability to provide for social and ecological services, it is necessary to achieve a systems-level understanding of the linkages among biophysical processes, human activities, and socioeconomic goals [7,8]. In this article, we first review critical research needs and knowledge gaps in organic agriculture, with special focus on water-limited environments. Second, we summarize current efforts to develop no-till and reduced tillage organic systems. Third, we explore potential avenues to integrate crop and livestock production in organic systems. Finally, we present preliminary lessons we are learning in a project we are conducting on the agronomic and weed management challenges of integrated crop-livestock organic systems aimed at reducing tillage intensity in a water-limited environment.

2. Critical Needs of Organic Agriculture in the Northern Great Plains, a Water Limited Ecosystem

The Northern Great Plains (NGP) is a vast prairie landscape in South Dakota, North Dakota, and Montana; parts of Northeastern Wyoming and Northwestern Nebraska; the arable regions of the Canadian provinces of Manitoba, Saskatchewan, and Alberta; and Northeastern British Columbia [8]. Traditionally, agriculture in the NGP has been based on drought-resistant crops such as spring wheat (*Triticum aestivum* L.), and summer fallow is commonly used to conserve soil moisture and release organic nitrogen (N). More recently, the adoption of reduced tillage systems in conventionally managed systems has increased soil moisture retention and facilitated diversified rotations that include oilseed, pulse, forage, and other specialty crops [9,10]. These advances have made the NGP one of the largest U.S. expanses of conventional no-till dryland small grain, pulse, and oilseed agriculture [11]. This region also has great potential for small grain organic production [9] and for low-intensity organic sheep production, as animals are raised on dry native range and can be finished on cover crops integrated with crop production [12–14]. Despite its potential, the challenges of organic agriculture in dryland agroecosystems are many.

With a continental climate characterized by long, cold winters and short, warm summers, large diurnal ranges in temperature, strong winds, and variable and unpredictable precipitation [15], several environmental and biological factors hinder the sustainability of dryland organic agriculture across the NGP. First, in most years, soil moisture becomes depleted early in the summer and crops undergo terminal drought after anthesis, which reduces yield and impacts quality. This worrisome trend gets compounded as late winter/early spring temperatures have increased in the region since 1950 [16] and projections indicate that in areas within the NGP evapotranspiration constraints in mid-summer will increase [15], further increasing moisture challenges. It is predicted that the impacts of these new climate scenarios will become much more pronounced if temperatures rise above 31 °C and 35 °C during spring wheat anthesis and grain fill, respectively, or significant periods of unpredictable drought are experienced [17]. Second, commodity specialization within conventional agriculture has resulted in vast monocultures which has led to the development of a specialized and interacting pest complex of insects, weeds, and pathogens. Despite these biological interactions, pest management strategies in conventional systems typically focus singularly on specific problems with specialized and highly effective pesticides. However, the lack of such options in organic systems and the existence of interactions between pest groups occurring at the same or different tropic levels complicates management decisions in organic settings and compromises the robustness, resilience, and environmental integration required in sustainable farming [18,19]. Third, weeds remain a top challenge for organic growers across the region due to both competition with crops and water-use during fallow periods, and their management commonly consists of heavy reliance on tillage which represents a major threat to the environmental sustainability of the organic enterprise [20]. Fourth, low soil organic matter and available N across the NGP limits soil fertility in organic settings [21] and cover crops, which are key components of organic farms to fix N and manage weeds, often fail to provide enough N to subsequent crops [22], and effective termination methods to preserve soil moisture while minimizing soil tillage are lacking. Finally, although the benefits of organic no-till farming have been demonstrated in wetter regions, this practice remains elusive in water-limited environments [21]. Addressing these challenges represents a required step in the development of sustainable and resilient organic production in the water-limited systems of the NGP.

3. The Failed Marriage between No Tillage and Organic Agriculture in Water-Limited Systems

Tillage is heavily relied upon in organic systems for weed management and cover crop termination, but has become the "Achilles heel" in dryland cropping regions of the NGP. For decades, it has been known that tilled soils in the NGP are especially prone to wind and water erosion, and precious soil organic matter is steadily depleted from thin 'A' horizons [23]. As a result, many conventional farms, especially throughout the drier sections of NGP, have reaped the environmental and economic benefits of no-till and reduced tillage farming [10,21,24], and encouraging results have been achieved in organic systems in wetter regions [25,26]. However, for numerous reasons, success has been elusive in organic farms within water-limited systems [21], and the "holy grail" of no-till organic farming is yet to be found. First, organic no-till systems rely heavily on cover crop and mulches to control weeds and contribute biologically-fixed N, but the establishment of a cover crop with a large amount of biomass is necessary to secure the benefits of this ecosystems service. One study conducted in Maryland, USA, estimated that greater than 8000 kg·ha^{-1} dry weight of cereal rye and a mulch thickness of 10 cm was needed to effectively suppress annual weeds [27]. In comparison with the Midwest and Northeast USA, where abundant moisture allows a consistent growth of cover crops, producing such quantities of cover crop biomass in the water-limited systems of the NGP creates a conundrum: high cover crop biomass to suppress weeds is difficult to achieve and, if possible, it may use excess soil moisture at the expense of subsequent crop yields [28,29] (see Table 1). Thus, organic farmers in water-limited environments must strike a balance among producing cover crop biomass for weed control (a difficult task with the available cover crop varieties), securing soil nutrient provisioning, and conserving soil moisture for cash crop growth. Out of economic necessity, organic farmers in the NGP usually choose to conserve soil water for cash crop production and, therefore, revert to at least some form of tillage for weed control.

Table 1. Impacts of different farming systems approaches to weed management and soil fertility on weed control, nutrient availability, soil quality, and water availability.

System	Weed Management	Soil Fertility	Impacts to Key Farm Characteristics			
			Weed Control	**Nutrient Availability**	**Soil Quality**	**Water Availability**
Conventional tilled	Tillage	Synthetic fertilizer	↑ [1] Generally effective in controlling weeds.	↑ Synthetic fertilizers generally adequate to supply crops with nutrients.	↓ [2] Long term tillage resulted in very poor soil quality across much of the Northern Great Plains and was the impetus for the adoption of no-till.	↓ Soil affected by tillage has less water holding capacity.
Conventional no-till	Herbicide	Synthetic fertilizer	↑ Generally effective in controlling weeds. [3]	↑ Synthetic fertilizers generally adequate to supply crops with nutrients.	↑ Improved soil quality compared to tilled soils.	↑ Improved water holding capacity compared to tilled soils.
Organic tilled	Tillage	Cover crops	↑ Generally effective in controlling weeds.	– [4] May still need off-farm inputs.	↓ Deteriorates soil quality, although somewhat mitigated by incorporation of cover crop green manure.	↓ Soil affected by tillage has less water holding capacity, although somewhat mitigated by increased organic matter.
Organic no-till	Cover crops	Cover crops	– ↑ Cover crops may provide adequate weed control if enough biomass is produced and grown late into summer, but this comes at the expense of soil water.	– Cover crops may provide adequate nutrients through sequestration and N fixation, but longer growth and tillage or grazing to accelerate nutrient release may be needed.	↑ No-till and cover crop incorporation improve soil quality.	↓ Adequate cover crop growth for weed control and nutrient supply will use excess water, at the expense of subsequent cash crop yields.
			↓ Cover crops terminated early to conserve water will not provide adequate weed control.	↓ Cover crops terminated early to conserve water will not provide adequate levels of soil nutrients.	↑ No-till and cover crop incorporation improve soil quality.	– ↑ Cover crops terminated early may increase water availability by increasing soil organic matter and cooling the soil surface.

[1] Upward arrow indicates high level of weed control, nutrient availability, soil quality, or water availability; [2] Downward arrow indicates poor level of weed control, nutrient availability, soil quality, or water availability; [3] While synthetic herbicides are generally effective in controlling weeds, the numerous cases of the evolution of herbicide resistance in weeds should be noted; [4] Horizontal dash indicates unknown impacts and/or potentially interacting factors that affect weed control, nutrient availability, soil quality, or water availability.

Second, difficulties in killing cover crops pose problems in no-till organic systems. Using a roller blade (aka roller-crimper) is a no-soil-disturbance method often used to terminate cover crops [30], but this technique is most efficient when used at advanced growth stages [26,31]. Unfortunately, as discussed above, allowing cover crops to reach an advanced growth stage in water-limited areas may come at the expense of over-utilizing soil moisture. For example, a study conducted in Montana found that a roller blade was ineffective in killing a pea (*Pisum sativum* L.) cover crop at an appropriate early growth stage (50% of plants with at least one flower open), but was effective later when peas were in the flat pod stage [32]. Another option for cover crop termination would be the use of organically-approved herbicides such as acetic acid, but in the same study, acetic acid (10% concentration) was not effective in terminating the cover crop. Combining the roller blade with multiple applications of acetic acid was able to kill the pea cover crop, but this method is likely cost-prohibitive [32]. Similarly, a study conducted in South Dakota reported that blade rolling was not effective in killing small grain or vetch cover crops unless rolling was delayed until the early milk or kernel development and the flat pod growth stages, respectively [21]. However, when cover crop termination was delayed, cash crops did not produce grain because there was not enough time left in the growing season before fall freeze-up.

Third, in addition to the climatic constraints on the efficacy of no-till organic cover crop mulch in the NGP, these practices may also be poorly adapted to the region due to their ineffectiveness of managing perennial weeds [33]. Perennial weeds, such as Canada thistle (*Cirsium arvense* L.) [34], field bindweed (*Convolvulus arvensis* L.) [35], and dandelion (*Taraxacum officinale* Weber) [36], remain a problem in organic systems across the NGP, and annual cover crops are unlikely to provide adequate suppression [37]. Thus, the adoption of continuous no-till organic systems in semi-arid agroecosystems must await unforeseen technological weed management breakthroughs. In the absence of translocated herbicides, long-term management tactics should aim at depleting the carbohydrate reserves stored in the root systems [38], and this is most often attempted via tillage [39]. However, in established stands of perennials weeds, a significant proportion of the roots occurs below soil horizons impacted by tillage, rendering mechanical practices ineffective unless applied frequently (i.e., every 2–3 weeks) [40]. Worse, resulting root fragments are capable of producing new vigorous independent plants [41]. Researchers and organic producers have explored approaches to manage field bindweed and Canada thistle without synthetic herbicides over many decades, but there is no clear consensus on the best management practices. We recently conducted a meta-analysis of the existing literature to identify management approaches for Canada thistle and field bindweed in the absence of synthetic herbicides and to determine which aspects of these species management methods warrant further study [42]. Mechanical control was the most studied management technique, accounting for 40% of the data extracted from the peer-reviewed literature, but it did not outperform most of the other single management actions, such as biocontrol, mowing, grazing, crop diversification, solarization, shading, flaming, and crop competition. Although the combination of tillage with two or more control methods emerged as the approach that caused the greatest decrease in abundance and survival of perennial creeping species, organic producers continue to struggle with their management. This discrepancy may originate from the fact that most of the studies we evaluated reported impacts over short time spans, with 53% being conducted for a period of one to two years, and only 9% conducted for five or more years, highlighting the importance of combining longer-term research on perennial weed management with assessment of the impacts of short-term interventions.

Finally, in organic no-till systems, cover crops are necessary to manage weeds, improve soil fertility and, when leguminous species are used, help fix atmospheric N [21]. This is especially true in the NGP where large farm size and scarcity of composted animal wastes prohibits the use of compost-based fertilizers and legume crops and cover crops are the sole source for N. However, nutrients that are scavenged or fixed by cover crops may require stimulation by tillage to be released at a suitable rate [30,43]. For example, a study conducted in Saskatchewan, Canada, utilized a pea and oat (*Avena sativa* L.) cover crop which was terminated by either roller blade or tillage, and results indicated that soil nitrate in the roller blade-terminated plots was one third less than in the tilled plots, and this contributed to reduced subsequent *T. aestivum* yields [30]. Another study in Montana, USA, assessed the ability of legume green manure of lentil (*Lens culinaris* Medik.) or pea to provide N to a subsequent wheat crop, and showed that there was inadequate N to maximize grain yield, even when tillage was applied to accelerate nutrient release [43].

These results, while showing some promise to manage annual organic cropping phases without tillage in multi-year cropping systems in relatively wetter agroecosystems, indicate the need for research on additional tools to manage weeds and nutrients in semi-arid systems. In the meanwhile, and based on successes observed in conventional systems [44] and organic vegetable farms [12,13], researchers and small-grain organic farmers are exploring approaches to minimize tillage intensity while maintaining or improving nutrient cycling and cover crop termination efficiency in the NGP.

4. Reducing Tillage Intensity in Organic Systems and Impacts to Weed Communities

Recent attention has been focused on integrating weed management practices including biological (e.g., cover crops, biocontrol, livestock), cultural (e.g., complex rotations, planting density, use of competitive varieties), and less intrusive mechanical approaches (e.g., crimp rolling, harrowing, limited shallow tillage) to reduce the need for tillage in organic systems [21,33]. An emerging trend of previous studies is that organic farmers who reduce tillage intensity should expect a shift in the aboveground and seedbank weed community composition and abundance. Tillage not only destroys weed seedlings but also impacts the weed seedbank by changing the vertical distribution of weed seeds within the soil profile and altering soil biological and physio-chemical properties, factors which affect seed dormancy, viability, germination, and seedling emergence [45]. Additionally, when tillage intensity is reduced, more weed seeds remain on the soil surface and within the first few centimeters of the soil [46], making them more susceptible to seed predators [47,48] and seedling desiccation [49]. While the exact changes to the seedbank associated with tillage reduction in organic settings may be highly variable and difficult to quantify [38], results suggest that weed seedlings that emerge within no-till and reduced-tillage soils encounter greater resistance, and emerge at lower rates from the top layer of the soil profile [50], compared to tilled soils that allow deeper emergence [51]. Furthermore, weed seeds that germinate on the soil surface often experience fatal germination because the radicle may have difficulty penetrating the soil surface in a timely manner [38]. These changes ultimately lead to a shift in the aboveground weed community, and although there is farm-to-farm variability, reduced and no-till systems may favor some perennial weeds that push through the soil surface via strong, spreading rhizomes, and annual grasses that can germinate and survive on the soil surface [52–54]. While the weed seedbank may become somewhat depleted and the weed community may differ in reduced tillage systems, weeds remain abundant, and with the lack of tillage or synthetic herbicides, an alternative weed control strategy is necessary. A solution may lie in the incorporation of livestock into cropping systems to enhance weed control, increase nutrient cycling, and help terminate cover crops.

5. Integrated Crop and Livestock Production

Integrating crop and livestock production has been proposed as a method of enhancing the economic and environmental sustainability of agroecosystems [55,56]. Crop-livestock integration is loosely defined as the practice of jointly managing crops and livestock, including cows, sheep, poultry, fowl, or others on the same farm [55]. Integration can be spatially separated, rotational, or fully combined. In spatially-separated systems, a practice commonly used in more humid regions than the NGP, animals are maintained on a separate part of the farm and fed at least partially with crops from the farm, with their manure added to the crop fields. Rotational systems utilize crops and animals in the same fields but at different times, such that fields are rotated between annual crop production and forage crops where livestock graze. In fully-combined systems, livestock graze within crops, receiving the benefit of nutrition while providing fertilizer for future crops [55]. Benefits of crop-livestock integration potentially include reducing inputs, increasing crop yield, enhancing nutrient cycling, reducing plant disease, improving crop quality (reviewed in [57]), decreasing tillage use in organic systems, and reducing weed abundance [55,56,58,59].

The potential of rotational integration of crops and livestock to reduce tillage associated with weed management and cover crop termination is of great interest for farmers and researchers, particularly due to the high forage value of several weed [56,59] and cover crop species [12]. Furthermore, the forage crops planted may have an even greater suppression on weeds through competition and allelopathy than commonly used cover crop species [60]. A four-year study conducted in Illinois, USA, compared continuous corn (*Zea mays* L.) production to an integrated system where livestock grazed on post-harvest corn stover and cover crops, found that weed biomass was approximately 4.5 times lower in the integrated system as a result of the suppressive effect of the forage cover crop that was used in it [61]. Another study in Manitoba, Canada, showed that forage cover crops terminated by simulated grazing before the planting of a cash crop of peas greatly reduced the density of wild oat (*Avena fatua*) compared to plots planted with wheat and managed via herbicide [62], but the effects on other weeds, including broadleaf species such as redroot pigweed (*Amaranthus retroflexus* L.), common lambsquarters (*Chenopodium album* L.), and wild buckwheat (*Polygonum convolvulus* L.), were variable. This study also found biennial crops and long-season systems, such as winter triticale and triticale intercrop, provided the best early and late season weed control, respectively.

Collectively, these studies offer hope that integrating forage crops into organic reduced tillage systems can help with weed management while reducing the risk of soil erosion. In dryland ecosystems, the reintegration of livestock into diversified farming systems has the potential to benefit both organic crop and livestock production [63] and, furthermore, the value gained from livestock grazing may, at least partially, offset losses from weeds in organic systems [12]. With 25% of the total 5.6 million U.S. sheep inventory, the semi-arid NGP has a tradition of large, extensive, non-confinement-based sheep operations [64] and a great potential for such reintegration. These low-capital entrepreneurial partnerships between sheep and crop producers can enhance the sustainability of the organic enterprise.

6. Integrating Crop and Livestock Organic Production. Preliminary Lessons from Montana

Previous research in Montana, USA, conducted in conventional and organic systems, has demonstrated that integrated crop-livestock systems have the potential to (1) reduce tillage intensity while improving soil quality [65]; (2) enhance nutrient cycling [66]; (3) take advantage of the positive impacts of grazing on insect pest and weed management [67]; (4) help organic farmers terminate cover crops [67]; and (5) enhance the economic sustainability of the organic enterprise as grazing livestock on cover-crops provides alternative sources of revenue for producers with no negative impacts on subsequent yields [12].

In a study, underway at the Montana State University's Fort Ellis Research and Extension Center, located approximately 6 km east of Bozeman, Montana, we are assessing the potential of integrating crop and livestock production as an approach to reduce tillage intensity in organic systems. The study is a split-plot design with three management treatments applied at the whole plot level: conventional no-till, tilled-organic, and grazed/reduced-till organic. Both organic treatments began the organic transition process in July 2012, making crops harvested in 2015 USDA certified as organic. Each whole plot is split into five 13 m × 90 m sections and randomly assigned a crop treatment out of a common five year cropping sequence of safflower (*Carthamus tinctorius* L.) undersown with sweet clover (*Melilotus officinalis* L.) (Year 1), sweet clover green manure (Year 2), winter wheat (Year 3), lentil (Year 4), and winter wheat (Year 5) (Figure 1). For a cropping history prior to planting of these crops see [68]. The conventional no-till system does not use tillage implements, but uses synthetic fertilizer and herbicide inputs reflective of typical conventional farm management practices in the NGP. The tilled organic system is reflective of typical dryland organic farms where tillage is the main mechanism for weed control, cover crop termination, and seedbed preparation. The goal of the grazed/reduced till organic system is to minimize the number of tillage events, using sheep to terminate cover crops, and as the primary residue and weed control method. Further details of the management practices used within each system can be found in [69].

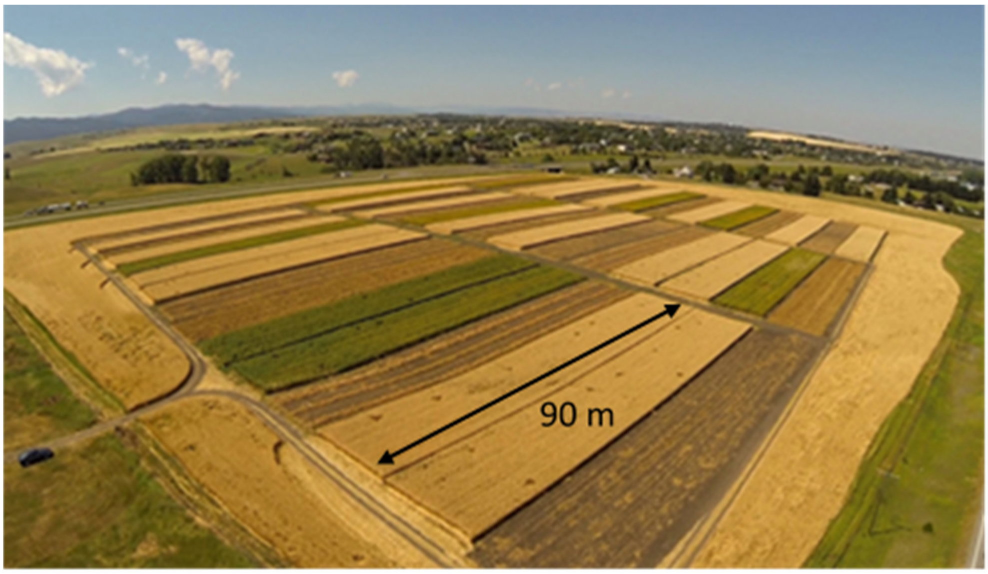

Figure 1. Fort Ellis study site located near Bozeman, MT, USA. The front row plots from left to right are organic-grazed minimum till, chemical no-till, and organic-till, respectively. The five subplots within plots are assigned to a five-year cropping sequence of safflower undersown with sweet clover (Year 1), sweet clover green manure (Year 2), winter wheat (Year 3), lentil (Year 4), and winter wheat (Year 5).

All split-plots were sampled for crop and weed biomass by species at peak biomass of cash crops or termination of the cover crop (starting in June before cover crop termination and lasting through July for all other crops). In each split-plot we placed eight 0.5 m × 1.0 m frames to estimate weed aboveground dry biomass by species. Plots were generally harvested with a commercial scale combine (4.2 m wide) by taking a full width swath from the center of the split-plots to estimate yield standardized to 12% moisture. Further information on data collection can be found in [69]. Weed biomass data were log-transformed prior to analysis, as needed, to account for non-normal residuals, and data were analyzed as a split-plot. Weed community dissimilarity in the different systems was assessed by Bray-Curtiss distances and visualized via principal coordinates analysis using the vegan package in R (version 3.2.2, R Foundation for Statistical Computing, Vienna, Austria).

Using timely sheep grazing made it possible to exclude tillage for a continuous 36-month period within a five-year crop rotation, but this came at the cost of winter wheat and lentil yields (Figure 2). In 2015, for the rotation of winter wheat following sweet clover, grazed/reduced till organic winter wheat yields were 47% and 56% of those in tilled organic and conventional plots, respectively. The low yields observed in the grazed/reduced till organic system were probably due to the heavy soil compaction and associated low wheat emergence that resulted from an unusually heavy rain event that occurred in August 2014 while sheep were grazing the cover crops. In spring 2015, those wheat split-plots were grazed at the beginning of stem elongation - first node at least 1 cm above tillering node (Zadoks 30 and 31, respectively) to manage the heavy weed abundance observed in them (mainly field pennycress (*Thlaspi arvense*) and shepherd's purse (*Capsella bursa-pastoris*)), so yield values are from wheat regrowth. Winter wheat yields for this rotational phase improved in 2016 and mean yields were 83% and 79% of tilled organic and conventional yields, respectively. For lentils, 2015 grazed organic yields were 50% and 51% of respective tilled organic and conventional yields. In 2016, similar to winter wheat yields, the grazed organic yields improved and were 72% and 69% of tilled organic and conventional yields, respectively. Future data will allow us to determine the extent to which yield gaps observed between the grazed/reduced till systems and the tilled organic and conventional systems evolve as the system matures. In the meanwhile, observed yield losses can be explained, at least in part, by the increased weed pressure present in grazed/reduced till organic plots. Overall, the total biomass of weeds sampled in grazed/reduced till organic plots generally increased over time, whereas weed biomass in tilled organic and conventionally managed plots remained unchanged or declined (Figure 3). We also detected a shift in weed communities associated with each cropping system (Table 2, Figure 4, based on Bray-Curtiss community dissimilarity). Despite the increased weed pressure observed in grazed/reduced-till organic plots, it is interesting to note that yield losses are not commensurate with the relative increase in weed pressure (e.g., 11 times more weed biomass in 2016 only resulted in a 21% lentil yield loss compared to conventional). Future studies should evaluate the extent to which potential changes in the mechanisms driving crop-weed interactions across systems could be responsible for the observed differences [70,71].

Potential avenues to improve yields in the grazed/reduced-till system should focus on developing a more competitive crop rotation. Based on our experience and in consultation with leading organic growers in the region, we believe that an improved integration of crop and livestock organic production in semi-arid agroecosystems could be achieved by (1) replacing safflower with yellow mustard (*Sinapis alba*) and seeding in late April; (2) replacing the fifth-year winter wheat crop with Kamut (khorosan wheat) sown in early May; (3) including foxtail millet (*Setaria italica*) broadcast prior to grazing of sweet clover to expand the grazing value through increased biomass; and (4) replacing the lentil phase with a flax (*Linum usitatissimum*)/chickpea (*Cicer arietinum*) intercrop seeded in late May. Other management practices, such as use of low-disturbance tillage implements (i.e., wide-sweep blade plows), adoption of more competitive cultivars, and weed seed collection, should also be integrated in the grazed/reduced-till system.

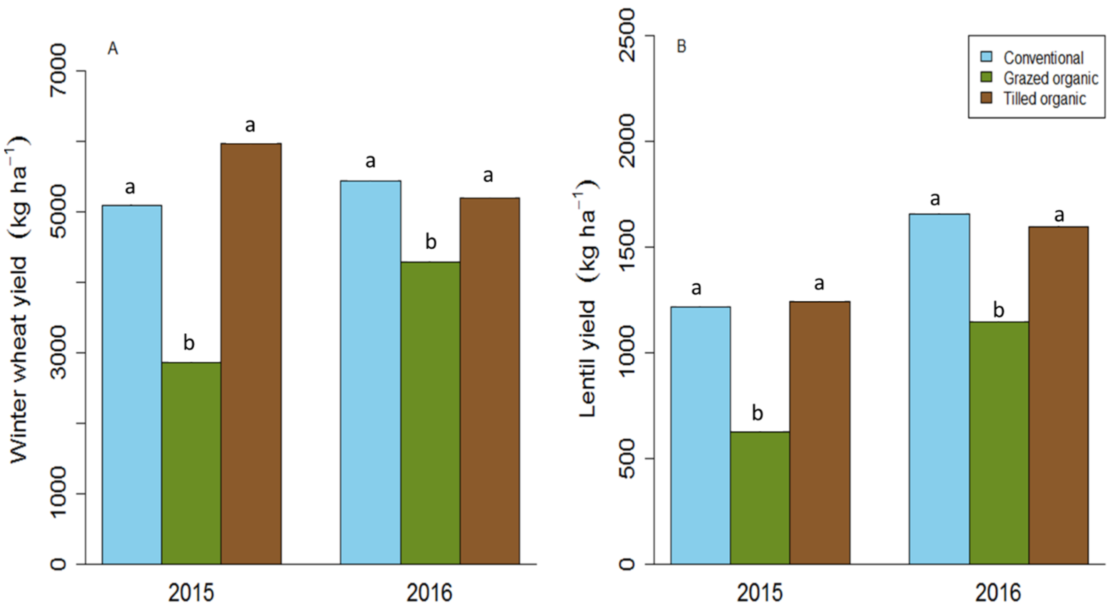

Figure 2. Yields of (**A**) winter wheat yield following sweet clover and (**B**) lentil yield from three cropping systems at Bozeman, MT, USA, 2015–2016. Bars marked with the same letters do not differ at $p < 0.1$ within year.

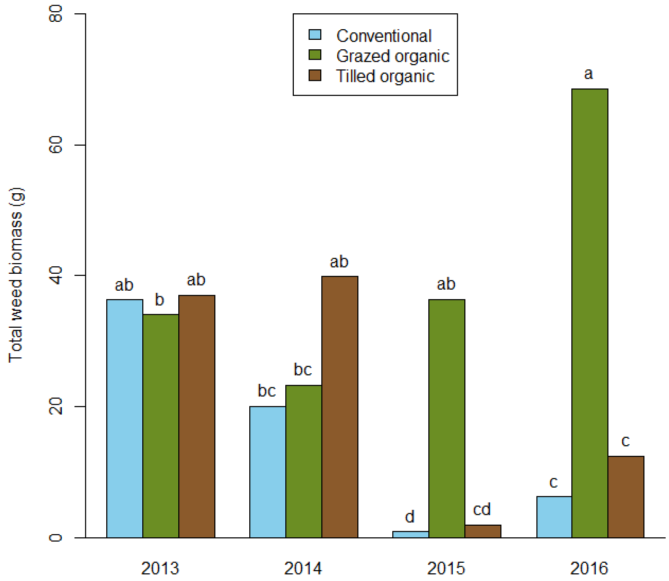

Figure 3. Weed biomass (log transformed) for split-plots that follow the rotation of safflower undersown with sweet clover (2013), sweet clover (2014), winter wheat (2015), and lentil (2016) from three cropping systems at Bozeman, MT, USA. Analysis was performed on log transformed biomass data. Bars marked with the same letters do not differ at $p < 0.1$ (note: while all rotations were present in the study, only one is shown for clarity).

Table 2. Top 10 weed species (by percent of total biomass) in conventionally-managed, grazed organic, and tilled organic plots within the safflower undersown with sweet clover (2013), sweet clover (2014), winter wheat (2015), and lentil (2016) rotation at Bozeman, MT, USA.

2013-Safflower	2014-Sweet Clover	2015-Winter Wheat	2016-Lentil
Conventionally Managed Plots			
Malva neglecta (22.1)	*Capsella bursa-pastoris* (38.6)	*Bromus tectorum* (100)	*Thlaspi arvense* (29.7)
Avena fatua (21.3)	*Chenopodium album* (22.1)	–	*Malva neglecta* (20.7)
Thlaspi arvense (13.9)	*Thlaspi arvense* (17.7)	–	*Lamium amplexicaule* (14.0)
Chenopodium album (12.5)	*Bromus tectorum* (4.7)	–	*Chenopodium album* (12.1)
Amaranthus retroflexus (10.0)	*Lactuca serriola* (3.5)	–	*Lactuca serriola* (12.0)
Cirsium arvense (8.2)	*Lamium amplexicaule* (3.3)	–	*Cirsium arvense* (6.9)
Capsella bursa-pastoris (5.3)	*Sisymbrium altissimum* (2.6)	–	*Triticum aestivum* (2.3)
Monolepis nuttalliana (2.6)	*Monolepis nuttalliana* (2.6)	–	*Capsella bursa-pastoris* (1.7)
Solanum triflorum (2.4)	*Avena fatua* (1.6)	–	*Asperugo procumbens* (0.2)
Prunus virginiana (0.7)	*Cirsium arvense* (1.5)	–	*Amaranthus retroflexus* (0.2)
Grazed Organic Plots			
Thlaspi arvense (39.2)	*Thlaspi arvense* (38.7)	*Capsella bursa-pastoris* (42.1)	*Thlaspi arvense* (65.5)
Malva neglecta (31.6)	*Chenopodium album* (25.6)	*Bromus tectorum* (25.5)	*Chenopodium album* (19.4)
Chenopodium album (18.9)	*Capsella bursa-pastoris* (25.4)	*Lactuca serriola* (14.1)	*Bromus tectorum* (4.2)
Amaranthus retroflexus (5.1)	*Sisymbrium altissimum* (4.6)	*Tragopogon dubius* (9.7)	*Taraxacum officinale* (2.7)
Capsella bursa-pastoris (1.4)	*Lactuca serriola* (2.5)	*Taraxacum officinale* (4.6)	*Capsella bursa-pastoris* (2.1)
Lactuca serriola (1.3)	*Androsace occidentalis* (0.8)	*Sisymbrium altissimum* (2.2)	*Malva neglecta* (1.2)
Solanum triflorum (1.1)	*Triticum aestivum* (0.7)	*Galium aparine* (0.6)	*Melilotus officinalis* (1.1)
Monolepis nuttalliana (0.7)	*Poa annua* (0.7)	*Thlaspi arvense* (0.5)	*Triticum aestivum* (1.0)
Hordeum jubatum (0.3)	*Monolepis nuttalliana* (0.3)	*Melilotus officinalis* (0.4)	*Lactuca serriola* (1.0)
Avena fatua (0.2)	*Lamium amplexicaule* (0.2)	*Asperugo procumbens* (0.2)	*Cirsium arvense* (0.6)
Tilled Organic Plots			
Chenopodium album (31.7)	*Capsella bursa-pastoris* (46.3)	*Thlaspi arvense* (79.7)	*Thlaspi arvense* (62.8)
Thlaspi arvense (30.2)	*Thlaspi arvense* (23.3)	*Lactuca serriolal* (14.7)	*Chenopodium album* (17.2)
Malva neglecta (17.0)	*Chenopodium album* (18.3)	*Capsella bursa-pastoris* (3.0)	*Capsella bursa-pastoris* (7.6)
Capsella bursa-pastoris (6.5)	*Androsace occidentalis* (3.2)	*Lamium amplexicaule* (2.6)	*Triticum aestivum* (4.6)
Hordeum jubatum (5.0)	*Avena fatua* (2.6)	*Chenopodium album* (<0.1)	*Avena fatua* (3.1)
Lactuca serriola (3.6)	*Lactuca serriola* (2.6)	–	*Lactuca serriola* (2.3)
Solanum triflorum (3.0)	*Bromus tectorum* (0.8)	–	*Malva neglecta* (1.5)
Avena fatua (0.9)	*Monolepis nuttalliana* (0.7)	–	*Lamium amplexicaule* (0.3)
Monolepis nuttalliana (0.8)	*Silene latifolia* (0.6)	–	*Monolepis nuttalliana* (0.2)
Amaranthus retroflexus (0.8)	*Sisymbrium altissimum* (0.5)	–	*Melilotus officinalis* (0.1)

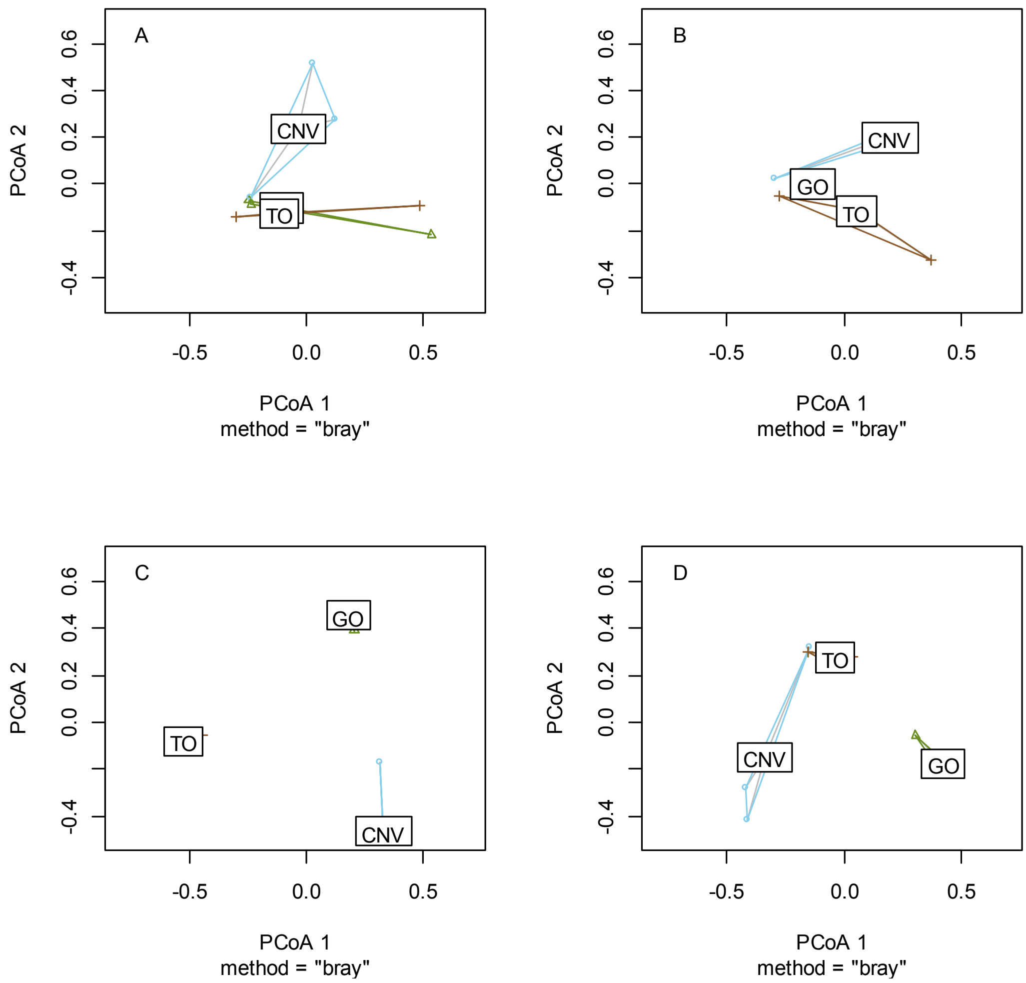

Figure 4. Principal coordinates analysis of weed biomass data in for conventionally managed (CNV), grazed organic (GO), and tilled organic (TO) plots within the safflower undersown with sweet clover ((**A**), year = 2013), sweet clover ((**B**), year = 2014), winter wheat ((**C**), year = 2015) and lentil ((**D**), year = 2016) rotation at Bozeman, MT, USA. The closer the points are together, the more similar the plant communities. Polygons that do not overlap are considered distinct weed communities.

7. A Path Forward

Worldwide population projections indicate that by the year 2050 there will be 9.7 billion people [72] for which agriculture will need to provide food, fiber, and energy. Coupled with changing food habits and increased demands for meat and dairy products, estimates suggest that farmers and ranchers will be required to produce 25%–70% more food, but this must be balanced with reductions in nutrient losses and agricultural production-related greenhouse gas emissions to respond to this unprecedented demand and ensure agroecosystem sustainability [73]. To secure its long-term efficiency, this increase in yield should be achieved without compromising the environmental sustainability of the agricultural enterprise and the economic welfare of rural communities. To solve this puzzle, research is needed to close yield gaps on underperforming systems [74] and increase cropping efficiency through production systems that maximize the ecosystem services provided by both the planned, as well as the associated, biodiversity [75]. What role does organic agriculture play in these scenarios? What practices can help organic farmers close the yield gaps between organic and conventional cropping systems [76]? Can premiums offset the yield losses we observed in grazed/reduced till organic systems? How do we value the services such as weed control and soil conservations provided by grazing?

Preliminary results of our current research aimed at re-integrating crop-livestock production in water-limited organic systems highlight the agronomic potential of such integrations to reduce tillage intensity in fragile environments. However, observed yield and economic penalties represent barriers that could hinder the wide adoption of the proposed tactics. Appropriately measuring the value added from grazing leases [77] and costs associated with investments in fencing and watering systems [78], in the context of lower yields, but improved soil health, under reduced tillage with grazing, is needed. While most farmers prize environmental stewardship, and this is a requirement to achieve organic certification, economic considerations remain a major barrier for a sustainable practice to be widely adopted [79]. This is particularly true in organic systems as the small size of organic markets commonly results in increased price variability, which, in turn, may limit market entry. Therefore, the next task to enhance adoption of integrated crop-livestock systems is to close the yield and economic gap between conventionally-tilled and grazed/reduced-till organic systems, as well as to demonstrate ecological sustainability of integration.

Agro-ecological tactics are site and system specific. Yet, lessons we are currently learning at the Fort Ellis experimental site suggest possible solutions for the increased weed abundance and reduced yields observed in the grazed/reduced-till organic system, and generalities can be extracted from this work. Initially, we designed the rotation to emphasize deep-rooted crops to combat Canada thistle, the most problematic weed in organic systems in Southwest Montana. Now, we need to quantify environmental risks associated with specific tillage practices and close the yield and economic gap between conventionally tilled and grazed/reduced-till organic systems to enhance adoption of integrated crop-livestock systems. There are numerous options to be considered to achieve this goal, including rotational crops with more strongly varied seeding dates, longer forage crop rotations, modifying the timing, and/or intensity of grazing, combining grazing and mowing for more uniform termination of cover crops, seeding more competitive crop varieties, use of intercropping that specifically targets the seasonality and/or life-cycles of weeds [80], and using weed cutting implements, such as sweep plow undercutters, that are not as damaging to soil [81]. Further research is needed to better understand mineralization and the availability of nutrients with grazing, and where reduced till/grazed systems stand in the balance between tillage with better mineralization of nutrients and no-till with better soil water conservation [43]. It is also essential to provide an economic value to the environmental benefits of reducing tillage intensity, and accurate estimates of the costs and benefits of providing high quality feed to grazers are needed. This analysis should consider the grazing service availability and factors influencing ranchers' willingness to participate in integrated production systems including willingness to pay, amount of premium for high quality grazing, readiness to travel, and length of distance ranchers will transfer animals for grazing opportunities. Clearly, our research to date highlights the complexities of managing weeds in organic crop production while preserving water and soil quality, and points to the need for additional site and system-specific research.

Acknowledgments: We would to thanks the United States Department of Agriculture, National Institute of Food and Agriculture (USDA NIFA) for its financial support. OREI grant 2012-51300-20004, ORG grant 2015-51106-23970.

Author Contributions: Fabian D. Menalled and Erik Lehnhoff critically reviewed existing literature and wrote all sections of this manuscript. Erik Lehnhoff and Perry Miller analyzed the data. All authors reviewed the manuscript and contributed to the field study presented here.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Trewavas, A. Urban myths of organic farming. *Nature* **2001**, *410*, 409–410. [CrossRef] [PubMed]
2. Smil, V. *Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food*; The MIT Press: Cambridge, MA, USA, 2001.
3. Bergstrom, L.; Kirchmann, H. Are the claimed benefits of organic agriculture justified? *Nat. Plants* **2016**, *2*, 16099. [CrossRef] [PubMed]

4. Reganold, J.P.; Wachter, J.M. Organic agriculture in the twenty-first century. *Nat. Plants* **2016**, *2*, 15221. [CrossRef] [PubMed]
5. Organic Trade Association. *U.S. Organic Industry Survey*; Organic Trade Association: Washington, DC, USA, 2016.
6. USDA-ERS Service. *Organic Market Overview*. Available online: https://www.ers.usda.gov/topics/natural-resources-environment/organic-agriculture/organic-market-overview.aspx (accessed on 30 March 2017).
7. Dore, T.; Makowski, D.; Malezieux, E.; Munier-Jolain, N.; Tchamitchian, M.; Tittonell, P. Facing up to the paradigm of ecological intensification in agronomy: Revisiting methods, concepts and knowledge. *Eur. J. Agron.* **2011**, *34*, 197–210. [CrossRef]
8. Robertson, G.P.; Gross, K.L.; Hamilton, S.K.; Landis, D.A.; Schmidt, T.M.; Snapp, S.S.; Swinton, S.M. Farming for ecosystem services: An ecological approach to production agriculture. *Bioscience* **2014**, *64*, 404–415. [CrossRef] [PubMed]
9. Padbury, G.; Waltman, S.; Caprio, J.; Coen, G.; McGinn, S.; Mortensen, D.; Nielsen, G.; Sinclair, R. Agroecosystems and land resources of the northern great plains. *Agron. J.* **2002**, *94*, 251–261. [CrossRef]
10. Tanaka, D.L.; Lyon, D.J.; Miller, P.R.; Merrill, S.D.; McConkey, B.G. Soil and water conservation advances in the semiarid northern great plains. In *Soil and Water Conservation Advances in the USA*; Soil Science Society of America Special Publications: Madison, WI, USA, 2010; Volume 60, pp. 81–102.
11. Johnston, A.M.; Tanaka, D.L.; Miller, P.R.; Brandt, S.A.; Nielsen, D.C.; Lafond, G.P.; Riveland, N.R. Oilseed crops for semiarid cropping systems in the northern great plains. *Agron. J.* **2002**, *94*, 231–240. [CrossRef]
12. McKenzie, S.; Goosey, H.; O'Neill, K.M.; Menalled, F. Integration of sheep grazing for cover crop termination into market gardens: Agronomic consequences of an ecologically-based management strategy. *Renew. Agric. Food Syst.* **2017**, in press. [CrossRef]
13. McKenzie, S.C.; Goosey, H.B.; O'Neill, K.M.; Menalled, F.D. Impact of integrated sheep grazing for cover crop termination on weed and ground beetle (coleoptera:Carabidae) communities. *Agric. Ecosyst. Environ.* **2016**, *218*, 141–149. [CrossRef]
14. Butler, M.; Ragen, D.; Westbrook, J.; Boles, J.; Layton, W.; Craig, T.; Hatfield, P. *Effects of Confinement Finish and Cover Crop Grazed Lambs on Performance, Carcass Quality and Parasite Loads*; Montana State University: Bozeman, MT, USA, 2015.
15. National Climate Assessment (NCA). *Great Plains*; National Climate Assessment: Washington, DC, USA, 2014.
16. Cutforth, H.; Judiesch, D. Temperature trends in the semiarid prairie of southwestern Saskatchewan revisited. *Can. J. Soil Sci.* **2012**, *92*, 803–806. [CrossRef]
17. Hatfield, J.L.; Boote, K.J.; Kimball, B.A.; Ziska, L.H.; Izaurralde, R.C.; Ort, D.; Thomson, A.M.; Wolfe, D. Climate impacts on agriculture: Implications for crop production. *Agron. J.* **2011**, *103*, 351–370. [CrossRef]
18. Keren, I.N.; Menalled, F.D.; Weaver, D.K.; Robison-Cox, J.F. Interacting agricultural pests and their effect on crop yield: Application of a bayesian decision theory approach to the joint management of bromus tectorum and cephus cinctus. *PLoS ONE* **2015**, *10*, e0118111. [CrossRef] [PubMed]
19. Meehan, T.D.; Werling, B.P.; Landis, D.A.; Gratton, C. Agricultural landscape simplification and insecticide use in the midwestern United States. *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 11500–11505. [CrossRef] [PubMed]
20. Tautges, N.E.; Goldberger, J.R.; Burke, I.C. A survey of weed management in organic small grains and forage systems in the northwest United States. *Weed Sci.* **2016**, *64*, 513–522. [CrossRef]
21. Carr, P.M.; Anderson, R.L.; Lawley, Y.E.; Miller, P.R.; Zwinger, S.F. Organic zero-till in the northern US great plains region: Opportunities and obstacles. *Renew. Agric. Food Syst.* **2012**, *27*, 12–20. [CrossRef]
22. Miller, P.R.; Lighthiser, E.J.; Jones, C.A.; Holmes, J.A.; Rick, T.L.; Wraith, J.M. Pea green manure management affects organic winter wheat yield and quality in semiarid Montana. *Can. J. Plant Sci.* **2011**, *91*, 497–508. [CrossRef]
23. Triplett, G.B.; Dick, W.A. No-tillage crop production: A revolution in agriculture! *Agron. J.* **2008**, *100*, S153–S165. [CrossRef]
24. Hansen, N.C.; Allen, B.L.; Baumhardt, R.L.; Lyon, D.J. Research achievements and adoption of no-till, dryland cropping in the semi-arid US great plains. *Field Crops Res.* **2012**, *132*, 196–203. [CrossRef]
25. Shirtliffe, S.J.; Johnson, E.N. Progress towards no-till organic weed control in western Canada. *Renew. Agric. Food Syst.* **2012**, *27*, 60–67. [CrossRef]

26. Mirsky, S.B.; Curran, W.S.; Mortensen, D.A.; Ryan, M.R.; Shumway, D.L. Control of cereal rye with a roller/crimper as influenced by cover crop phenology. *Agron. J.* **2009**, *101*, 1589–1596. [CrossRef]
27. Teasdale, J.R.; Mohler, C.L. The quantitative relationship between weed emergence and the physical properties of mulches. *Weed Sci.* **2000**, *48*, 385–392. [CrossRef]
28. Tanaka, D.L.; Bauer, A.; Black, A.L. Annual legume cover crops in spring wheat-fallow systems. *J. Prod. Agric.* **1997**, *10*, 251–255. [CrossRef]
29. Townley-Smith, L.; Slinkard, A.E.; Bailey, L.D.; Biederbeck, V.O.; Rice, W.A. Productivity, water use and nitrogen fixation of annual legume green manure crops in the dark brown soil zone of Saskatchewan. *Can. J. Plant Sci.* **1993**, *73*, 139–148. [CrossRef]
30. Vaisman, I.; Entz, M.H.; Flaten, D.N.; Gulden, R.H. Blade roller-green manure interactions on nitrogen dynamics, weeds, and organic wheat. *Agron. J.* **2011**, *103*, 879–889. [CrossRef]
31. Mischler, R.; Duiker, S.W.; Curran, W.S.; Wilson, D. Hairy vetch management for no-till organic cornpproduction. *Agron. J.* **2010**, *102*, 355–362. [CrossRef]
32. Izard, E. *Seeking Sustainability for Organic Cropping Systems in the Norhern Great Plains: Legume Green Manure Strategies*; Montana State University: Bozeman, MT, USA, 2007.
33. Briar, S.S.; Carr, P.M.; Gramig, G.G.; Menalled, F.D.; Miller, P.R. Current Status and Soil Biology Impacts of Organic Conservation Tillage in the U.S. Great Plains. In Proceedings of the International Seminar on Emerging Trends in Organic Farming and Sustainable Agriculture, Kottayam, India, 29–31 December 2016.
34. Gruber, S.; Claupein, W. Effect of tillage intensity on weed infestation in organic farming. *Soil Tillage Res.* **2009**, *105*, 104–111. [CrossRef]
35. Rusu, T.; Bogdan, I.; Moraru, P.; Pop, A.; Oroian, I.; Marin, D.; Ranta, O.; Stanila, S.; Gheres, M.; Duda, M.; et al. Influence of minimum tillage systems on the control of convolvulus arvensis l. On wheat, maize and soybean. *J. Food Agric. Environ.* **2013**, *11*, 563–566.
36. Sans, F.X.; Berner, A.; Armengot, L.; Mader, P. Tillage effects on weed communities in an organic winter wheat-sunflower-spelt cropping sequence. *Weed Res.* **2011**, *51*, 413–421. [CrossRef]
37. Carr, P.M.; Gramig, G.G.; Liebig, M.A. Impacts of organic zero tillage systems on crops, weeds, and soil quality. *Sustainability* **2013**, *5*, 3172–3201. [CrossRef]
38. Mohler, C.L. Mechanical management of weeds. In *Ecological Management of Agricultural Weeds*; Liebman, M., Mohler, C.L., Staver, C.P., Eds.; Cambridge University Press: Cambridge, UK, 2001.
39. Hakansson, S. Soil tillage effects on weeds. In *Weeds and Weed Management on Arable Land: An Ecological Approach*; CABI Publishing: Cambridge, MA, USA, 2003; pp. 158–196.
40. Franzke, C.J.; Hume, A.N. *Field Bindweed and Control Methods for South Dakota*; Bulletins, South Dakota Agricultural Experiment Station: Brookings, Soud Dakota, USA, 1936; Volume 305, pp. 5–47.
41. Sciegienka, J.K.; Keren, E.N.; Menalled, F.D. Impact of root fragment dimension, weight, burial depth, and water regime on cirsium arvense emergence and growth. *Can. J. Plant Sci.* **2011**, *91*, 1027–1036. [CrossRef]
42. Orloff, N.; Mangold, J.M.; Miller, Z.; Menalled, F. A meta-analysis of field bindweed (*Convolvulus arvensis* L.) and Canada thistle (*Cirsium arvense* L.) management in organic agricultural systems. *Agric. Ecosyst. Environ.* **2017**, submitted.
43. Burgess, M.; Miller, P.; Jones, C.; Bekkerman, A. Tillage of cover crops affects soil water, nitrogen, and wheat yield components. *Agron. J.* **2014**, *106*, 1497–1508. [CrossRef]
44. Lenssen, A.W.; Sainju, U.M.; Hatfield, P.G. Integrating sheep grazing into wheat-fallow systems: Crop yield and soil properties. *Field Crops Res.* **2013**, *146*, 75–85. [CrossRef]
45. Peigne, J.; Ball, B.C.; Roger-Estrade, J.; David, C. Is conservation tillage suitable for organic farming? A review. *Soil Use Manag.* **2007**, *23*, 129–144. [CrossRef]
46. Mohler, C.L.; Frisch, J.C.; McCulloch, C.E. Vertical movement of weed seed surrogates by tillage implements and natural processes. *Soil Tillage Res.* **2006**, *86*, 110–122. [CrossRef]
47. Harrison, S.K.; Regnier, E.E. Postdispersal predation of giant ragweed (ambrosia trifida) seed in no-tillage corn. *Weed Sci.* **2003**, *51*, 955–964. [CrossRef]
48. Jacob, H.A.; Minkey, D.M.; Gallagher, R.S.; Borger, C.P. Variation in postdispersal weed seed predation in a crop field. *Weed Sci.* **2006**, *54*, 148–155. [CrossRef]
49. Anderson, R.L. A multi-tactic approach to manage weed population dynamics in crop rotations. *Agron. J.* **2005**, *97*, 1579–1583. [CrossRef]

50. Grundy, A.C.; Mead, A.; Burston, S. Modelling the emergence response of weed seeds to burial depth: Interactions with seed density, weight and shape. *J. Appl. Ecol.* **2003**, *40*, 757–770. [CrossRef]
51. Franke, A.C.; Singh, S.; McRoberts, N.; Nehra, A.S.; Godara, S.; Malik, R.K.; Marshall, G. Phalaris minor seedbank studies: Longevity, seedling emergence and seed production as affected by tillage regime. *Weed Res.* **2007**, *47*, 73–83. [CrossRef]
52. Menalled, F.D.; Gross, K.L.; Hammond, M. Weed aboveground and seedbank community responses to agricultural management systems. *Ecol. Appl.* **2001**, *11*, 1586–1601. [CrossRef]
53. Moyer, J.R.; Roman, E.S.; Lindwall, C.W.; Blackshaw, R.E. Weed management in conservation tillage systems for wheat production in north and south America. *Crop Prot.* **1994**, *13*, 243–259. [CrossRef]
54. Tuesca, D.; Puricelli, E.; Papa, J.C. A long-term study of weed flora shifts in different tillage systems. *Weed Res.* **2001**, *41*, 369–382. [CrossRef]
55. Hilimire, K. Integrated crop/livestock agriculture in the United States: A review. *J. Sustain. Agric.* **2011**, *35*, 376–393. [CrossRef]
56. Martens, J.R.T.; Entz, M.H. Integrating green manure and grazing systems: A review. *Can. J. Plant Sci.* **2011**, *91*, 811–824. [CrossRef]
57. Hendrickson, J.R.; Hanson, J.D.; Tanaka, D.L.; Sassenrath, G. Principles of integrated agricultural systems: Introduction to processes and definition. *Renew. Agric. Food Syst.* **2008**, *23*, 265–271. [CrossRef]
58. Entz, M.H.; Bullied, W.J.; KatepaMupondwa, F. Rotational benefits of forage crops in Canadian prairie cropping systems. *J. Prod. Agric.* **1995**, *8*, 521–529. [CrossRef]
59. Popay, I.; Field, R. Grazing animals as weed control agents. *Weed Tech.* **1996**, *10*, 217–231.
60. Bhowmik, P.C.; Inderjit, J. Challenges and opportunities in implementing allelopathy for natural weed management. *Crop Prot.* **2003**, *22*, 661–671. [CrossRef]
61. Tracy, B.F.; Davis, A.S. Weed biomass and species composition as affected by an integrated crop-livestock system. *Crop Sci.* **2009**, *49*, 1523–1530. [CrossRef]
62. Schoofs, A.; Entz, M.H. Influence of annual forages on weed dynamics in a cropping system. *Can. J. Plant Sci.* **2000**, *80*, 187–198. [CrossRef]
63. National Center for Appropriate Technology (NCAT). *Organic Livestock Workbook*; National Center for Appropriate Technology: Butte, MT, USA, 2004.
64. USDA Service. *Sheep and Goats*; USDA National Agriculture Statistics Service: Washington, DC, USA, 2010.
65. Hatfield, P.G.; Goosey, H.B.; Spezzano, T.M.; Blodgett, S.L.; Lenssen, A.W.; Kott, R.W.; Marlow, C.B. Incorporating sheep into dryland grain production systems iii. Impact on changes in soil bulk density and soil nutrient profiles. *Small Rumin. Res.* **2007**, *67*, 222–231. [CrossRef]
66. Sainju, U.M.; Lenssen, A.W.; Goosey, H.B.; Snyder, E.; Hatfield, P.G. Dryland soil carbon and nitrogen influenced by sheep grazing in the wheat-fallow system. *Agron. J.* **2010**, *102*, 1553–1561. [CrossRef]
67. Hatfield, P.G.; Blodgett, S.L.; Spezzano, T.M.; Goosey, H.B.; Lenssen, A.W.; Kott, R.W.; Marlow, C.B. Incorporating sheep into dryland grain production systems I. Impact on over-wintering larva populations of wheat stem sawfly, *Cephus cinctus* Norton (Hymenoptera: Cephidae). *Small Rumin. Res.* **2007**, *67*, 209–215. [CrossRef]
68. Barroso, J.; Miller, Z.J.; Lehnhoff, E.A.; Hatfield, P.G.; Menalled, F.D. Impacts of cropping system and management practices on the assembly of weed communities. *Weed Res.* **2015**, *55*, 426–435. [CrossRef]
69. Johnson, S. *Effects of Organic and Conventional Cropping Systems on Plant Diversity and Plant Soil Feedbacks*; Montana State University: Bozeman, MT, USA, 2015.
70. Smith, R.G.; Mortensen, D.A.; Ryan, M.R. A new hypothesis for the functional role of diversity in mediating resource pools and weed-crop competition in agroecosystems. *Weed Res.* **2010**, *50*, 37–48. [CrossRef]
71. Johnson, S.; Miller, Z.; Miller, P.; Lehnhoff, E.; Menalled, F. Cropping systems modify soil biota effects on wheat (*Triticum aestivum* L.) growth and competitive ability. *Weed Res.* **2017**, *57*, 6–15. [CrossRef]
72. UN. World Population Projected to Reach 9.7 Billion by 2050. Available online: http://www.un.org/en/development/desa/news/population/2015-report.html (accessed on 27 January 2017).
73. Hunter, M.C.; Smith, R.G.; Schpanski, M.E.; Atwood, L.W.; Mortensen, D.A. Agriculture in 2050: Recalibrating Targets for Sustainable Intensification. *Bioscience* **2017**. [CrossRef]
74. Foley, J.A.; Ramankutty, N.; Brauman, K.A.; Cassidy, E.S.; Gerber, J.S.; Johnston, M.; Mueller, N.D.; O'Connell, C.; Ray, D.K.; West, P.C.; et al. Solutions for a cultivated planet. *Nature* **2011**, *478*, 337–342. [CrossRef] [PubMed]

75. Tscharntke, T.; Clough, Y.; Wanger, T.C.; Jackson, L.; Motzke, I.; Perfecto, I.; Vandermeer, J.; Whitbread, A. Global food security, biodiversity conservation and the future of agricultural intensification. *Biol. Conserv.* **2012**, *151*, 53–59. [CrossRef]
76. Kniss, A.R.; Savage, S.D.; Jabbour, R. Commercial crop yields reveal strengths and weaknesses for organic agriculture in the United States. *PLoS ONE* **2016**, *11*, e0165851. [CrossRef] [PubMed]
77. Russelle, M.P.; Entz, M.H.; Franzluebbers, A.J. Reconsidering integrated crop-livestock systems in north America. *Agron. J.* **2007**, *99*, 325–334. [CrossRef]
78. Undersander, D.J.; Albert, B.; Cosgrove, D.; Johnson, D.; Peterson, P. *Pastures for Profit: A Guide to Rotational Grazing*; University of Wisconsin Extension: Madison, WI, USA, 2002.
79. Swinton, S.M.; Rector, N.; Robertson, G.P.; Jolejole-Foreman, C.B.; Lupi, F. Farmer decisions about adopting environmentally beneficial practices. In *The Ecology of Agricultural Landscapes: Long-Term Research on the Path to Sustainability*; Hamilton, S.K., Doll, J.E., Robertson, G.P., Eds.; Oxford University Press: New York, NY, USA, 2015; pp. 340–359.
80. Ominski, P.D.; Entz, M.H.; Kenkel, N. Weed suppression by medicago sativa in subsequent cereal crops: A comparative survey. *Weed Sci.* **1999**, *47*, 282–290.
81. Wortman, S.E.; Francis, C.A.; Bernards, M.A.; Blankenship, E.E.; Lindquist, J.L. Mechanical termination of diverse cover crop mixtures for improved weed suppression in organic cropping systems. *Weed Sci.* **2013**, *61*, 162–170. [CrossRef]