AGRONOMIC AND SOCIOLOGICAL ASPECTS OF
ORGANIC CROPPING SYSTEMS IN THE
DRYLAND PACIFIC NORTHWEST

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Of the 4.8 million acres devoted to organic winter wheat (*Triticum aestivum* L.) production in the U.S., less than 1% of organic wheat acreage is located in Washington State, despite the highly productive soils and record wheat yields of eastern Washington. Growers reported inadequate organic weed and pest control methods and low yields as being the main barriers to producing organic grains. To improve our understanding of organic management practices in the wheat production region of the inland Pacific Northwest, a survey was conducted of certified organic small grains and forage producers in five northwestern states. A field study investigated weed control in organic wheat rotations via crop competitiveness and rotation design, as well as the ability of poultry versus green manure to maintain soil nitrogen. The resultant organic wheat grain yields and quality were compared to conventional yields to assess the viability and potential of certified organic wheat production.

Crops in rotation with wheat impacted relative weed biomass and weed species composition. Perennial crops competed most strongly with the perennial weeds Canada thistle (*Cirsium arvense* [L.] Scop.) and field bindweed (*Convolvulus arvensis* L.), two of the most
troublesome weeds reported by growers in the survey. Barley (*Hordeum vulgare* L.) and triticale (*x Triticosecale*), two alternative grain crops in wheat rotations, competed more with all weed species than wheat. Rotation crop choices could be made based on competitiveness with weeds. The use of poultry manure as fertilizer resulted in wheat yields and quality similar to conventional wheat. Winter pea (*Pisum sativum* L.) green manure did not accumulate sufficient levels of biomass and nitrogen, and subsequent wheat yields were low due to nitrogen deficiency. Levels of soil inorganic nitrogen following alfalfa (*Medicago sativa* L.) were sufficient for high-yielding wheat the following year, but volunteer alfalfa created weed pressure in the wheat crop. Alternatively, intercropping spring pea with spring wheat as a green manure strategy in organic wheat systems increased subsequent winter wheat yields by 1000 kg ha\(^{-1}\). This study demonstrated the potential to produce competitive winter wheat yields and identified successful weed and soil nitrogen management strategies under certified organic production.
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CHAPTER 1

Amber Waves of Organic Grain: A Review of Twelve Years of Dryland Reduced Tillage

Organic Wheat Production Research in Eastern Washington

Abstract

Eastern Washington is a wheat (*Triticum aestivum* L.) production region characterized by low rainfall and limited use of irrigation, but highly productive soils, making the region a promising area for organic wheat production. However, adoption of organic practices is low due to weed and soil nitrogen (N) management challenges, and geographic isolation creates social and economic barriers for communication and dissemination of information. To address these challenges, a long-term reduced tillage trial was established in 2002 near Pullman, Washington, and weed pressure, soil N, yields, and grain quality were measured over twelve years in organic wheat rotations. Weed pressure was low in an alfalfa (*Medicago sativa* L.)/orchardgrass (*Dactylis glomerata* L.) forage mix grown during the transition period, which competed especially well with perennial weeds and was followed by high certified organic wheat yields. The alternative grains winter triticale (*x Triticosecale*) and spring barley (*Hordeum vulgare* L.) tended to be more competitive with weeds than wheat, especially for winter annual grass weeds. Three years of continuous winter pea (*Pisum sativum* L.) green manure during transition produced sufficient N for two years of subsequent wheat cropping, but one year of winter pea green manure did not fix adequate N to support a high-yielding wheat crop for two years after transition. Winter wheat receiving poultry manure fertilizer produced grain yields similar to or greater than conventionally managed winter wheat. Grain quality was generally comparable between organic and conventional management systems, though organic hard red spring wheat
did not meet the 14% protein standard in most years. Interviews and a survey of certified organic small grains growers in the inland Pacific Northwest (PNW) revealed that many certified organic growers in the region are operating large hectarages (>1,000) and intend to maintain or increase their level of organic production. However, growers reported that they suffer from a lack of information on organic management in the region, and need more support with managing perennial weeds, maintaining soil N fertility, and marketing their products. Results from this study indicate that producing organic small grains in the inland PNW is feasible and profitable given either alfalfa in the rotation (Fuerst et al., 2009) or access to manure, but that managing perennial weeds is a major challenge and that growers require more institutional support to continue producing small grains organically (Appendix).
Introduction

Eastern Washington is situated in the inland PNW on deep, rich silt loam soils recognized for producing world record grain yields of non-irrigated winter wheat (*Triticum aestivum* L.) (Schillinger et al., 2006). In 2012, Washington State alone produced 10% of the conventional winter wheat grown in the U.S., with a winter wheat yield state average 1.5 times greater than the national average (USDA-NASS). Despite the state’s ideal wheat production environment, less than 1% of the national organic wheat hectarage was grown in Washington State, lagging behind neighboring wheat-producing states Idaho and Montana, which account for 3.5% and 21%, respectively, of national organic wheat hectarage (USDA-ERS). The three-year “organic transition” period to certified organic production following conventional production serves as a significant barrier to producing organic wheat (Walz, 1999; Jones et al., 2006; Rodriguez, 2009). During this period, growers often experience decreased yields (Liebhardt et al., 1989; Temple et al., 1994) and soil N, accompanied by increased weed pressure and financial risk (MacRae et al., 1993; Delate et al., 2003).

The need to build up soil health and nutrient levels is especially important during the organic transition period, as USDA certified organic rules prohibit the use of chemical-based fertilizers, and soil organic matter levels are generally insufficient to release adequate levels of N via mineralization following many years of conventional practices (Scow et al., 1994). Failure to increase inherent soil fertility via organic matter addition during the transition period could jeopardize the survival of the organic operation once certified organic. The certified organic rules also require growers to build soil health and engage in erosion- and contamination-limiting management practices by improving soil organic matter levels (USDA-AMS, 2016). The soil organic matter pool contains large reserves of the macronutrients N, phosphorus, potassium, and
sulfur (Stockdale et al., 2002); therefore, building soil organic matter and microbial populations is a key component of managing soil fertility in the absence of chemical-based fertilizers. Soil organic matter transformations via soil microbial activity drive nutrient cycling, decontamination processes, and healthy soil structure (Kibblewhite et al., 2008). As heavy tillage disrupts soil structure and increases nutrient losses via leaching or volatilization (Tebrugge and During, 1999; Tilman et al., 2002; Kibblewhite et al., 2008), limiting tillage is a goal in organic systems despite tillage being a primary form of pre- and post-emergence weed control.

Managing weeds to prevent yield loss is a primary challenge for organic growers (Sooby et al., 2007). The use of herbicides for direct weed control in conventional systems is often replaced with mechanical controls in organic systems, including pre-plant tillage and secondary weed control implements, such as harrows and hoes. However, reliance on intensive tillage methods for weed control would violate soil conservation principles in eastern Washington, where tillage on the steep slopes increase water- and wind-mediated soil loss in an agricultural region highly susceptible to soil erosion. Instead, organic growers must rely more on cultural weed control measures, including increased seeding rate, maintaining heavy residue mulch, crop rotation, and cover cropping (Bond and Grundy, 2001; Mason and Spaner, 2006). However, perennial weeds tend to become problematic in reduced tillage organic systems (Légère et al., 2013; Lorent et al., 2016). Designing integrated weed management programs using system-wide approaches that maximize crop competitiveness with troublesome weeds, especially perennial species, is needed to create organic wheat cropping systems that yield competitively with conventional systems.

Low grain yield and quality as a result of low soil N is a major challenge, as the availability of animal manure is limited in the region. Without access to affordable animal
manure, many organic growers rely on green manure cover crops as their primary fertility input (Walz, 1999). However, low summer precipitation limits cover crop growth and N input (Lorent et al., 2016). Once a grower achieves certification, maintaining sufficient plant-available N levels to produce high-yielding crops is a challenge, as nutrient release from organic materials is often asynchronous with crop need and uptake (Sooby et al., 2007). As N is often the limiting nutrient in organic cereal production systems (Dawson et al., 2008, Miller et al., 2011), especially in systems relying on legumes to provide crop N, producing organic hard red spring wheat with 14% protein (a common market standard in the region) is a challenge.

Growers in Washington State planted over 920,000 hectares of wheat in 2006 (USDA-NASS, 2016), of which only about 100 ha was certified organic wheat (Kirby and Granatstein, 2014). The low levels of adoption of organic wheat production in Washington State, relative to surrounding states, prompted Washington State University researchers to include questions about organic adoption in a survey of conventional Washington State wheat growers. Only 14% of conventional wheat growers reported interest in transitioning any hectarage to certified organic production, and a majority of respondents stated that inadequate weed control methods and low yields were the primary barriers to adoption (Jones et al., 2006). Economic barriers, such as the lack of a well-developed marketing structure, and the large distance to urban markets where organic products are in high demand (Lorent et al., 2016), may contribute to the low levels of adoption in eastern Washington. In areas with few organic growers, those who have transitioned to certified organic practices have reported feeling socially marginalized and received opposition from their neighbors who are farming conventionally (Lorent et al., 2016). Organic management often requires more labor, and growers have reported working longer hours when converting to certified organic production (Lorent et al., 2016). Organic growers in eastern Washington may
also be suffering from a lack of institutional support. Goldberger (2008), in a 2007 survey of all certified organic producers in Washington State, found that organic producers rarely interacted with university researchers or Extension agents, though most respondents read Extension bulletins. These results indicated that certified organic growers in Washington State were interested in information provided by university researchers and Extension agents, but that communication between growers and university representatives could be improved.

Given the challenges endemic to organic wheat production in eastern Washington and the inland PNW, a survey of certified organic small grain and forage producers in five states was conducted in 2014 to better communicate with and understand the perspectives of those growers who were producing certified organic wheat in the region. Survey questionnaires were sent to 432 certified organic small grains and forage producers in Idaho, Montana, Oregon, Utah, and Washington, and 157 completed questionnaires were received, for a response rate of 38% (Tautges et al., 2016b). Economic or financial considerations were the most frequently mentioned reason for transitioning to certified organic production, followed by environmental protection, concerns about agribusiness and agrichemicals, and the welfare of family, workers, and livestock. Similar to the findings of many other surveys (Walz, 2004; Jones et al., 2006; Sooby et al., 2007; Goldberger, 2008), respondents reported the high cost of organic inputs, weed-related production losses, and variable or low yields to be the primary challenges faced by certified organic growers. Despite these challenges, 98% of all respondents to the 2014 survey planned on maintaining their organic certification over the next five years, and of those, 41% planned to increase production. Respondents reported that the most profitable certified organic products were alfalfa and dairy products (Appendix 1).
A grower’s rotational crop selection, farm size, and demographic characteristics influence the type of weed and soil management program implemented on the farm. Average certified organic land area operated differed greatly between the states surveyed, ranging from 133 ha in Washington State to 1,526 ha in Montana and 2,176 ha in Utah. Forty-eight percent of survey respondents grew grain crops, 48% grew forage crops, and 31% produced livestock. While the extent of certified organic small grain production remains low relative to conventional small grain production in the inland PNW, results of this survey indicate that those who have already adopted organic agriculture have little intention of giving up on organic management (Appendix 1). Past surveys in the region have indicated that limited demand and marketing opportunities for organic products and high input costs have served as significant challenges for certified organic producers (Goldberger, 2008; Goldberger, 2010). However, respondents in this survey reported financial factors to be the strongest motivator to grow organic small grains and forages. Additionally, respondents reported limited demand for organic products to be a challenge at lower rates than those found in previous surveys, suggesting that demand for certified organic small grains and forages may be increasing in the inland PNW. However, the number of organic small grains and forage producers in the inland PNW remains low compared to other regions, such as the Midwest and Northeast (USDA-NASS, 2014). Consequently, these growers struggle with problems that result from the organic market being relatively small and undeveloped, such as feeling underserved by public researchers and the agricultural industry as a whole. Enabling the practice of organic agriculture on large hectarages could also extend the ecological benefits derived from organic agriculture to a greater land area, as opposed to researchers focusing on small organic vegetable farms operating on few hectares. To improve communication between public researchers, certified organic growers, and the public, a series of case studies were
produced that report on the farming philosophies and practices of 12 organic small grain growers across Washington, Oregon, and Idaho operating dryland and irrigated farms of different sizes (Lorent et al., 2016).

As this study was undertaken to develop sustainable alternatives to conventional agriculture, it was essential that the project address environmental, economic, and social factors (Altieri, 1988; Allen et al., 1991) involved with certified organic production in this region. In our examination of producing certified organic wheat in eastern Washington and the inland PNW, this paper aims to review the successes and failures we experienced with 1) controlling weeds to limit weed competition with crops, 2) building soil N levels, 3) the production potential and limitations of organic wheat production, compared to conventional wheat production, 4) long-term soil health indicators, and 5) the social and economic implications of organic wheat production from the perspective of growers in the inland PNW.

**Cropping System Design**

*Organic Transition Phase*

A “transition to organic” from conventional production field trial was initiated in fall 2002 at the Boyd Farm, located near Pullman, Washington, by Gallagher et al. (2010) to evaluate how three-year rotations of wheat/legume, continuous green manure, and an alfalfa (*Medicago sativa* L.)/oat (*Avena sativa* L.)/spring pea (*Pisum sativum* L.) forage mix (hayed) grown during the organic transition period impacted the yield of organically produced wheat for two years after the transition. Winter crops were planted in the fall of 2002 and the transition rotations were maintained from 2003 through 2005, when the land achieved full organic certification. Spring wheat and winter wheat were planted in 2006 and 2007, respectively, to measure the residual effects of the transition rotations on subsequent organic grain.
Certified Organic Production Phase

To apply what was learned during the organic transition field trial, and to take advantage of fully certified organic land, a “certified organic production study” was initiated in fall 2007. Full funding was received in 2009 and complete soil and plant data collection was conducted thereafter in the field trial. Objectives of the production phase field trial were to identify which crop rotations and organic management practices maximized 1) productivity, 2) weed control, and 3) soil fertility. The production phase field trial consisted of four organic cropping systems using poultry manure, legumes, or a combination of the two, as a source of crop N. Crop rotations were designed around the cash crop winter wheat, on the advisement of grower consultants, and utilized alfalfa and winter pea as pulse rotational crops following observations of these crops’ superior weed competitiveness and productivity compared with other pulse crops tested during the transition phase. Two conventionally managed cropping systems were established in 2008 adjacent to the certified organic plots to allow direct comparisons of yield, grain quality, and profitability between organic and conventional management systems.

Weed Management

Cultural practices, especially increased seeding rate, were an important component of integrated weed management throughout the study. Increased seeding rates of spring-sown barley (*Hordeum vulgare* L.), wheat, and pea were found to reduce competition from wild oat (*Avena fatua* L.) in eastern Washington (Manuchehri, 2012). Despite higher seed costs, organic growers in Washington have reported using increased seeding rates for less competitive crops (Lorent et al., 2016). Certain crops have been observed to compete more strongly with weeds than others. For example, barley has been reported to have superior competitiveness with weeds than wheat (Cousens, 1996; Manuchehri, 2012), and was included in a rotation with wheat.
during the certified organic production study. Winter triticale (*x Triticosecale*) was included in rotation with winter pea during certified organic production specifically to assess its competitiveness with field bindweed (*Convolvulus arvensis* L.). Winter triticale is considered an alternative grain crop in eastern Washington (Herdrich, 2006) and is grown for both forage and grain. While the market for triticale in the region is not as strong as that for wheat, it is growing because of livestock producers’ increasing preference for triticale in grain rations (Herdrich, 2006).

To limit soil erosion in a region with steep cultivated slopes on grades of 8 to 45% (Schillinger et al., 2006), Gallagher et al. (2010) managed the organic land under transition using reduced tillage practices. Crops were planted using a no-till drill and tillage for weed management was conducted using only low-disturbance implements. A rotary harrow, which smooths the soil surface but does not use disks or shanks that cut into or invert the soil, was used to prepare the seedbed. Rotary harrows can also flick small weeds out of the soil, but are ineffective against well-established weeds (Lorent et al., 2016). After crop emergence, two to three passes a year were made with a rotary hoe, which is operated at high speeds and also flicks weed seedlings out of the soil to a depth of ~5 cm. Rotary hoeing was performed until crops reached a height of ~25 cm, after which it was discontinued to prevent crop damage. The rotary hoe tended to uproot broadleaf seedlings more than grasses, possibly because grass seedlings were more firmly rooted. Additionally, timing of rotary hoeing was important, as dry conditions following rotary hoeing helped prevent uprooted seedlings from re-establishing. An undercutter (sweep plow) was used to cut taproots in patches of perennial weeds, though re-rooting occurred and the undercutter did not adequately reduce perennial weed pressure in the long-term. Mowing was used to terminate the leguminous green manures and was an essential weed control.
operation throughout the duration of the study. Cultivation of hay crops allowed mowing to be performed several times during the season with different timing than wheat harvest, preventing selection for weed species with phenologies similar to that of grain crops. Additionally, thick patches of weeds were mowed prior to seed set, for weed seedbank management.

In year 1 of the transition phase, weed biomass was lowest in spring wheat and the forage mix, and greatest in spring pea and faba bean (Vicia faba L.), where wild oat and prickly lettuce (Lactuca serriola L.) dominated the stand and significantly reduced spring pea grain yield. In transition year 2, weed biomass in wheat in the grain-intensive rotations was similar to weed biomass in the green manure and forage systems, indicating that the green manure and forage legumes competed with weeds as strongly as wheat. However, weeds were allowed to go to seed in the wheat crop and were not in the green manure and forage crops, as the stand was mowed prior to weed seed set (Gallagher et al., 2010). A vigorous winter pea stand in year 3 competed well with weeds, whereas a poorly developed stand of spring pea contained weed biomass levels in excess of 3000 kg ha\(^{-1}\) and suffered primarily from competition with wild oat.

In organic spring wheat grown the first year after the transition (2006), weed biomass was lowest following the forage mix and three-year green manure rotations, at 20 kg ha\(^{-1}\) and 120 kg ha\(^{-1}\), respectively (Borrelli et al., 2014). Vigorous legume growth and mid-season mowing in these two systems likely led to weed suppression and a decreased weed seedbank going into the certified organic production period, achieving an important goal of successful transitional cropping systems. The greatest weed biomass immediately following the transition period was observed in spring wheat following transition crop rotations that included two years or more of spring crops, which competed poorly with weeds during the transition period, and following transitional rotations with one green manure crop phase or less (Borrelli et al., 2014).
A lack of soil N led to poor wheat crop growth in those rotations, which resulted in decreased crop competitiveness with weeds. Enhanced crop competitiveness is a key component of weed management in organic systems, and low levels of soil fertility following the transition period may contribute to the large weed populations and low grain yields many transitioning growers experience. In winter wheat grown two years after the transition period, no differences in weed biomass were observed between systems (Borrelli et al., 2014), suggesting that the competitive abilities of winter wheat were greater than the residual effects of the transitional rotations two years into certified organic production.

In the subsequent certified organic production phase (2007 to 2014), relative total weed biomass and relative biomass of two perennial weed species, Canada thistle (*Cirsium arvense* [L.] Scop.) and field bindweed, and three annual weed species, downy brome (*Bromus tectorum* L.), jointed goatgrass (*Aegilops cylindrica* Host.), and wild oat, were compared among the legume rotational crops alfalfa and winter pea, the fall-sown grain crops wheat and triticale, and the spring-sown grain crops wheat and barley. Second- and third-year alfalfa was highly competitive with both perennial weed species. Compared with pea, the more common legume rotational crop, alfalfa was more competitive with perennial weeds and provided a greater rotation benefit to wheat. Alfalfa was less competitive with the winter annual grasses downy brome and jointed goatgrass, and high populations of downy brome and jointed goatgrass were observed in the following winter wheat crop. In comparing weed pressure between the winter cereals, Canada thistle, downy brome, jointed goatgrass, and total weed biomass were lower in triticale than wheat. Among the spring cereals, pressure from field bindweed, jointed goatgrass, and wild oat was lower in barley than in wheat (Tautges et al., 2016a).
The identification of rotational crops with a competitive advantage over wheat could be grown in place of or prior to a wheat crop, to reduce weed pressure in a subsequent cash crop. For example, spring barley could be grown instead of spring wheat if a grower knew their field was infested with wild oat. Wild oat is a particularly troublesome weed in spring wheat systems, as it emerges at the same time as wheat but shatters prior to wheat grain maturity, leaving no opportunity for limiting wild oat contributions to the weed seedbank. However, during certified organic production, wild oat biomass was 80% lower in spring barley than in spring wheat, suggesting greater inter-specific competitiveness of barley than wheat with wild oat (Tautges et al., 2016a). Although the barley cultivar used in this study was short-statured, barley still displayed greater overall competitive ability with weeds than wheat, and could possibly afford the opportunity to control weeds reaching above the crop canopy. For winter cereals, triticale could be planted in fields where a grower is concerned about winter annual grass weed pressure in winter wheat, as triticale showed superior competitiveness with winter annuals commonly troublesome in wheat crops. Knowledge of species-specific competitive interactions between crops and weeds could enable the design of cropping systems tailored to compete with the weed species present on a particular farm, and could reduce the need for direct interventions to manage weeds within a crop.

While reduced tillage often results in greater perennial weed pressure (Swanton and Weise, 1991; Buhler et al., 1994; Léger et al., 2013), the results of this study indicate that planting a competitive perennial crop, such as alfalfa, can compensate for increased perennial weed survival in conservation tillage systems. Several perennial forage crops have been reported to compete well with Canada thistle, especially when mowed multiple times a year (Wilson and
Kachman, 1999). Reports of alfalfa suppressing Canada thistle may be found in the literature 
(Derscheid et al., 1961; Thrasher et al., 1963; Schreiber, 1967), though investigation of alfalfa’s 
weed suppressive abilities has been largely neglected in the literature in the last 50 years. Alfalfa 
and other perennial forage crops, especially when cut multiple times a year, could play a critical 
role in weed management in reduced tillage organic systems.

In a survey of certified organic small grain producers in the inland PNW, all growers 
reported using cultural controls such as crop rotation, increased seeding rates, and cover crops at 
high rates (Table 1). Survey results indicate that certified organic growers are actively managing 
weeds and desire more information on organic weed management. When asked which weeds 
have proven difficult to control on certified organic hectarage and/or have negatively impacted 
their certified organic products, growers most often mentioned two perennial weeds, Canada 
thistle and field bindweed. Correspondingly, the most frequently mentioned research need for 
organic growers, as reported by respondents, was the need for methods to control perennial 
weeds in organic systems, especially under reduced tillage (Tautges et al., 2016a).

**Soil N Fertility Management**

The three-year rotations tested during the transition period compared the legumes faba 
bean, winter pea, spring pea, and alfalfa as the sole N source to support subsequent grain 
cropping. Faba bean was selected in the first year as a green manure crop because of its 
perceived ease of establishment and tolerance of disturbance from its large seed size, but was 
poorly adapted to the region and produced low biomass (Gallagher et al., 2010). Faba bean was 
subsequently replaced with winter pea, which demonstrated cold tolerance during winter and was 
more drought-hardy during the summer, and accumulated high levels of biomass and N. A three-
year alfalfa/oat/spring pea forage mix was included to compare the residual effects on soil N of a
three-year green manure rotation with a forage mix cut for hay, which could be sold to generate income.

In the first year of the transition period trial, there was generally poor crop establishment (Borrelli et al., 2012), demonstrating the riskiness of the transition period. Soil inorganic N levels were similar following all rotations in the transition period trial, but organic hard red spring wheat protein was greater following rotations that included winter pea green manure, suggesting that more N was provided to the wheat crop over the course of the season by soils receiving a legume green manure (Borrelli et al., 2014). While inorganic N levels were similar following the forage mix and winter pea green manure systems, soil inorganic N levels declined more rapidly following the forage mix system than the winter pea green manure systems. Mineralization of winter pea biomass continued to provide N for the crop into the second year of grain production following the transition period, whereas root tissue mineralization following the forage mix contributed more N immediately but was depleted quickly after one year of grain production (Borrelli et al., 2014). The findings of this study suggest that a grower could produce forage mix for hay during the transition period to build soil N, but only follow with one wheat crop in the first year of certified organic production, and grow a legume green manure crop prior to grain cropping again to maintain adequate soil N mineralization.

During certified organic production, composted poultry manure (~5% N) was applied at a rate of 2250 and 4850 kg manure ha⁻¹ (depending on yield goal and residual soil N content) to wheat at planting, as it was recognized during the transition period that green manure did not always provide sufficient inorganic N immediately available to the following grain crop. Throughout certified organic production, soil inorganic N was compared between rotations treated with green manure and poultry manure. Soil inorganic N following winter pea green
manure prior to wheat was lower than when following winter pea hay in a system receiving poultry manure. High levels of plant-available N observed in the organic wheat rotation receiving poultry manure resulted in the high yields in that system. However, soil inorganic N following three-year alfalfa was similar to the poultry-manured system, suggesting three-year alfalfa could possibly supply adequate soil N for a following winter wheat crop, along with marketable high-value hay, in the dryland conditions of eastern Washington. The low amounts of soil inorganic N supplied to wheat systems receiving fertility from winter pea green manure alone was likely responsible for the lower grain yields in those systems, similar to the low grain yields observed following the green manure rotations during the transition period (Borrelli et al., 2014). These results call into question the potential for winter pea green manure to consistently produce enough N to support organic grain yields competitive with conventional yields in eastern Washington, though poultry manure supported high-yielding winter wheat under organic management.

Survey results indicate that organic small grains growers are employing a number of methods to manage soil N. A majority (78%) of survey respondents conducted soil sampling and/or soil tests to monitor the nutrient status of soils on their certified organic land, and 69% of respondents reported having applied livestock and/or poultry manure on their farm. Seventy-four percent of those who applied manure reported that the manure was generated on-farm, indicating that nutrients were being retained and recycled within farms, as well as suggesting that a minority of organic growers obtain manure from off-farm sources, which is often cost-prohibitive (Appendix 1). In Idaho, two farm operations in Blaine and Camas Counties collaborated with local Extension educators to research the effectiveness of applying composted manure to their fields. Crops in those counties are organic by default as yield potentials are
inherently low due to the short growing season at high altitude. Fertilizer and chemical inputs seldom prove economically viable, but composted manure is readily available at an affordable cost from organic dairies in the area (Hunter et al., 2012). Other on-farm studies highlighted the challenges associated with manure application in the region, as fertilizers derived from manure tended to be highly heterogeneous, making application with equipment difficult in some instances. On-farm trials in eastern Washington compared two commercially available, organic fertilizers, Perfect Blend™ (4-4-4) and Nature Safe™ (13-0-0) in a wheat-fallow rotation. The heterogeneous texture of Nature Safe sometimes complicated mechanized application.

Survey results indicated that after use of livestock manures, green manure was the most common soil fertility management tactic employed by respondents. Fifty-five percent of respondents grew cover or green manure crops on their certified organic hectarage to supply N to their soil, with the majority of green manure growers using pea or vetch. When asked what soil fertility issues they would like to see addressed by public researchers and Extension agents, growers most often mentioned the development of affordable soil fertility amendments or products (16%) and cover crops research (13%). Growers also mentioned strategies to achieve sufficient levels of plant-available N (12%) and phosphorus (10%) (Appendix).

**Productivity**

*Crop Vigor and Yield*

During the transition period, winter crops accumulated more biomass and achieved greater yields than spring-sown crops in both wheat and pea, though wheat grain yields were still less than the regional average during the transition period (Gallagher et al. 2010). Spring pea grown for grain and faba bean grown for green manure experienced crop failure and demonstrated little potential for success in dryland organic reduced tillage cropping systems.
However, winter pea green manure produced between 1.5 and 2.5 t ha\(^{-1}\) and the forage mix produced between 1.5 and 3.5 t ha\(^{-1}\), indicating that legume crops adapted to the region can be highly productive and competitive during the transition period.

Organic spring wheat yields grown after the transition period were greatest following three years of forage mix (~4000 kg ha\(^{-1}\); Borrelli et al., 2014). Spring wheat yields were also high following three years of green manure (one year faba bean and two years winter pea) at 3650 kg ha\(^{-1}\) and following one year of winter wheat and two years of winter pea green manure at 3350 kg ha\(^{-1}\) (Borrelli et al., 2014). In contrast to spring wheat, winter wheat yields in the second year after the transition period were 20% lower after the forage mix transition system than after two years of green manure. N mineralization and release from crop biomass likely occurred for a longer period (2 yr) following three-year winter pea green manure, compared with N release from alfalfa roots, which was reduced to insufficient levels for crop production after a single year of crop production (Borrelli et al., 2014). A longer period of residual N following termination of the forage mix may have occurred had N not been removed from the system each year via hay cutting. However, the choice to grow green manure crops during the transition period represents a sacrifice of immediate profit on the part of the grower, though increased profit is expected later through the yield boost gained from the previous green manure crop. The forage mix could offer a transitioning grower increased flexibility and risk management, as hay cutting offers an opportunity to control weeds through several cuttings throughout the season, and the harvested hay is marketable, in contrast to green manures.

In the certified organic production phase, winter wheat yields were greatest (5650 kg ha\(^{-1}\) on average) when poultry manure was applied at planting, compared with conventional winter wheat in an identical rotation, and were comparable to county averages for conventional winter
wheat yield (USDA-NASS, 2014). Wheat fertilized with poultry manure had greater yields than wheat receiving fertility from legumes alone. The addition of poultry manure to winter wheat boosted grain yields from 70 to 125%, compared to wheat grown with legume residual N alone. Winter wheat following three years of alfalfa hay had yields of 3300 kg ha\(^{-1}\), and winter wheat following one year of winter pea green manure had yields of 2500 kg ha\(^{-1}\), averaged over all years of the certified organic production phase (2008 to 2014). The low yields observed in green manure-only systems during certified organic production suggest that a more winter-hardy pea variety is needed, or that an organic grower must find an off-farm source of fertility if their goal is to produce wheat yields that are competitive to those achieved under conventional production. These findings run somewhat contrary to the spring wheat yield trends observed in the transition period trial in 2006, where yields following the alfalfa forage mix and winter pea green manure were similar to the county average (USDA-NASS). Winter pea green manure biomass accumulation was much lower in the certified organic production phase than in the transition period, possibly due to harsher winter conditions in the certified organic production phase that resulted in pea winterkill. Winter pea breeding efforts are ongoing in the region to develop more productive and cold-tolerant winter pea cultivars.

In the certified organic production phase, the three-year organic winter wheat-spring wheat-winter pea rotation produced winter wheat yields that were competitive with conventional yields, but organic spring wheat yields were lower than conventional spring wheat. Low organic spring crop yields were largely the result of lower competitiveness of spring crops with weeds, compared to winter crops. Organic wheat grain protein was often lower than conventional, even with ample levels of soil N from the poultry manure, possibly as a result of low soil N availability at the time of grain fill. Organic growers in the region have also reported low grain
protein levels (Lorent et al., 2016). Results from the field trials indicate that organic spring crop yields that are competitive with conventional yields will be more difficult to achieve in this region than for winter crops, though rotations with both spring and winter crops are likely necessary from a crop rotation and weed management standpoint (Anderson, 2010), and many organic growers in the area report success with growing spring grains organically (Lorent et al., 2016). For the alternative grain winter triticale, under high levels of competition from a well-established field bindweed population, organic winter triticale produced grain yields of 5300 kg ha\(^{-1}\), on average, achieving yields similar to winter wheat supplied with poultry manure. Results from this trial demonstrated triticale to be a high-yielding, competitive alternative grain to wheat in organic systems.

**Grain Quality**

Hard red spring wheat grain produced the first year following the transition period contained the greatest percent protein when following winter pea green manure, though no organic hard red spring wheat grain met the 14% protein market standard. During certified organic production, organic hard red spring wheat fertilized with poultry manure contained less grain protein than conventionally fertilized hard red spring wheat in two of the three years it was produced, though was similar to conventional grain in 2013, when it met the 14% market standard. Results suggest that producing hard red spring wheat organically, even with external sources of fertility, may be risky in the region in terms of meeting the standards of the bread-quality wheat market. However, as is the case with many studies comparing grain yield and quality between organic and conventional systems, varieties bred under high-input conventional conditions were used in this study. Plant breeders interested in breeding for organic agriculture are increasingly advocating for organic breeding programs to make selections under organic or
low-input conditions (Dawson et al., 2008; Murphy et al., 2007), as some traits selected for in high-input systems have been shown to reduce nutrient use efficiency and grain protein (Reid et al., 2011; van Bueren et al., 2011). As the majority of organic spring wheat grain produced in this trial came within 1% of the bread making standard, it is expected that organic breeding efforts could improve organic hard red spring wheat protein content to meet end-use quality standards.

In addition to evaluating grain protein, more extensive grain quality analyses were performed during the organic production phase trial by Park et al. (2015), who analyzed grain produced in 2009 and 2010 for kernel size, hardness, and test weight, and analyzed flour for ash, protein, and mineral content. Park et al. (2015) found that test weight and kernel diameter of soft white winter and hard red spring wheat was greater in organic grain than conventional grain, and that flour ash and magnesium content was similar between organic and conventionally managed wheat. Interestingly, wheat grain phosphorus content in organic wheat receiving N fertility from poultry manure and legume green manure-only was similar to or greater than conventional grain P content. While other studies have found soil P to be a limiting nutrient in organic grain systems (Kitchen et al., 2003; Ryan et al., 2004; Welsh et al., 2009), wheat P uptake did not appear to differ between organic and conventional systems in this study, using wheat grain as an indicator.

**Soil Quality**

*Soil C*

Organic management practices usually include repeated applications of organic matter (e.g., composts, manure, etc.) to the soil over time, and soil C levels have frequently been found to increase in organic agricultural systems relative to conventional systems (Pimentel et al., 2005; Marriott and Wander, 2006). Baseline soil total C content, following decades of
conventional tillage, was similar among all systems in 2003 at the initiation of the study, and while soil C was greater in the more productive organic rotations immediately following the transition period, differences among systems were not significant. However, soil total C increased significantly in all organic systems during the transition period (2003 through 2005) and the subsequent two years of certified organic grain production (2006 and 2007; Figure 1). In addition to the use of organic management practices, the conversion to reduced tillage likely contributed to the increase in soil total C during the transition period.

In the certified organic production phase, soil C was greatest in the three-year organic alfalfa forage-winter wheat system and an organic poultry-manured system, compared with the two-year rotation of organic winter wheat-winter pea green manure system, which can be attributed to low winter pea productivity leading to reduced N inputs and subsequent wheat productivity. However, after nine years, soil C was greater in all organic wheat production systems than conventional wheat production systems. In contrast to the transition period, changes in soil C over time were not significant during the certified organic production phase; however, a slight increasing trend was observed in the most productive organic systems, whereas a negative trend in soil C was observed in the conventional systems (Figure 2). Twelve years of soil C observation in this study indicate that soil C accrual occurs rapidly during the transition from conventional to organic production, supporting the claim that organic agriculture contributes to C sequestration in agricultural soils (Rodale Institute, 2014).

Soil Microbial Parameters

Soil microbial sampling was conducted at the end of certified organic production to investigate differences in microbial diversity and activity between organically and conventionally managed soils under identical winter wheat-spring wheat-winter pea crop
rotations, and bacterial and fungal gene copy numbers, community level physiological profiling, T-RFLP, and soil enzyme activity analyses were performed (Tautges et al., 2016c). Greater soil C levels in the organically managed soil, compared to conventionally managed soil, sustained greater fungal and bacterial abundance and enzyme activity, as evidenced by greater C substrate utilization by bacterial communities in organically managed soils. Poultry manure amendments also raised soil pH over time, which likely contributed to increased microbial activity, compared to the conventional system, especially in soil bacteria, which are particularly sensitive to low soil pH (Rousk et al., 2010). Interestingly, pea hay yield and tissue N content was highly positively correlated with fungal and bacterial abundance, indicating that fostering successful soil microbial communities can have direct benefits for some crop yields and grower profits. Greater knowledge of microbial activity and competition for soil nutrients could enable organic producers to take advantage of greater soil microbial activity during crop production, or to compensate for microbial competition with crops.

Conclusions

The results from twelve years of research on organic wheat production in the inland PNW indicate that organic winter wheat grain yields can compete with conventional yields with the addition of poultry manure fertilizer; however, winter wheat yields were consistently low in the system with one year of winter pea green manure due to low winter pea biomass accumulation and may not be the most reliable system for supplying adequate N fertility. The use of other legume species that produce greater biomass in one year, or the use of a longer green manure sequence in the crop rotation, may be required to support wheat cropping solely on the N input of a green manure crop. While manure may be costly, interviews revealed that many organic growers in the region choose to purchase manure from off-farm sources, suggesting that relying
on legumes as the sole source of N is often not feasible in the region. However, alfalfa forage mixes were profitable and left residual inorganic N levels adequate for high-yielding winter wheat produced the following year. Additionally, of all rotational crops, alfalfa was the most competitive with all weed species and especially with perennial weeds, which are generally the most troublesome weed species to organic growers. The profitability of certified organic alfalfa hay and its inherent competitiveness with weeds makes alfalfa a rotational crop well suited to winter wheat rotations in the inland PNW.

Spring-sown crops, including wheat and pea, were low-yielding in organic systems and less competitive with weeds throughout the duration of the study. However, spring crops are an important component of wheat rotations and provide a good opportunity to control winter annual weeds emerging in the spring, prior to sowing. Many organic growers in the region produce hard red spring wheat, despite field trials where organic spring wheat yields and grain protein were observed to be consistently lower than conventional yields, likely due to high weed pressure and low N mineralization rates in the summer. The organic wheat industry in the inland PNW would greatly benefit from increased breeding efforts for hard red spring wheat to improve N use efficiency and competitiveness with weeds.

Organically managed soils under reduced tillage developed greater soil C, higher soil pH, and increased microbial activity and diversity compared to conventionally managed soils, meeting the goals of the organic management paradigm. In a region where tillage and soil erosion are commonplace and accepted aspects of wheat cropping, the potential of organic reduced tillage systems to produce winter wheat yields equivalent to conventional yields, while increasing soil health, is promising for sustaining soil quality in the long-term. Future research in wheat cropping systems in eastern Washington should examine the potential of alternative
fertility amendments that couple N input with C inputs, such as manure and composts, to contribute to long-term soil fertility and health while meeting wheat production goals. Growers in the region have clearly voiced their desire for more information on alternative management practices that preserve and ensure soil health in the long-term, whether or not they choose to organically certify their land. We hope that, after twelve years of research on organic wheat production in eastern Washington, research continues on exploring ways to expand organic production in the region, especially in the areas of alternative fertility amendments applied on a large scale, and on controlling perennial weeds. For organic production to grow in the region, public support and information available to organic growers must gain greater parity with the resources enjoyed by conventional growers.
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Table 1. Results of a survey of certified organic small grains and forage growers in Idaho, Montana, Oregon, Utah, and Washington, performed in 2014. The table displays the percentage of respondents who reported using selected implements for mechanical weed control. Percentages shown include those who used these implements only on their certified organic land, and those who used them on both their certified organic and conventional land.

<table>
<thead>
<tr>
<th>Weed Control Practice</th>
<th>Grain Crop Producers(^a) (%)</th>
<th>Forage Crop Producers(^b) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mechanical Controls</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-plant tillage</td>
<td>78</td>
<td>43</td>
</tr>
<tr>
<td>Rod weeder</td>
<td>43</td>
<td>19</td>
</tr>
<tr>
<td>Tine weeder</td>
<td>32</td>
<td>22</td>
</tr>
<tr>
<td>Inter-row cultivator</td>
<td>30</td>
<td>11</td>
</tr>
<tr>
<td>Root undercutter</td>
<td>22</td>
<td>13</td>
</tr>
<tr>
<td>Rotary harrow</td>
<td>17</td>
<td>15</td>
</tr>
<tr>
<td>Rotary hoe</td>
<td>11</td>
<td>4</td>
</tr>
<tr>
<td><strong>Cultural Controls</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crop rotation</td>
<td>89</td>
<td>59</td>
</tr>
<tr>
<td>Increased seeding rate</td>
<td>71</td>
<td>46</td>
</tr>
<tr>
<td>Cover crop</td>
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<td>35</td>
</tr>
<tr>
<td>Selection of competitive varieties</td>
<td>64</td>
<td>41</td>
</tr>
<tr>
<td>Residue mulch</td>
<td>45</td>
<td>18</td>
</tr>
<tr>
<td>Relay- or inter-crop</td>
<td>32</td>
<td>18</td>
</tr>
</tbody>
</table>

\(^a\) Includes respondents who produced winter wheat, spring wheat, beans (dry), barley, chickpeas, oats, triticale, peas, and/or lentils, and not the crops in the forage category (see footnote b).

\(^b\) Includes respondents who produced alfalfa, grass hay, and/or silage, and not the crops in the grain crop category (see footnote a).
Figure 1. Soil total carbon in organically managed soils during the transition study. The transition period began in 2003 and ended in 2005, after which certified organic production was continued. Spring wheat was grown in 2006 and winter wheat was grown in 2007 following all transition crop rotations.
Figure 2. Soil total carbon in the most productive cropping systems (Systems 1, 2, and 4) during the certified organic production phase trial, initiated in 2008. System 3 was not included because of its poor soil N fertility, leading to low levels of productivity. Soil was not collected in 2008, but sampling and analysis was resumed in 2009 and was performed through the end of the study, in 2014. The black regression line and equation corresponds to the organic systems, and the gray line and equation to the conventional systems.
CHAPTER 2

A Survey of Weed Management in Organic Small Grains and Forage Systems in the Northwest U.S.

Abstract

A lack of information regarding weed control, relative to conventional systems, has left organic growers largely on their own when devising weed management systems for organic crops. As interest in organic weed management increases, researchers need more information regarding the type and number of weed control practices undertaken on organic farms. A survey of certified organic growers was conducted in five states in the northwest U.S. to identify organic weed management programs and what grower and farm operation characteristics were factors in weed management program design. Three types of weed management programs with varying diversity of weed control practices were identified. Stepwise binary logistic regression indicated that the likelihood of an organic grower using a more diverse weed management program increased if a grower engaged in grain production, and as the number of crops produced on an organic farm operation in one year increased. The probability of operating a more diverse weed management program also increased as a grower’s education level increased. Organic hectarage operated was positively correlated with weed management program diversity, and with the adoption of cultural controls. Additionally, awareness of weeds as a factor causing yield loss was correlated with increased weed management program diversity. An increased awareness among researchers of the differing needs and abilities of organic growers in managing weeds on their farms will improve communication and outreach efforts when assisting growers with designing organic weed management programs.
Introduction

Since the widespread adoption of herbicides following their development in the late 1940s, the application of herbicides has become the primary method for weed management (Bastiaans et al. 2008). As a consequence of the generally high effectiveness of herbicides, growers have become accustomed to “clean rows” free of weeds (Burton 2004; Carolan 2006; Doohan 2010). Conversion to organic practices often results in higher weed populations in crop fields, which is generally perceived as a sign of poor farm management by grower peers (Burton 2004; Carolan 2005, 2006). Surveys of conventional growers have identified the perception of increased weed pressure and inadequate control methods in organic systems as major barriers to adopting organic production practices, and weed control remains a major concern for organic farmers (Walz 1999; Rodriguez et al. 2009). Improving weed control methods in organic production systems could increase the adoption of organic agriculture and increase productivity.

Similar to “integrated pest management” (IPM), “integrated weed management” (IWM) applies to multiple physical and ecological tactics to control weeds (Liebman and Davis 2000), combining cultural (e.g., cultivar choice, seeding rate and date, etc.), physical (e.g., mowing, preplant tillage, mulching, etc.), preventive (residue management, clean machinery, management of field margins, etc.), and biological controls. IWM is well-suited for adoption by organic farmers without the option to use conventional herbicides to mitigate weed outbreaks and integrates diverse weed management methods. However, generalizations regarding the weed management approaches of particular types of growers must be made with caution. Many IWM practices are crop specific (Bastiaans et al. 2008; Mace et al. 2007), meaning that a tactic found to be effective in one crop may have neutral or even negative effects in another crop. Therefore, the usefulness of IWM practices in the context of the crops being grown on-farm should be
assessed for each individual case, and all crop rotations should not be treated as equal candidates for the effective use of IWM practices.

The degree of integration of physical and cultural approaches on organic farms has been found to be variable, with some studies finding increased emphasis on physical and others on cultural controls, whereas preventive and biological controls are rarely mentioned. Turner et al. (2007) performed a survey in the UK in which 52 organic farmers were asked about their weed control measures, and found that physical controls were mentioned more often than cultural controls as weed management techniques. In contrast, a national survey of U.S. organic farmers found that growers most often used the cultural controls of crop rotation and late planting and a limited number of physical measures for weed control (Walz 1999). A survey of organic growers in the Midwest U.S. found varying emphases on cultural and physical controls between growers (DeDecker et al. 2014). In an attempt to identify the driving factors of these differing approaches, organic growers were grouped into three categories that represented different approaches to weed management. Researchers found that the number of weed management practices used by growers was affected by a number of factors, including the amount of formal education, years of farming experience, and the information-seeking behavior of growers (DeDecker et al. 2014). These findings are similar to demographic characteristics identified in other studies, which include age, background, education, and farm size (Burton et al. 1999; Genius et al. 2006; Padel 2001; Daberkow and McBride 2003; Knowler and Bradshaw 2007) that have been found to influence adoption of technologies (e.g., organic agriculture, sustainable practices, conservation tillage, etc.).

Given the differences in climate, crops produced, common weed species, and farm size among the agricultural regions of the U.S., weed management behaviors and practices also may
differ among regions. For example, a survey of Midwestern organic growers performed by DeDecker et al. (2014) found an average area farmed of 109 hectares. In the northwest U.S. where farm sizes are larger, the 2014 Certified Organic Production Survey (USDA-NASS 2015) found that average organic crop hectarage ranged from 45 ha in Washington State to 875 ha in Montana. Larger farm operation sizes could increase the labor requirements and cost of each practice and potentially limit the number of weed management practices employed by organic growers in the northwest U.S., relative to the Midwest and other regions of the country. Or, larger farm sizes could allow producers to capture economies of scale and increase the profitability of more weed management practices.

Research focusing on organic weed control methods is lacking relative to the information available to conventional producers, despite interest among organic grain producers in accessing the findings of researchers. A majority of organic growers surveyed in Washington State in 2008 expressed an interest in working with university representatives on organic research; however, less than one-third of respondents had previously met with a university representative (Goldberger 2008). Surveys were previously conducted targeting all certified organic growers in the northwestern states of Washington and Idaho (Goldberger 2008; Goldberger et al. 2010); however, their focus was largely on marketing and sources of information and not management practices. Additionally, the majority of respondents to the Washington survey were tree fruit and vegetable producers, whereas only 23% of respondents reported producing forages, 7% grains and oilseeds, and 6% cattle and calves (Goldberger 2008). As agricultural management of field crops and vegetable and fruit (horticultural) crops is very different, a survey targeting only grain and forage producers would be useful in obtaining information specific to larger-scale organic farm operations. The survey of Idaho organic producers, of which the majority of respondents
were forage and grain crop producers, found that over 51% of respondents reported weed-related production losses as a major challenge faced by certified organic producers in Idaho (Goldberger et al. 2010).

The objectives of this study were to 1) identify the number and type of weed management practices in field crops on certified organic farms in the northwest U.S., and 2) analyze how demographic and farm operation characteristics impact weed management program diversity. The information collected in this survey will establish a baseline for organic weed management practices already employed on grain farms in the region, and can help university researchers and Extension agents develop future research projects and informational materials tailored to the needs of organic forage and small grains producers in the region.

**Materials and Methods**

*Survey Design and Administration*

The area of interest for this survey consists of the wheat production region of the inland Pacific Northwest, which includes eastern and central Washington and Oregon and the intermountain region of southeastern Idaho, northern Utah, and western Montana (Schillinger et al. 2006). To avoid drawing potentially arbitrary boundaries within states, certified organic farm operations located within the states of Idaho, Montana, Oregon, Utah, and Washington were identified as the target population. A list of all certified organic farm operations in these states was obtained from the 2012 List of Certified USDA Organic Operations, a publicly available searchable database that can be accessed online and includes certified grower information from all USDA-accredited organic certifying agencies (USDA-AMS 2012). Farm operations were selected for inclusion in the survey based on agricultural products grown, where the majority of products grown on a farm were field crops (defined here as including cereals, pulses, forage
crops, hay, and pasture). Farm operations with livestock were included in the survey only if they also contained certified organic land on which field crops were grown, as growers producing only livestock would presumably engage in little weed control if they were not also producing their own forages/pasture. Organic farm operations that primarily produced vegetable, fruit, or herb crops were excluded from this study. In the five states, 432 certified organic farm operations were identified as meeting these criteria.

The survey questionnaire consisted of three sections. The first section included closed- and open-ended questions about farm operation characteristics, including land history (e.g., when land was placed under organic certification, if the land certified was transitioned from conventional to organic management), farm operation composition (e.g., percentage of land under organic and conventional management, cropland vs. pasture or rangeland, etc.), crops produced, and challenges encountered by growers while producing organic crops. The second section focused on weed management practices and was divided into mechanical control and cultural control sections. For each weed control practice listed (Table 1), respondents were asked if they had used that weed control practice 1) only on certified organic land or 2) on none of their certified organic land. The section concluded with two open-ended questions; one asked respondents to list weeds that have been problematic on their certified organic land, and the second asked growers to list which weed management issues they would like to see addressed by university researchers and Extension agents in their region. The third section consisted of closed- and open-ended questions regarding the demographic characteristics of the respondent.

The survey was administered from February 21 to May 27, 2014 using the Tailored Design Method (Dillman et al. 2009), during which survey recipients received four mailings, including an introductory letter, questionnaire, reminder postcard, and replacement
questionnaire. Survey recipients had the option to complete the survey via the paper questionnaire or on the web. All questionnaires included a respondent ID number to track completion via mail or the web, and to maintain respondent confidentiality.

Data Analysis

Cluster analysis was used as an exploratory data analysis tool to identify growers who used similar weed management practices and to assign them to groups, to enable analysis of a complex data set through dimension reduction. Once grower respondents with similar weed management programs were grouped, farm operation and demographic characteristics could then be compared between groups. Cluster analysis groups objects (in this case, grower respondents) by comparing attributes of individuals and maximizing similarity within a group while minimizing similarity between groups, based on computed distances (Kaufman and Rousseeuw 2005). Cluster analysis has been used in previous studies to analyze survey data by identifying groups of producers with similar management practices (DeDecker et al. 2014; Sellmer et al. 2004). Hierarchical agglomerative cluster analysis using the average-linkage-between-groups method and simple matching distance measures (Norusis 2008) was performed using the IBM Statistical Package for the Social Sciences (IBM SPSS Statistics for Windows, Version 22.0. Armonk, NY, IBM Corp.) to group respondents by their use (or non-use) of the 13 weed management practices included in the survey. Use was coded as a binary variable, with “1” indicating use on certified organic land and “0” indicating no use on certified organic land. Exploratory hierarchical agglomerative cluster analysis identified three distinct groups of growers, and members of those three groups generally used a total number of weed control practices within a certain range according to the group; however, some outliers were found within groups. Therefore, k-means cluster analysis was performed, where the number of groups
is defined (Norusis 2008) and was set to 3 according the findings of hierarchical clustering. Sturn et al. (2002) recommend the use of hierarchical clustering as a data exploration tactic to define the number of groups present, followed by k-means clustering, to increase clustering accuracy. The three groups identified by k-means cluster analysis were used to identify ranges of the total number of weed control practices for each group (found by summing the number of weed control practices used per respondent), with “low,” “medium,” and “high” intensity of weed management (Table 2).

The three groups of growers defined by k-means cluster analysis were then treated as the independent variable “group” with three categories and cross-tabulated in SPSS with farm operation and demographic characteristics (e.g., history of land use, crop rotation, and farm products). Measures of association (Wald’s chi-squares) were used to identify differences between groups. Stepwise binary logistic regression in SAS with PROC GENMOD was used to determine which farm operation and demographic characteristics of organic growers were associated with group membership and, by extension, weed management program diversity. Knowler and Bradshaw (2007) state that regression analyses offer insight into adopter characteristics and are superior to using correlations and ordinary least squares methods alone to identify attributes that increase the probability of adoption of new technologies, as regression models generally imply causal relationships between dependent and independent variables. In this study, three models were created to compare 1) Group 1 to Group 2, 2) Group 2 to Group 3, and 3) Group 1 to Group 3. Group membership was the dependent variable and was treated as a dichotomous binary response variable (Villamil et al. 2012; DeDecker et al. 2014). Grower/farm operation characteristics, including certified organic land operated, type of crops produced, number of crops produced, age, years of experience farming, and education level were the
independent variables. A cutoff significance level of 0.05 was used for entry into the model, and odds ratios were calculated to assess the impact of characteristic factors on group membership/weed management practices employed.

Open-ended questions were coded by counting the number of times a response was mentioned. Percentages were calculated by dividing the number of times a response was mentioned by the number of respondents who answered the question.

Results and Discussion

A total of 157 complete responses to the survey were returned, for a response rate of 37.7%. Eighteen percent of responses were from growers in Idaho, 19% from Montana, 29% from Oregon, 5% from Utah, and 29% from Washington. The low number of responses returned from Utah was due to the low number of eligible growers identified in Utah (n=29), where arable land is restricted to the northern part of the state and the dry conditions limit cropping to dryland small grains such as wheat (Zollinger and Krannich 2001). Twenty-nine percent of respondents operated land under conventional management, in addition to organic management. The average amount of organic land operated was lowest in Washington (133 ha) and greatest in Utah (2,176 ha) (Table 3). Forty-eight percent of respondents grew grain crops, 48% grew forage crops, and 31% produced livestock on-farm in 2013.

Eighty-six percent of respondents were male and only 13% female. The percentage of female growers among organic farmers found in this survey was below the national average, as two national organic surveys conducted by the Organic Farming Research Foundation in 1997 and 2002 found that 21 to 24% of organic growers surveyed were female (Walz 1999, 2004). The grains- and forage-based crop production emphasized in this survey may explain the low number of female respondents, as women have been found to comprise a higher proportion of
organic horticulturalists when compared to conventional vegetable growers (Padel 2001). The mean age of respondents was 55 yrs, and respondents reported having been an owner, manager, or primary decision maker on a farm for an average of 28 yrs. Thirteen percent had completed a high school diploma or equivalent, 36% had pursued some post-secondary education, and 48% percent of respondents had completed a four-year college degree.

Weed Management Practices of Grower Groups

Three clusters were identified using hierarchical agglomerative cluster analysis (Figure 1) and refined using k-means cluster analysis. Growers within a cluster had similar average numbers of tillage controls, cultural controls, and total number of weed control practices, and these differed between clusters (Table 2). The number of weed control practices reported by grower respondents was the defining difference between groups, and indicated differences in the intensity of weed management practiced by the organic growers who responded to this survey. Group 1 growers reported use of 0 to 3 weed management practices, Group 2 growers reported use of 4 to 7 weed management practices, and Group 3 growers reported use of 8 to 13 weed management practices, which were defined as “low,” “medium,” and “high” management groups, respectively (Table 2).

Growers in the low management group (LMG) on average used 1.3 weed control measures, with a greater reliance on cultural controls. Sixty-nine percent of growers in the LMG used no mechanical control measures and 24% used one mechanical control measure, whereas 53% used 1 to 3 cultural control measures. Infrequent use of tillage in the LMG is likely due to a majority (85%) of growers in this group producing forage crops (alfalfa and grass hay). The perennial phenology of these crops makes preplant tillage impractical, and the use of secondary tillage implements may be viewed as unnecessary because perennial crops are generally very
competitive with weeds (Anderson 2010). Crop rotation was the most commonly reported (37%) cultural control in the LMG and, in the absence of mechanical controls, including perennial crops in the rotation is likely the primary or only weed control measure utilized by growers in the LMG. Of the 30% of growers in the LMG who did use tillage, the most common mechanical control used was preplant tillage. Grain producers in the LMG were more likely to use tillage than forage producers, though the use of cultural controls was similar between both types of farm operations.

Growers in the medium management group (MMG) used an average of 5.4 weed control measures and favored the use of cultural over mechanical controls, though use of both types of controls was greater than those in the LMG. Sixty-nine percent of growers in the MMG used two or more mechanical controls and 84% used three or more cultural controls to manage weeds. Almost all (95%) growers in the MMG reported using crop rotation, and 72% used an increased seeding rate to increase crop competitiveness with weeds. Cover cropping as a weed control measure was used by 59% of respondents, indicating that growers view cover cropping as a weed management practice in addition to other benefits cover crops may provide, such as erosion mitigation and soil improvement.

The most common mechanical control used by growers in the MMG was preplant tillage (84%), followed by the tine weeder (29%) and rod weeder (27%). Rod weeding typically takes place before planting to create a stale seedbed (Bond and Grundy 2001) or in fallow to control weeds, and can be found on conventional farm operations in the region. Tine weeders are generally not used on conventional farm operations, and are used as a secondary tillage field operation to control both intra- and inter-row weeds after the crop has emerged (Bowman 2002).
The MMG included both forage (77%) and grain (61%) growers, and use of rod and tine weeders was reported on both types of farm operations.

Growers in the high management group (HMG) used 9.0 weed control measures on average and five (61%) or six (29%) cultural control measures out of the six included in the survey. All respondents in the HMG reported using crop rotation, selection of competitive crop varieties, and cover crops; 97% used increased seeding rates, 74% used residue mulch, and 48% used relay- or inter-cropping as cultural weed control measures. While producers in the HMG preferred the same mechanical controls most commonly used by growers in the MMG (94% used preplant tillage, 65% a tine weeder, and 61% a rod weeder), rates of usage of all mechanical controls included in the survey were higher in the HMG. In particular, use of a root undercutter was much more common in the HMG than the MMG.

Farm Operation Characteristics of Grower Groups

Differences in cropping regimes existed between groups and could drive weed management decisions made by growers. Growers in the MMG and HMG used more control measures and were significantly more likely (p = 0.007) to produce both grain and forage crops than growers in the LMG, who were unlikely to grow grain crops and tended toward forage production (85% of LMG growers) (Table 4). The number of certified organic crops produced in one year differed between groups, with HMG growers producing the most and LMG growers the fewest (Table 4). The choice to produce organic grain crops and the number of certified organic crops produced in one year was correlated with a greater number of weed control measures used, as the likelihood of a grower to produce grain crops, and a greater number of crops within one year, increased as weed management program diversity increased (Table 4).
Differences in innate crop competitiveness can determine the necessity of deliberate weed control measures taken by the grower. For example, alfalfa is generally more competitive with weeds than winter wheat and therefore not as much benefit would be incurred from a “responsive” mechanical control measure taken in alfalfa as it would be in wheat. Forage crops such as alfalfa and grass mixes are fairly competitive with weeds, and weed control often has little effect on yield in an established stand (Dillehay et al. 2011). However, as a farm becomes more diversified (i.e., growing both grains and alfalfa), the efficacy and applicability of weed control measures is variable between crops, possibly necessitating the use of more diverse measures on different crops grown within a year. As alfalfa and grass hay were the most common forage crops produced by growers in the LMG, it is possible that the perception of the low impact and necessity of weed control measures in forage crops compared to grain crops is driving the difference in weed management intensity between the LMG and the other two groups. Fewer LMG growers reported “weed-related production losses” to be a “moderate to considerable” challenge to their organic farm operation, compared to MMG and HMG growers. However, LMG growers reported “variable or low yields” to be a “moderate or considerable” challenge at the same rates as MMG and HMG growers and did not report fertility or inputs to be a problem, indicating that weeds may be causing yield losses for LMG growers, but are not recognized as a yield-reducing factor. LMG growers producing only forages were not restricted to regions where alfalfa and hay monocultures are the predominant agricultural production system and grain production is rare due to climate conditions (such as southern Idaho). Rather, LMG growers were found throughout the five-state survey area, indicating that many chose not to produce grain crops where it was possible to do so. Cropping choice on organic farms is likely impacted by factors other than regional climate and soil differences.
Demographic Characteristics of Grower Groups

Gender was similar among management groups (p = 0.393), which was not surprising given the low number of female respondents (n=20). Years of farming experience was also similar among management groups (p = 0.1815), which differs from the findings of DeDecker et al. (2014), who found years of farming experience to be positively correlated with more complex weed management programs. However, growers in the HMG were more likely to have completed a four-year college degree or higher level of education than growers in the LMG (Table 5). A relationship between education and greater adoption of new “technologies” was also observed by Burton et al. (1999), Duram (1997), and Genius et al. (2006), who found that younger, more educated growers were more likely to adopt new management practices. While noting that farm operations within any management regime are highly diverse from farm to farm, these findings suggest that a technology adoption continuum exists even among those growers who have adopted the “innovation” of organic farming (Rogers 2003). Education was also positively correlated with the number of certified organic crops grown on organic farms, suggesting that more educated organic growers managed more diversified farm operations, who then practiced more diversified weed management practices. Agroecosystem diversity is a pillar of the organic agricultural paradigm (Gomiero et al. 2008), though the results of this survey suggest that crop diversity on organic farms is variable and may be connected to certain demographic characteristics, like education level. Higher levels of education among HMG growers may enable them to manage more complex systems and a greater land area under organic cropping (Table 5) compared to their less-educated peers, and may be a driver of greater innovation when designing weed management programs. Daberkow and McBride (2003) also found that grower education level and farm size were related to adoption of new technologies. A
greater willingness to handle complex systems and to employ more diverse weed management methods may be a factor in the decision to add small grains to organic rotations and manage larger certified organic farms in the northwest U.S. Alternatively, larger farms could have more staff to manage decision-making and carry out field operations, which could enable a grower to practice a more diverse weed management program.

Stepwise Binary Logistic Regression

The three groups identified by cluster analysis necessitated that three binary logistic regression models be created, to compare the 1) LMG to MMG, 2) MMG to HMG, and 3) LMG to HMG. No farm operation or demographic characteristics met the 0.05 significance level cutoff for entry into the model comparing the LMG to the MMG, though differences in crops produced between the LMG and MMG were detected using ANOVA (Table 4). In the second and third models, HMG growers were more likely to produce grain crops, produce a greater number of certified organic crops in one year, and to have completed a four-year college degree than MMG (Table 6) and LMG growers (Table 7). The likelihood of HMG growers operating more diversified farms and to be more educated was greater when compared to the LMG than the MMG (Tables 6 and 7). The percentage of growers who produced both types of crops increased with the number of weed control measures used (21% of LMG, 43% of MMG, and 54% of HMG). The number of certified organic crops produced in one year was a significant predictor of membership in the MMG or HMG over the LMG. Mean numbers of products produced in one year were 2.7 in the LMG, 3.6 in the MMG, and 6.8 in the HMG. Forage production was not a significant predictor of group membership in the model because most growers in the MMG and HMG rotated forages with grains. The models indicate that these factors increase the likelihood that organic growers use eight or more weed control measures in their certified organic crops and
utilize the IWM approach to a greater extent by practicing a more diverse weed management program, and could be due to greater knowledge or skill in managing complex agricultural systems or to the necessity of different types of weed controls in different crops.

The finding that education level is positively associated with technology adoption has been observed in other studies (Warriner and Moul 1992; Daberkow and McBride 2003; DeDecker et al. 2014), and can improve the ability of an individual to access and interpret more information.

Very few studies on grower adoption have examined crop rotation as a factor related to adoption. In a review of studies on adopter characteristics, Knowler and Bradshaw (2007) found only 3 of 31 studies examined cropping system/crop rotation as related to new agricultural practices, and that all three of those studies found it to be an insignificant predictor of adoption, contrary to the findings of this study. The finding in this study that producing grain crops as well as a greater number of crops within a year was a significant predictor of more diverse weed management methods undertaken is likely related to the specificity of weed management methods within a crop. While certified organic hectarage operated was found to be greater among HMG growers using ANOVA analysis, farm size did not significantly increase the likelihood of HMG membership in the logit model. Knowler and Bradshaw (2007) found variable results in farm size being related to adoption of new agricultural practices, and the findings of this study do not conclusively indicate that the amount of certified organic land operated increases the probability of practicing a more diverse weed management program, though a correlation was observed.

Research Needs of Organic Growers

Respondents most commonly mentioned Canada thistle [Cirsium arvense (L.) Scop.] (30%) as a weed that has proven difficult to control on certified organic land. Field bindweed was the next most commonly-mentioned weed (24%), followed by thistle spp. (18%), mustards
(Brassica spp.) (14%), and pigweeds (Amaranthus spp.) (12%). While the most commonly mentioned species were all broadleaf weeds, several species of annual and perennial grasses were mentioned by growers as well, including wild oat (Avena fatua L.), jointed goatgrass (Aegilops cylindrica Host), and quackgrass [Elymus repens (L.) Gould]. The perennial broadleaf weeds Canada thistle and field bindweed were the most commonly-reported weeds in all states surveyed; however, some annual weeds were mentioned more often in some states than others. For example, Brassica species were reported as problematic in Oregon and Washington only, and kochia [Kochia scoparia (L.) Schrad.] was mentioned by respondents in Idaho.

Methods to control the perennial weeds field bindweed and Canada thistle was the most common area of weed control need that growers reported needed addressing by university researchers and Extension agents. Other surveys of organic growers have found that perennial weeds are the most troublesome and difficult to control (Entz et al. 2001; Turner et al. 2007), indicating that research in this area is required and desired by organic growers. Interestingly, lower counts of perennial weed control mentions were found among LMG growers. Only 4% of LMG growers mentioned controlling field bindweed and 7% controlling Canada thistle as a research need, compared to 24% and 17% in the MMG and 38% and 28% in the HMG, respectively, which suggests that growing perennial forage crops, such as alfalfa or grass hay, can mitigate perennial weed pressure. Correspondingly, HMG growers mentioned most often that research was needed into cultural or systems approaches to weed management, and mentioned least needing more organic-approved weed control sprays, compared to LMG and MMG growers. These findings suggest that one-size-fits-all prescriptions for organic weed management will not be appropriate for all growers, and that a variety of practices must be developed that is appropriate for the crop rotation being used.
Results of this survey indicate that cropping practices, including grain production and the number of crops produced, in addition to the demographic characteristics education level and farm size traditionally thought to influence adoption of new technologies (Rogers 2003), are associated with organic weed management decisions and the diversity of weed control measures used on certified organic farms in the northwest U.S. Regression analysis found education level, grain production, and the number of crops produced within a year, to be positive predictors of certified organic growers managing more diversified weed management programs. Should an organic grower be contemplating added grains to a forage-only rotation, the results of this survey suggest that diversifying the weed management program will be necessary to manage weeds in grain crops. Furthermore, an awareness of weeds causing production losses was correlated with a grower utilizing a more diverse weed management program. Growers in the LMG, who used few weed control practices reported variable or low yields to be challenges at the same rate as growers in the MMG and HMG, who used more weed control practices, but did not attribute yield losses to weeds (or organic inputs, like fertility) at the same rates as MMG or HMG growers. These findings suggest that awareness of weeds causing yield loss in organic systems may be correlated with more diversified weed management programs.

Survey responses reveal that growers in the northwest U.S. are operating large areas under organic management. Consequently, researchers should address and investigate issues surrounding organic forage and small grains production, in addition to organic horticultural farms that traditionally have represented organic agriculture. Such knowledge could enable Extension agents and organic farming groups in the region to improve weed management on organic farms by identifying specific organic weed management practices appropriate for different types of farm operations, and to target knowledge-sharing within grower groups.
Research into IWM approaches could also hold relevance for conventional grain and forage producers in the region looking to diversify weed management practice in the face of the development of herbicide resistance in weeds.
**Literature Cited**


Carolan MS (2005) Barriers to the adoption of sustainable agriculture on rented land: an examination of contesting social fields. Rural Sociol 70:387–413


Liebman M, Davis AS (2000) Integration of soil, crop and weed management in low-external-
input farming systems. Weed Res 40:27–47


**Table 1.** Weed control practices included in survey questionnaire. Options to select for each field operation were 1) used only on certified organic land, 2) used only on conventional land, 3) used on both types of land, and 4) used on no land, within a respondent’s farm operation. For analysis, options 1) and 3) were pooled to indicate if a grower used the weed control practice on their certified organic land, whereas options 2) and 4) were pooled to indicate non-usage on certified organic land.

<table>
<thead>
<tr>
<th>Type of Weed Control</th>
<th>Weed Control Practice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical</td>
<td>Rod weeder</td>
</tr>
<tr>
<td></td>
<td>Tine weeder</td>
</tr>
<tr>
<td></td>
<td>Rotary hoe</td>
</tr>
<tr>
<td></td>
<td>Inter-row cultivation</td>
</tr>
<tr>
<td></td>
<td>Root undercutter</td>
</tr>
<tr>
<td></td>
<td>Rotary harrow</td>
</tr>
<tr>
<td>Cultural</td>
<td>Crop rotation</td>
</tr>
<tr>
<td></td>
<td>Relay- or inter-crop</td>
</tr>
<tr>
<td></td>
<td>Increased seeding rate</td>
</tr>
<tr>
<td></td>
<td>Selection of competitive varieties</td>
</tr>
<tr>
<td></td>
<td>Residue mulch</td>
</tr>
<tr>
<td></td>
<td>Cover crop</td>
</tr>
</tbody>
</table>
Table 2. Clusters identified following k-means cluster analysis, using total number of mechanical and cultural control practice ranges as cutoffs.

<table>
<thead>
<tr>
<th>Cluster</th>
<th>n</th>
<th>Weed Management Program Diversity</th>
<th>Total Number of Weed Control Practices</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>51</td>
<td>Low</td>
<td>0-3</td>
</tr>
<tr>
<td>2</td>
<td>62</td>
<td>Medium</td>
<td>4-7</td>
</tr>
<tr>
<td>3</td>
<td>31</td>
<td>High</td>
<td>8-13</td>
</tr>
</tbody>
</table>
Table 3. Mean and median certified organic hectarage reported by survey respondents in five states.

<table>
<thead>
<tr>
<th>State</th>
<th>Mean</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>Idaho</td>
<td>217</td>
<td>105</td>
</tr>
<tr>
<td>Montana</td>
<td>1,526</td>
<td>566</td>
</tr>
<tr>
<td>Oregon</td>
<td>235</td>
<td>129</td>
</tr>
<tr>
<td>Utah</td>
<td>2,176</td>
<td>2,058</td>
</tr>
<tr>
<td>Washington</td>
<td>133</td>
<td>69</td>
</tr>
<tr>
<td>All States</td>
<td>541</td>
<td>142</td>
</tr>
</tbody>
</table>
**Figure 1.** The dendrogram solution from hierarchical agglomerative cluster analysis. Clusters are labeled with names assigned to groups following analysis of the number of weed control practices used, within each group. LMG = low management group, MMG = medium management group, HMG = high management group.
Table 4. Crop type and number produced by respondents in three weed management groups.

LMG = low management group, MMG = medium management group, HMG = high management group.

<table>
<thead>
<tr>
<th>Organic Products</th>
<th>LMG</th>
<th>MMG</th>
<th>HMG</th>
<th>$\chi^2$</th>
<th>$P &gt; \chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grains</td>
<td>33 c</td>
<td>61 b</td>
<td>83 a</td>
<td>20.992</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Forage</td>
<td>85 a</td>
<td>77 a</td>
<td>67 a</td>
<td>3.549</td>
<td>0.107</td>
</tr>
<tr>
<td>Grains+Forage</td>
<td>21 b</td>
<td>43 a</td>
<td>53 a</td>
<td>9.855</td>
<td>0.007</td>
</tr>
<tr>
<td>No. Crops</td>
<td>2.7 c</td>
<td>3.6 b</td>
<td>6.8 a</td>
<td>60.804</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

*Percentage of respondents who produced organic products within each management group.*

*Letters denote significant differences between management groups at the $\alpha = 0.05$ level.*

*The number of organic crops and animal products produced in one year.*
Table 5. Demographic characteristics of organic growers in three management groups. LMG = low management group, MMG = medium management group, HMG = high management group.

<table>
<thead>
<tr>
<th>Demographic Characteristics</th>
<th>Units&lt;sup&gt;a&lt;/sup&gt;</th>
<th>LMG</th>
<th>MMG</th>
<th>HMG</th>
<th>F Value</th>
<th>P &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic Area Operated</td>
<td>Hectares</td>
<td>880 b&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1165 b</td>
<td>1890 a</td>
<td>3.42</td>
<td>0.0356</td>
</tr>
<tr>
<td>Age</td>
<td>Years</td>
<td>58 a</td>
<td>54 a</td>
<td>51 b</td>
<td>3.08</td>
<td>0.0489</td>
</tr>
<tr>
<td>Farming Experience</td>
<td>Years</td>
<td>31 a</td>
<td>26 a</td>
<td>27 a</td>
<td>1.73</td>
<td>0.1815</td>
</tr>
<tr>
<td>Education&lt;sup&gt;c&lt;/sup&gt;</td>
<td>%</td>
<td>37 b</td>
<td>48 ab</td>
<td>68 a</td>
<td>7.18&lt;sup&gt;d&lt;/sup&gt;</td>
<td>0.0280</td>
</tr>
</tbody>
</table>

<sup>a</sup> Units of means within weed management groups.

<sup>b</sup> Letters denote significant differences between management groups at the α = 0.05 level.

<sup>c</sup> Coded as a dichotomous binary variable with “1” = four-year college degree or higher, and “0” = less than a four-year college degree. Cross-tabulation (IBM Corp.) was performed to compare means between groups.

<sup>d</sup> Pearson chi-squared statistic from cross tabulation; p-value is for P > χ².
Table 6. Parameters obtained from stepwise binary logistic regression for membership of the high management group (HMG), over the medium management group (MMG). Group membership was a dichotomous response variable with “1” = HMG membership and “0” = LMG membership.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate</th>
<th>Standard Error</th>
<th>Wald $\chi^2$</th>
<th>$P &gt; \chi^2$</th>
<th>Odds Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-2.060</td>
<td>0.615</td>
<td>11.20</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Grain</td>
<td>1.151</td>
<td>0.573</td>
<td>4.04</td>
<td>0.044</td>
<td>0.760</td>
</tr>
<tr>
<td>No. Crops$^a$</td>
<td>0.290</td>
<td>0.082</td>
<td>12.58</td>
<td>&lt;0.001</td>
<td>0.572</td>
</tr>
<tr>
<td>Education$^b$</td>
<td>0.878</td>
<td>0.493</td>
<td>3.16</td>
<td>0.075</td>
<td>0.706</td>
</tr>
</tbody>
</table>

$^a$ The number of organic crops and animal products produced in one year.

$^b$ Coded as a dichotomous binary variable with “1” = four-year college degree or higher, and “0” = less than a four-year college degree. Cross-tabulation (IBM Corp.) was performed to compare means between groups.
Table 7. Parameters obtained from stepwise binary logistic regression for membership of the high management group (HMG), over the low management group (LMG). Group membership was a dichotomous response variable with “1” = HMG membership and “0” = LMG membership.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate</th>
<th>Standard Error</th>
<th>Wald $\chi^2$</th>
<th>P &gt; $\chi^2$</th>
<th>Odds Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-4.057</td>
<td>0.881</td>
<td>21.22</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Grain</td>
<td>1.480</td>
<td>0.665</td>
<td>4.96</td>
<td>0.026</td>
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$^a$ The number of organic crops and animal products produced in one year.

$^b$ Coded as a dichotomous binary variable with “1” = four-year college degree or higher, and “0” = less than a four-year college degree. Cross-tabulation (IBM Corp.) was performed to compare means between groups.
CHAPTER 3

Competitive Ability of Rotational Crops with Weeds in Dryland Organic Wheat Production Systems

Abstract

While demand continues to grow and prices for organic grains have remained almost double those of conventional grains, few growers in the dryland wheat production region of eastern Washington produce organic grain. Growers have cited weed control constraints as a top factor preventing adoption of organic production practices. In organic systems, inherent competitive ability of crops is very important in managing and preventing weed infestations. The objective of this study was to identify crop species that could reduce weed pressure and compete with perennial weeds in a wheat (*Triticum aestivum*) rotation. To assess weed suppressive ability of alternative rotational crops, relative total weed biomass and relative biomass of two perennial and three annual weed species were examined over four years in three organic cropping systems where winter wheat was in rotation with alternative crops, as part of a long-term study examining dryland organic wheat production. Three years of continuous alfalfa (*Medicago sativa*) production reduced Canada thistle (*Cirsium arvense*) biomass during the alfalfa production phase, and reduced Canada thistle biomass in winter wheat following alfalfa, compared to wheat following winter pea (*Pisum sativum*). Alfalfa was competitive with wild oat (*Avena fatua*), though it competed poorly with winter annual grass weeds. Spring barley (*Hordeum vulgare*), when established successfully, suppressed jointed goatgrass (*Aegilops cylindrica*) more than winter triticale (*x Triticosecale*), winter wheat, and spring wheat, and demonstrated some competitiveness towards field bindweed (*Convolvulus arvensis*). Winter triticale competed
poorly with field bindweed, but suppressed Canada thistle and downy brome (*Bromus tectorum*). All alternative rotational crops contained lower weed biomass than winter pea, the crop typically rotated with wheat in the region. Organic and conventional growers could gain benefits in perennial and winter annual weed suppression by incorporating alternative rotational crops into wheat rotations.
Introduction

The deep loess soils of the Palouse region of eastern Washington and northern Idaho produce world record dryland winter wheat yields (Schillinger et al., 2006). However, adoption of certified-organic grain production in Washington remains low, despite growing demand for organic small grains. Sales of organically-produced bread and grain have more than doubled in the past decade in the U.S. (Greene, 2014), and meat and dairy producers have struggled to source organic feed as a result of low organic grain production (Greene et al., 2009). Of the 950,000 hectares of winter wheat harvested in Washington in 2011, less than 0.1% of that area was planted to organic wheat (USDA-NASS, 2012). Washington wheat growers reported inadequate organic weed and pest control methods as the main barriers to organic grain production (Jones et al., 2006).

Weeds serve as the primary barrier to conversion to organic production for most regions (Bond and Grundy, 2001; Rodriguez et al., 2009), and there have been calls for more holistic research into weed management in organic systems (Barberi, 2002; Sooby et al., 2007). Reviews of non-chemical weed management emphasize the use of mechanical and cultural controls, including pre-plant tillage, deep ploughing, increased seeding rate, maintaining residue mulch, and cover cropping (Bond and Grundy, 2001; Mason and Spaner, 2006, Brainard et al., 2013). In place of herbicides, organic growers rely mostly on pre-plant and in-crop tillage to control weeds, using harrows, hoes, and inter-row cultivators. The use of these types of mechanical controls is more restricted on the Palouse, where tillage on the steeply-sloped hills raises soil conservation concerns (Schillinger et al., 2007). Cover cropping is not practiced on the Palouse, an area that receives less than 600 mm of rain a year, due to the risk that cover crops could deplete too much soil moisture prior to the grain crop. However, crop diversification can reduce
the need for mechanical weed controls by altering control measures and crop life cycles from year to year, especially when perennial forages are integrated into a rotation (Liebman and Davis, 2000). Crop rotation is an important, established weed management tool that offers growers the opportunity to manage weeds when producing organic grains. Typically, growers use a three-year winter wheat/spring wheat/spring pea, chickpea (*Cicer arietinum*), or lentil (*Lens culinaris*) rotation to alter planting times year to year in order to mitigate pressure from winter annual weeds (Papendick, 1996). In this rotation, pressure from spring annual weeds lowers yields in organic spring cereals, especially spring wheat (Manuchehri et al., 2012). Rotating away from spring cereals to winter cereals or a legume crop leads to increased competition with spring-emerging weeds, which is critical for managing wild oat (Harker et al., 2009).

An added challenge in converting from conventional to organic production is the shift in weed species and weed community composition, which requires changing management tactics to target specific weed species. Growers who have transitioned land from conventional to organic production have reported differences in weed communities following the transition. A survey comparing weeds on organic and conventional farms on the eastern Canadian prairie found that Canada thistle, wild mustard (*Sinapis arvensis*), redroot pigweed (*Amaranthus retroflexus*), and common lambsquarters (*Chenopodium album*) were much more prevalent in organic than conventional systems (Entz et al., 2001). In reduced- or no-till organic systems, perennial weeds have been reported as the most problematic for organic producers to control (Samuel and Guest, 1990; Légère et al., 2013), and can imperil the survival of an entire organic operation. Sooby et al. (2007), following a series of meetings with organic producers, identified the need for research into crop rotation and other system-wide approaches for managing the perennial weeds bindweed.
and Canada thistle. A survey of certified organic small grains and forage producers in the northwestern U.S. found that field bindweed and Canada thistle were the most problematic weed species in those organic systems (Tautges and Goldberger, 2015). Where reduced- or no-till is practiced in organic systems, adding competitive crop species to rotations is one of few cultural weed management inputs that could have an impact on reducing perennial weed populations.

Certain cereal crops, like barley and triticale, have greater competitive ability with weeds than wheat and incorporating them into the rotation could provide a year of successful competition with weeds. Triticale, a hybrid of rye (Secale cereale) and wheat, grows taller than wheat and forms a canopy that intercepts more light, a characteristic associated with reducing weed dry matter and the number of weed inflorescences (Cosser et al., 1997). Triticale has been found to compete well with both monocot and dicot weeds when tall winter varieties were planted, with competitive attributes comparable to those of rye (Beres et al., 2010). On the Palouse, cereal or feral rye (Secale cereale) is a troublesome weed in winter wheat, and therefore is not a viable candidate for a rotational crop in organic systems. Triticale has attributes similar to rye but will not contribute to feral rye weed populations, and an emerging market for triticale in Washington makes it a more acceptable crop for growers to plant than rye.

A study in Manitoba, Canada, found that winter triticale in rotation with field pea competed with weeds more successfully than single-year alfalfa, winter rye, or wheat preceding pea (Schoofs and Entz, 2000). Beres et al. (2010) observed lower relative weed biomass in tall winter triticale compared to wheat, and similar relative weed biomass between short triticale and wheat in a study in Alberta, Canada. Weed biomass accumulation in barley was also very low, and barley was found to compete with dicot weeds, despite being the shortest cereal in the study (Beres et al., 2010). Barley cultivars grown on the Palouse are generally shorter than wheat;
however, Bertholdsson (2005) observed that barley competed more effectively with weeds than wheat, likely as a result of early, rapid accumulation of biomass and possible allelopathy. Spring barley has historically been a part of wheat rotations on the Palouse and so could be a viable rotational crop with wheat in the region.

Alfalfa as a rotational crop has the potential to compete strongly with weeds and reduce weed populations in cereal rotations. While the low levels of precipitation inherent to dryland systems will limit alfalfa hay yields, alfalfa’s extensive root system can tap into water deep below ground that is inaccessible to other plants and thereby outcompete weeds. Alfalfa has been found to decrease weed seed production and emergence in low-input corn and soybean rotations (Clay and Aguilar, 1998; Kegode et al., 1999) by increasing the variance of crop phenological cycles. When comparing the competitive ability of alfalfa across several studies, three years of alfalfa cropping decreased weed seedling emergence by an average of 75% (Anderson, 2010). A study of 24 organic winter wheat fields found that an alfalfa crop preceding winter wheat limited weed density in the winter wheat crop, especially for spring-emerging weeds (David et al., 2005).

In eastern Washington, wild oat, downy brome, and jointed goatgrass are the most prevalent winter annual weeds found in cereal cropping systems (Young and Thorne, 2004; Schillinger and Papendick, 2008), and proliferate in the winter wheat crop of cereal rotations. Canada thistle and field bindweed have been reported to be the weeds most problematic for organic producers to control (Tautges and Goldberger, 2015). Before the advent of herbicides to control Canada thistle and field bindweed, these perennial weeds caused yield losses in small grains ranging from 20 to 90% (Freed, 1980; Jacobs, 2007). Any cropping system designed to produce organic cereals in eastern Washington must be competitive with these weed species in order to be productive and feasible.
A 7-year cropping systems study was conducted from 2008 to 2014 in eastern Washington to compare cereal grain yields, soil quality, and weed pressure in three organically-managed crop rotations with varying fertility sources, and two conventionally-managed rotations. Here, we will focus on weed biomass found in the organic crop rotations, with the objective of determining which rotations, and specifically which rotational crops, reduce overall weed pressure in the grain crop and compete well with winter annual and perennial weeds.

**Materials and Methods**

**Site Description**

Research was conducted at a site near Pullman, WA (46°45′N; -117°4′W) in the Palouse region of eastern Washington. The field was situated on a west-facing slope on a Palouse silt loam soil (fine-silty, mixed, superactive, mesic Pachic Ultic Haploxerolls). Average annual precipitation for the area is 509 mm with the majority falling between November and March (Gallagher et al., 2010). The field had been transitioned to certified organic management during a crop rotation study conducted from 2003 to 2007 (Gallagher et al., 2010; Borrelli et al., 2012; Borrelli et al., 2014), and organic certification was maintained throughout the duration of the study.

**Cropping Systems Design**

Crop rotations were designed to optimize winter wheat production, the main cash crop in the area, and included a variety of rotational crops to test their ability to build soil fertility and compete with weeds (Gallagher et al., 2010). Reduced-tillage was practiced on this study, where all tillage operations were performed to a maximum depth of 10 cm in order to minimize erosion on the slope where this study was located. In eastern Washington, low precipitation levels in the summer restrict crop choices in rotations as crops dependent on summer rainfall, like forages, are
generally low-yielding. Past studies have identified winter pea and alfalfa as legumes that achieved the greatest biomass production, weed suppression, and soil nitrogen levels (Gallagher et al., 2010; Borrelli et al., 2012). System 1 was a five-year alfalfa (cv. ‘Ladak’)/orchardgrass (Dactylis glomerata)-alfalfa/orchardgrass-alfalfa/orchardgrass-winter wheat (cv. ‘Brundage 96’)-spring barley (cv. ‘Bob’) rotation. In the establishing alfalfa year, orchardgrass was planted with alfalfa to increase crop competition with weeds. However, as orchardgrass comprised less than 10% of standing biomass in Year 2 and Year 3 alfalfa, the three years of alfalfa/orchardgrass cropping in System 1 will be referred to as “establishing alfalfa,” “Year 2 alfalfa,” and “Year 3 alfalfa.” System 2 was a two-year winter triticale (cv. ‘Trimark 336’)-winter pea hay (cv. ‘Windham’) rotation, and System 3 was a three-year winter wheat (cv. ‘Brundage 96’)-spring wheat (cv. ‘Kelse’)-winter pea hay (cv. ‘Windham’) rotation (Table 1).

System 1 was intended to represent an “alternative” forage rotation. Alfalfa production is not common on the Palouse, but is grown where a hay market is accessible. System 2 was designed around winter triticale, in an attempt to assess the competitive ability of winter triticale with field bindweed, which was prevalent on site. Winter triticale was considered for a perceived ability to compete successfully with field bindweed, as field bindweed leaves have been reported to be intolerant to shade (Jacobs, 2007) and winter triticale accumulates biomass early in the season. System 3 was included to represent the most common rotation on the Palouse, where wheat is rotated with a spring pulse crop, though in this rotation winter pea was planted and cut for hay to increase competitiveness with weeds and integrate a mechanical input. A quail farm nearby provided composted quail manure for the study, which was applied as an added source of nitrogen (N) just after planting spring barley in System 1, winter triticale in System 2, and winter and spring wheat in System 3 (Table 1). Manure application rates were calculated based on crop
yield goals and residual soil N levels and ranged between 2250 and 4850 kg manure ha\(^{-1}\) to supply 115 to 250 kg N ha\(^{-1}\). The trial was arranged in a randomized complete block design with 5 blocks. The three cropping systems were planted with a staggered start, where the rotations were initiated at the different cropping phases, so that crops within the rotations were replicated in time and space (Posner et al., 2008) (Table 1). The seedbed was prepared to a six-inch depth with a sweep plow and a rotary harrow. Crops were planted with a Fabro minimum disturbance double disc drill with 19 cm row spacing (Fabro Enterprises Ltd., Swift Current, SK, Canada). All organic systems were rotary hoed 1 to 4 times as needed after planting to control weeds (Table 2). System 3 winter pea was cut for hay with a swather at first- or mid-bloom. Establishing alfalfa did not accumulate enough biomass to cut for hay, and was rotary mowed to control weeds. Year 2 and Year 3 alfalfa in all three system replicates yielded one to two cuts per year, depending on summer precipitation.

Data Collection and Analysis

Legume crops were harvested at early bloom, which occurred between 1400 and 1750 accumulated growing degree days, depending on the year. Weeds were sampled just before legume harvest and used to measure the peak weed biomass accumulation in those crops, as little regrowth was observed after cutting. Weed biomass in the grain crops was collected between 2700 and 3150 growing degree days, when biomass accumulation peaked, but before crop and weed dry-down. Three 0.1-m\(^2\) quadrats were collected per plot and combined. Plants were collected at ground level and samples sorted by separating crop from weed and then separating weeds by species. Samples were dried in an oven for 3 days at 55°C and biomass was recorded by species. Though the study began in 2008, complete weed biomass sampling was not
performed until 2011. Therefore, analysis will be presented for weed biomass data from 2011 through 2014.

Statistical analysis of weed biomass data was performed using the Mixed procedure in SAS (SAS Institute Inc., 2012). Block was treated as a random effect and crop within system and year were treated as fixed effects. Due to the variance in precipitation between years, there was a significant interaction between crop within system and year. Consequently, weed biomass will be calculated as a percentage of total standing biomass to standardize between years, using the equation:

\[
\text{Relative Weed Biomass (\%) = } \frac{B_i}{B_t}
\]  

where \( B_i \) is the aboveground biomass of the \( i \)th weed species and \( B_t \) the total amount of aboveground biomass, including weed and crop, within a plot. Relative weed biomass computed for crops within systems was then averaged across the four years of the study. Relative biomass percentages were transformed using the arcsine square root function to decrease heteroscedasticity (Derksen et al., 1995) where ANOVA was performed.

As the cropping systems in this study were developed as part of a larger study, not all rotational crops included in this paper were followed directly by winter wheat. Therefore, this paper will consist of two parts: in the first, relative weed biomass in the legume rotational crops alfalfa (System 1) and winter pea (System 3) will be compared, and the residual weed suppressive effects will be compared in the following winter wheat crop (winter wheat following alfalfa vs. winter wheat following winter pea). In the second part, relative weed biomass in the rotational grain crops spring barley and winter triticale will be compared within the crop only, as these crops are not followed by wheat in the rotations as they were originally designed.
Results and Discussion

Annual precipitation was highly variable during the period from 2011 to 2014 (Figure 1). Monthly distribution of rainfall also varied between years, and impacted both crop and weed biomass accrual. In eastern Washington, precipitation falling between November and April largely determines soil moisture levels available to crops in the summer, and so weed biomass accumulation generally followed moisture patterns. For example, weed biomass accumulation was greatest in System 1 alfalfa, winter wheat, and spring barley, System 2 winter triticale, and System 3 winter wheat and winter pea (Table 3) in 2012, when spring rain deposition was greater that year than it was in 2011, 2013, and 2014 (Figure 1).

Legume Rotational Crops: Alfalfa and Winter Pea

Establishing alfalfa (Year 1) did not compete well with weeds due to late emergence and a failure to reach canopy closure. Slow alfalfa establishment was likely a result of the low soil pH (5.5 to 6.0) inherent to the site, as alfalfa yield decreases have been observed in soils with pH values lower than 6.5 (Vitosh et al. 2000). In the establishment year, weed biomass comprised 75 to 89% of the stand (Table 3), with weed pressure coming mainly from common lambsquarters, field bindweed, Canada thistle, and downy brome. Despite the difficulty of establishing a stand, once developed, alfalfa yielded 3500 to 6800 kg ha\(^{-1}\) in one to two cuttings (depending on the year). After establishment, Year 2 and Year 3 alfalfa was competitive with weeds, limiting weed biomass accumulation to 10 to 22% of aboveground biomass, depending on the year (Table 3). Field bindweed, Canada thistle, and downy brome biomass comprised 9, 7, and 11% of total standing biomass, respectively (Figure 2). However, by the end of alfalfa cropping phase, relative weed biomass of the two perennial weeds, field bindweed and Canada thistle, was lower than in establishing alfalfa (Figure 2) and comprised 1% or less of total standing biomass. By
contrast, alfalfa failed to compete with the winter annual grasses downy brome and jointed goatgrass. Relative weed biomass of downy brome and jointed goatgrass did not change during the three years of alfalfa production (Figure 2). The lack of competition by alfalfa with downy brome and jointed goatgrass was likely due to the early emergence and biomass accumulation of the winter annual grasses.

Relative weed biomass was, overall, greater in System 3 winter pea than in System 1 third-year alfalfa. Relative weed biomass ranged from 30% in a dry year (2014) up to 89% in a wet year (2012) in winter pea (Table 3). While pea is not considered to be an especially competitive crop with weeds compared to cereals (Blackshaw et al. 2007), Canada thistle pressure was moderate in winter pea, comprising 0 to 5% of total standing biomass in the three years System 3 winter pea was grown, which suggests that the winter pea crop included in System 3 is providing some suppression of perennial broadleaf weeds (Table 4). Year 3 alfalfa and winter pea displayed similar competitive ability with Canada thistle, as relative Canada thistle biomass was similar between winter pea and alfalfa. Winter pea did not compete with field bindweed as well as alfalfa. Field bindweed comprised 15% of total standing biomass in winter pea, on average, which was numerically higher than that in alfalfa (Table 4). Downy brome and jointed goatgrass were the most abundant annual weeds in System 3 winter pea, and relative downy brome biomass was higher in winter pea compared to alfalfa (Table 4).

Notably, wild oats comprised 15% of total standing biomass in System 3 winter pea in 2014 (data not shown). Wild oats were observed in establishing alfalfa, at a relative biomass of 15%, but no wild oats were found in Year 2 and Year 3 alfalfa, suggesting that a well-developed alfalfa crop will outcompete wild oat. Relative wild oat biomass in the following winter wheat crop in System 3 did not exceed 2%, suggesting that winter pea in rotation with winter wheat
effectively broke the wild oat life cycle, though wild oat was found in System 3 spring wheat following winter wheat, where relative wild oat biomass was 5% on average. Before the advent of herbicides for wild oat control, wild oat had a long history of infesting wheat crops (Cudney et al., 1991) and was especially a problem in spring wheat. The prevalence of wild oat on the Palouse generally precludes growing spring wheat in organic rotations (Manuchehri, 2012). While alfalfa was not rotated with spring wheat in this study, future studies could explore if the wild oat suppressive effect observed in alfalfa could carry over into a following spring wheat crop.

**Winter Wheat Following Legumes**

While relative weed community biomass in alfalfa was lower than in winter pea (Table 4), relative weed biomass in winter wheat following alfalfa was numerically greater than in wheat following winter pea (Table 3). Winter annual and perennial weed biomass were similar in winter wheat following alfalfa and winter pea, but relative volunteer alfalfa biomass was 20%, on average, in winter wheat following alfalfa (Figure 4). The shallow tillage practices (~10 cm deep) used to reduce soil disturbance and erosion in this study failed to effectively terminate alfalfa. Results suggest that deeper, more aggressive tillage or different timing might be necessary to terminate alfalfa and reduce the risk of competition from volunteer alfalfa in subsequent grain crops.

The lack of suppression of downy brome and jointed goatgrass during alfalfa’s growth cycle carried over into the following winter wheat crop, where downy brome and jointed goatgrass comprised 7 and 19% of total standing biomass, respectively (Figure 3). Downy brome biomass in wheat was similar following either alfalfa or winter pea, but jointed goatgrass biomass was higher following pea than alfalfa (Figure 3). The suppressive effects of both legume
rotational crops on perennial weeds carried over into the following winter wheat crop, where field bindweed and Canada thistle biomass levels were low (Figure 3). Field bindweed biomass in winter wheat following alfalfa and winter pea was similar. However, Canada thistle biomass was lower in winter wheat following alfalfa (Figure 3), suggesting that in the following winter wheat crop, alfalfa provided superior carryover suppression of Canada thistle compared to winter pea. The competitive ability of three-year alfalfa with Canada thistle suggested that alfalfa could possibly be used to reduce Canada thistle pressure in an already-infested field. The biggest challenge in using alfalfa for remediation would exist in the establishment year, possibly requiring deep tillage prior to planting to control weeds, or a grass nurse crop to compete with weeds during the establishment when alfalfa growth is usually slow (Sturgul et al., 1990; Stanger et al., 2008).

While organic alfalfa can be valuable provided that a market is accessible, organic alfalfa production is rare in the region, likely due to the low rainfall during the growing season and lack of profit during the establishment year. Pulse crops, like winter pea in System 3, are more common, though spring pea is generally grown instead of winter pea. The results of this study indicate that three years of alfalfa production can lead to greater suppression of Canada thistle and jointed goatgrass in the following winter wheat crop, compared to winter pea. Alfalfa could be used in place of an annual pulse crop as a rotational crop if high levels of Canada thistle and jointed goatgrass are found in wheat crops, and could increase system-wide crop competitiveness in organic rotations.

*Grain Rotational Crops: Spring Barley and Winter Triticale*

In 2012, spring barley establishment was poor following a wet spring and crop biomass accumulation was low, which resulted in a lack of competition with weeds and high weed
biomass (Table 3). As initial sampling determined grain yields to be below 1000 kg ha\(^{-1}\), the spring barley crop was determined to be a crop failure in 2012 and subsequent analyses include spring barley planted in 2013 and 2014 only. In those drier years when spring barley was successfully established, barley contained lower relative total weed biomass than System 3 winter and spring wheat and similar weed biomass as winter triticale (Figure 5a). A 55 to 85% reduction in relative total weed biomass was observed in spring barley following System 1 winter wheat (2012 winter wheat to 2013 spring barley, and 2013 winter wheat to 2014 spring barley; see Table 3). The competitive ability of spring barley with Canada thistle and field bindweed was similar to that of winter wheat, though there was less relative field bindweed biomass in spring barley, compared to spring wheat (Figure 5c,d).

Spring barley competitiveness with winter annual grass weeds was superior to winter wheat, which is not surprising given that spring-planted crops allow for spring tillage to control winter annual weeds. However, relative jointed goatgrass biomass was lower in spring barley, compared to spring wheat, winter triticale, or winter wheat (Figure 5f). Relative downy brome biomass was greater in spring barley than in spring wheat (Figure 5e). Relative biomass of wild oat, generally a problematic weed in spring-planted cereals, was lower in spring barley than in spring wheat (Figure 5b).

Unfortunately, the ability of spring barley to decrease weed pressure in wheat planted the following year was not examined in this study, as the crop rotation design of System 1 did not follow spring barley with winter wheat. However, the reduction in weed biomass observed from planting spring barley after winter wheat suggests that spring barley may have the potential to suppress weeds in a following crop. In particular, spring barley following three-year alfalfa in rotation could lead to multi-year suppression of perennial weeds and could compete with jointed
goatgrass, the weed that alfalfa competed with the least. While planting four years of potentially low-revenue crops may be economically risky, this strategy could be employed to reclaim or repair fields with large weed infestations without removing them from organic certification. In winter wheat production systems, spring barley could be more effective than spring wheat in competing with certain weed species. Benefits of replacing spring wheat with spring barley could include increased crop competitiveness with field bindweed (Figure 5d), jointed goatgrass (Figure 5f), and possibly wild oat (Figure 5b).

Winter triticale contained lower relative total weed biomass compared to System 3 winter wheat, and similar weed pressure as spring barley and wheat (Figure 5a). At the initiation of the study it was hypothesized that winter triticale would compete more with field bindweed than other cereal crops, but winter triticale did not fulfill original expectations of superior competitive ability with field bindweed. Winter triticale harbored the greatest relative field bindweed biomass of all organic cereal crops and contained greater relative field bindweed biomass than System 3 winter wheat and spring barley (Figure 5d). Rather than being shaded out by the thick triticale stems, bindweed twisted around triticale stems until it reached the top of the canopy, thereby accumulating large amounts of biomass. However, winter triticale suppressed Canada thistle, which was widespread throughout the organically-managed field. Relative Canada thistle biomass was lower in winter triticale than in spring barley and winter and spring wheat (Figure 5c).

Of the fall-planted cereals examined in this study, triticale was more competitive with winter annual grass weeds than winter wheat. Jointed goatgrass was the second most abundant weed, after field bindweed, in winter triticale, but relative jointed goatgrass biomass was lower than in System 3 winter wheat (Figure 5f). The competitiveness of winter triticale with downy
brome was superior to winter wheat and spring barley, but equal to spring wheat (Figure 5e). Winter triticale and winter wheat competed similarly with wild oat, but relative wild oat biomass in winter cereals was lower than in spring wheat (Figure 5b).

In comparing competitiveness with weeds across all rotational crops in this study, relative weed biomass was similar among winter triticale, spring barley, and Year 2 and 3 alfalfa (Table 3). However, relative weed biomass was lower in the alternative rotational crops than in System 3 winter pea (p < 0.001) (Table 3). Pea is often the only rotational crop in wheat production systems on the Palouse, and the findings of this study indicate that alfalfa, winter triticale, and spring barley are superior rotational crops compared to pea, in terms of competitiveness with weeds.

**Conclusions**

Alfalfa, as a legume rotational crop, contained lower relative weed biomass than winter pea and reduced Canada thistle biomass during three years of production, an effect that carried over into the following winter wheat crop. Field bindweed also decreased over the three-year alfalfa production period, though to a lesser extent than Canada thistle. Alfalfa failed to compete with the winter annual grasses downy brome and jointed goatgrass, and winter annual grass weed pressure was high in the following winter wheat crop, though jointed goatgrass biomass was greater in wheat following winter pea. Though wild oat was present in the alfalfa establishment year, very little wild oat was found in cereals following alfalfa. The results of this study indicate that alfalfa has potential as a rotational crop to manage an existing weed infestation, especially for Canada thistle and wild oat. Replacing pea with alfalfa as a rotational crop with wheat could lead to decreased overall weed biomass, and decreased Canada thistle and jointed goatgrass pressure in following winter wheat crop. The inclusion of alfalfa in a crop rotation with wheat,
however, would mandate an effective alfalfa termination method, as volunteer alfalfa proved to negatively impact winter wheat following in a rotation.

Spring barley was more competitive with all weeds than winter wheat, and was the most competitive crop with jointed goatgrass of all crops in this study. Barley was more competitive with field bindweed than winter triticale, which was the least competitive with field bindweed of all cereal crops in this study. While winter triticale failed to shade out field bindweed, it was more competitive with Canada thistle than spring barley and wheat and similar to alfalfa. Organic producers struggling to control perennial weeds could incorporate alfalfa and spring barley to suppress field bindweed, and alfalfa and winter triticale to suppress Canada thistle. In organic systems with high winter annual grass pressure, winter triticale could be planted to compete with downy brome, and spring barley could be planted to compete with jointed goatgrass. Both organic and conventional producers could experience increased system-wide suppression of weeds by incorporating alfalfa, winter triticale, and spring barley in place of, or in addition to, pea in wheat production systems.
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Table 1. Organic cropping system designs from 2010-2014, planted at a site near Pullman, WA. The three organic cropping systems were replicated to observe several crops within a rotation in one year. System replicates were planted using a staggered start. For example, System 1 had three replicates, 1-A, 1-B, and 1-C, which were planted to establishing alfalfa in 2008, 2009, and 2010, respectively. Crops shown within years correspond to a system replicate, shown here.

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<tr>
<td>2</td>
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<td></td>
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</tr>
<tr>
<td>2-A</td>
<td>Winter Pea Hay</td>
<td>Winter Triticale(^a) (M)</td>
<td>Winter Pea Hay</td>
<td>Winter Triticale(^a) (M)</td>
<td>Winter Pea Hay</td>
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<td>2-B</td>
<td>Winter Triticale(^a) (M)</td>
<td>Winter Pea Hay</td>
<td>Winter Triticale(^a) (M)</td>
<td>Winter Pea Hay</td>
<td>Winter Triticale(^a) (M)</td>
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<tr>
<td>3</td>
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<td></td>
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</tr>
<tr>
<td>3-A</td>
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<td>Winter Pea Hay</td>
<td>Winter Wheat (M)</td>
<td>Spring Wheat (M)</td>
<td>Winter Pea Hay</td>
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</tr>
<tr>
<td>3-B</td>
<td>Winter Wheat (M)</td>
<td>Spring Wheat (M)</td>
<td>Winter Pea Hay</td>
<td>Winter Wheat (M)</td>
<td>Spring Wheat (M)</td>
<td></td>
</tr>
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\(^a\) Alternative rotational crop  
\(^b\) Crop failure  
M = received quail manure at planting
Table 2. Secondary tillage operations performed for weed control in organic Systems 1-3.

<table>
<thead>
<tr>
<th>Year</th>
<th>Rotary Harrow</th>
<th>Rotary Hoe</th>
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<tr>
<td>– Fall - Spring –</td>
<td>9/30/10, 10/13/10</td>
<td>5/2/11, 5/19/11, 5/31/11</td>
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<td>10/12/11, 4/23/12</td>
<td>4/9/12, 4/23/12, 5/7/12</td>
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<td>10/19/12, 4/23/13</td>
<td>3/28/13, 4/16/13, 4/26/13, 5/6/13</td>
</tr>
<tr>
<td>2012 - 2013</td>
<td>10/17/13, 10/18/13, 4/10/14</td>
<td>3/31/14, 4/10/14, 5/1/14, 5/30/14</td>
</tr>
</tbody>
</table>

a tillage before fall planting  
b tillage before spring planting
Figure 1. Monthly precipitation on-site for four water years, corresponding to the winter cropping cycle.
Table 3. Total aboveground crop and weed biomass dry matter accumulation, collected prior to harvest, at a site near Pullman, WA, 2011-2014. Dashes (—) are placed in years when no system replications were planted to the crop.

<table>
<thead>
<tr>
<th></th>
<th>Aboveground Crop Biomass</th>
<th>Aboveground Weed Biomass</th>
<th>Relative Total Weed Biomass</th>
<th>Average Relative Weed Biomassa</th>
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<tbody>
<tr>
<td><strong>System 1</strong></td>
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<td></td>
<td></td>
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<tr>
<td><strong>Establishing</strong></td>
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<tr>
<td>Alfalfa (YR1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>–</td>
<td>–</td>
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<td>–</td>
</tr>
<tr>
<td>2012</td>
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<td>120</td>
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<tr>
<td>2014</td>
<td>110</td>
<td>50</td>
<td>640</td>
<td>180</td>
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<td>Alfalfa (YR2)</td>
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<tr>
<td>2011</td>
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<td>1270</td>
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<td>2014</td>
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<tr>
<td><strong>Winter Wheat</strong></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>2011</td>
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<td><strong>Winter</strong></td>
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<td>Triticale</td>
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<td>2014</td>
<td>11140</td>
<td>1500</td>
<td>1470</td>
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### System 3

**Winter Wheat**

<table>
<thead>
<tr>
<th>Year</th>
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<th>YR3</th>
<th>YR4</th>
<th>YR5</th>
<th>YR6</th>
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</thead>
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<tr>
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<td>–</td>
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<td>–</td>
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<td>–</td>
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<td>1540</td>
<td>420</td>
<td>14</td>
<td>–</td>
</tr>
<tr>
<td>2014</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>23 cd</td>
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</table>

**Spring Wheat**

<table>
<thead>
<tr>
<th>Year</th>
<th>YR1</th>
<th>YR2</th>
<th>YR3</th>
<th>YR4</th>
<th>YR5</th>
<th>YR6</th>
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</thead>
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<tr>
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<td>480</td>
<td>1360</td>
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<td>22</td>
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<tr>
<td>2012</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<tr>
<td>2013</td>
<td>6970</td>
<td>690</td>
<td>1610</td>
<td>170</td>
<td>19</td>
<td>–</td>
</tr>
<tr>
<td>2014</td>
<td>7650</td>
<td>950</td>
<td>1050</td>
<td>460</td>
<td>12</td>
<td>18 de</td>
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</table>

**Winter Peas (hay)**

<table>
<thead>
<tr>
<th>Year</th>
<th>YR1</th>
<th>YR2</th>
<th>YR3</th>
<th>YR4</th>
<th>YR5</th>
<th>YR6</th>
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</thead>
<tbody>
<tr>
<td>2011</td>
<td>1270</td>
<td>120</td>
<td>860</td>
<td>420</td>
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<td>2012</td>
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<td>60</td>
<td>3240</td>
<td>250</td>
<td>89</td>
<td>–</td>
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<tr>
<td>2014</td>
<td>2320</td>
<td>430</td>
<td>990</td>
<td>240</td>
<td>30</td>
<td>47 b</td>
</tr>
</tbody>
</table>

YR1 = Year 1
YR2 = Year 2
YR3 = Year 3

*a Average relative total weed biomass was calculated by averaging relative total weed biomass percentages over all years the crop was planted. Letters indicate significant differences at the α = 0.05 level.*
Figure 2. Relative weed biomass, as a percent of total standing biomass, of two perennial and two winter annual weed species over the three production years of alfalfa, in the five-year System 1 rotation. Alfalfa was established in the spring of year 1 and terminated in the fall of year 3 at a site near Pullman, WA, 2011-2014.
Table 4. Relative weed biomass, as a percent of total standing biomass, averaged over 2011 and 2012 when both Year 3 alfalfa (System 1) and winter pea (System 3) were present. P-values shown represent the results of pairwise comparisons for relative weed biomass in alfalfa vs. winter pea using ANOVA.

<table>
<thead>
<tr>
<th>Contrast</th>
<th>Alfalfa (Year 3)</th>
<th>Winter Peas</th>
<th>P &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative Weed Community Biomass</td>
<td>15.7 ± 4.5</td>
<td>46.6 ± 9.9</td>
<td>0.005</td>
</tr>
<tr>
<td>Relative Field Bindweed Biomass</td>
<td>1.4 ± 0.9</td>
<td>14.8 ± 6.3</td>
<td>0.057</td>
</tr>
<tr>
<td>Relative Canada Thistle Biomass</td>
<td>0.3 ± 0.2</td>
<td>3.0 ± 1.9</td>
<td>0.164</td>
</tr>
<tr>
<td>Relative Downy Brome Biomass</td>
<td>7.9 ± 3.3</td>
<td>26.7 ± 7.3</td>
<td>0.028</td>
</tr>
<tr>
<td>Relative Jointed Goatgrass Biomass</td>
<td>3.3 ± 2.1</td>
<td>14.5 ± 5.4</td>
<td>0.1076</td>
</tr>
</tbody>
</table>
Figure 3. Composition of aboveground biomass in System 1 winter wheat (WW) following alfalfa and System 3 WW following winter pea. Life history categories (winter annuals, summer annuals, perennials) correspond to weeds observed in the wheat crop.
Figure 4. Relative weed biomass, as a percent of total standing biomass, of four weed species in winter wheat (WW) following alfalfa (System 1) and WW following winter pea (System 3).
**Figure 5.** Relative weed biomass in System 1 spring barley (excluding 2012 due to crop failure), System 2 winter triticale, System 3 winter wheat, and System 3 spring wheat. Plots: a) relative total weed biomass, b) relative wild oat (WO) biomass, c) relative Canada thistle (CNT) biomass, d) relative field bindweed (FB) biomass, e) relative downy brome (DB) biomass, f) relative jointed goatgrass (JGG) biomass.
CHAPTER 4
Yield, Grain Protein, and Nitrogen and Carbon Dynamics in Dryland Organic Wheat Systems

Abstract
Decreased grain yields and quality serve as major barriers to producing wheat (*Triticum aestivum* L.) organically, but identifying organic sources of nitrogen (N) that provide adequate levels of soil nutrients could improve organic wheat productivity. A six-year organic and conventional wheat rotations trial was established in dryland eastern Washington to investigate the potential for producing organic wheat grain competitively with conventional systems. An organic winter wheat-spring wheat-winter pea (*Pisum sativum* L.) rotation receiving poultry manure achieved winter wheat yields similar to or greater than its conventional counterpart (5664 and 4610 kg ha$^{-1}$, respectively), likely due to high soil inorganic N levels resulting from manure application. Average inorganic N levels of 62 kg N ha$^{-1}$ were observed following alfalfa (*Medicago sativa* L.) forage, where organic winter wheat yielded lower than conventional systems but greater than organic winter wheat following winter pea green manure, which supplied an average of only 55 kg N ha$^{-1}$ to the subsequent wheat crop. Organic hard red spring wheat grain yields (2255 kg ha$^{-1}$) were lower than conventional yields (2875 kg ha$^{-1}$) and grain protein was lower in organic (13.5%) than conventional (14.2%) grain, indicating that producing bread-quality wheat is difficult under organic production. Total soil N and C was higher in the organic systems than the conventional systems, regardless of the fertility source. The results of our study indicate that dryland organic wheat systems have the potential to produce winter grain yields comparable to...
conventional systems, given access to a manure source, and that organic fertility amendments contribute significantly to soil N and C pools.

**Introduction**

While certified organic hectarage of fruits, vegetables, and dairy products in the U.S. is growing, expansion of certified organic grains production has slowed and livestock producers have struggled to source organic feed grain (Greene et al., 2009). Despite high demand for organic grains in the market, the lower yields and end-product quality attained under organic production practices, where synthetic fertilizers are prohibited, have been a large barrier to more widespread adoption of organic grain production (Uematsu and Mishra, 2012). Many studies comparing organic grain yield and quality to conventionally-produced grains have been conducted to examine the parity or disparity in grain crop productivity between organic and conventional management. In western Canada, Mason et al. (2007) found conventional grain yields to be greater than organic, but reported no differences in whole meal protein content between conventional and organic spring wheat (*Triticum aestivum* L.), both of which met the minimum standard of 13.5%. In Australia, Kitchen et al. (2003) and Ryan et al. (2004) observed that grain yield was 17 to 84% lower under organic production, compared to conventional production, as a result of phosphorus deficiency. However, Ryan et al. (2004) observed similar N content in both organic and conventional wheat grain, even in the presence of low soil available phosphorus. A survey of 14 organic farms in the dryland northern Great Plains found that, on average, spring wheat yields were 77% and 74% of conventional yields, respectively (Entz et al., 2001) but some growers reported maximum yields for organic cereal crops that greatly exceeded long-term conventional yields, suggesting that high yields are possible in organic systems. Additionally, Entz et al. (2001) observed spring wheat yields following alfalfa (*Medicago sativa*...
L.) to be 19% higher than following a grain crop, indicating that selection of crop rotation has a large effect on grain yield outcomes. These studies in aggregate indicate that dryland production of organic grains is likely to yield less than under conventional production; however, they also suggest that organic systems may have greater resilience and yield better under adverse climatic conditions (Entz et al., 2001; Lotter et al., 2003).

The high precipitation zone of the inland Pacific Northwest is known for world-record grain yields of dryland winter wheat, receiving 600 mm of precipitation on average, the majority of which falls between November and April (Schillinger et al., 2006). Three-year winter wheat/spring wheat/spring legume [e.g., pea (Pisum sativum L.), chickpea (Cicer arietinum L.), or lentil (Lens culinaris L.)] rotations are the most common conventional crop rotation in the region, though occasionally growers will plant spring barley (Hordeum vulgare L.) in place of spring wheat (Papendick, 1996). Local climatic characteristics make the region an ideal candidate for organic wheat production, as the dry, hot summers limit foliar disease pressure to lower levels than are observed in other wheat-producing regions (Schillinger et al., 2006). However, challenges like perennial weed pressure, long distance from urban markets, and a lack of availability of external fertility inputs have limited organic wheat production in the inland Pacific Northwest. Livestock production is limited in the region and affordable animal manures are not widely available (Gallagher et al., 2010), necessitating the use of green manures as the main source of soil fertility in organic systems (Miller et al., 2011).

As high-biomass legume crops are also uncommon in the inland Pacific Northwest, incorporating drought-hardy legumes that are able to accumulate sufficient biomass and provide residual N levels capable of supporting subsequent grain yields without supplemental fertility is a challenge. Lower grain yields and quality in organic cereal systems commonly result from low
available inorganic soil N following legumes, or a lack of synchronicity between legume-N mineralization and crop needs, to satisfy N requirements of subsequent cereal crops (Miller et al., 2011; Tonitto et al., 2006). However, at the same location as the current study in Pullman, WA, Borrelli et al. (2014) reported that alfalfa forage and Austrian winter pea green manure achieved adequate biomass production and N fixation to build soil inorganic N levels of 127 and 111 kg ha\(^{-1}\), respectively, which supported spring wheat grain yields of 4290 and 3870 kg ha\(^{-1}\) the following spring. Tonitto et al. (2006) found organic grain yields following a green manure crop to be similar to conventionally-fertilized systems when legume biomass provided \(\geq 110\) kg N ha\(^{-1}\), a level that has been observed in alfalfa (Badaruddin and Meyer, 1990; Kelner et al., 1997; Carpenter-Boggs et al., 2000). In a long-term semiarid spring wheat-annual legume green manure rotation, Zentner et al. (2004) observed a gradual and significant increase over time in grain protein, soil inorganic N, and N mineralization, suggesting that annual legume green manures can satisfy the N requirements of wheat, though those effects may only be observable over a period of several years.

Yield gains observed three or more years following transition to organic agriculture are likely the result of crop nutrient requirements being met by mineralization of a large soil organic matter pool (Altieri, 1995). Soil organic matter is composed of several different fractions, and C and N partitioning between fractions is influenced by soil management practices (Cambardella and Elliott, 1994). Increases in soil organic matter from the application of organic soil amendments has been linked to increased ecosystem function and greater N and C cycling (Drinkwater et al., 1998). Knowledge of N fractionation between plant-available inorganic and unavailable organic pools as a result of management practices or crop rotation could enable improved soil fertility management in organic systems.
In dryland cropping areas where biomass accumulation is limited, organic soil
amendments, in addition to legumes, may be necessary for providing adequate N to produce
organic wheat yields comparable to conventional yields. Although Borrelli et al. (2014) observed
the greatest organic wheat yields following winter pea green manure and perennial alfalfa forage,
they found these yields to be lower than conventional grain yields when supplying N solely using
legumes. They concluded that organic managers will likely need to supplement crops with
additional organic nutrient sources, such as animal manure, and not rely on legumes alone to
support the N requirements of a high-yielding organic wheat crop. Manure application could also
contribute to C sequestration in soils, as Fliebbach et al. (2007) observed a 12 to 26% increase in
soil organic C in manure-amended soils after 21 years of organic management, with greater
increases observed when manure was fully composted.

While many studies have compared organic and conventional corn and soybean yields in
humid regions, research on organic small grain production in dryland regions is limited, with
most published studies taking place in Canada and Australia. Few studies have compared crop
rotations for their ability to sustain soil fertility and optimize wheat grain yield and quality in
organic production systems. However, wheat, barley, and other small grains can be grown
without irrigation in areas too dry for corn and soybean cultivation, making these crops essential
for maintaining agricultural production in dryland areas. Developing productive organic small
grain systems could enable greater adoption of organic agriculture in dryland crop production
areas. Our six-year study, conducted in the wheat-producing region of the inland Pacific
Northwest, compared winter and spring wheat grain yields and protein in three organic crop
rotations with two conventional rotations to determine the potential of organic wheat systems to
reach production parity with conventional systems. Additionally, N partitioning between organic
and inorganic pools and soil organic C levels was compared among cropping systems to determine the effects of crop rotation and soil fertility amendments on soil organic N and C dynamics, which could affect long-term soil health.

**Materials and Methods**

*Site and Cropping System Design*

Research was conducted at a site near Pullman, WA (46°45’N; -117°4’W) in the Palouse region of eastern Washington. The field was situated on a west-facing slope on a Palouse silt loam soil (fine-silty, mixed, superactive, mesic Pachic Ultic Haploxerolls) (Gallagher et al., 2010) with low pH (values ranged from 5 to 6 across the site). The field had been transitioned to certified organic management during a crop rotation study conducted from 2003 to 2007 (Gallagher et al., 2010; Borrelli et al., 2012; Borrelli et al., 2014), and certification was maintained on the organic portion of the field throughout the duration of the study. The trial discussed herein was established in fall of 2007; however, crop rotation designs were not finalized until fall of 2008. Consequently, analysis of six years of data, from 2009 to 2014, will be presented here.

Crop rotations were designed around winter wheat, the main cash crop in the region, and the three organic systems (Table 1) employed various tactics to manage soil fertility and weeds. Organic System 1 (ORGSYS1) was a five-year alfalfa (cv. ‘Ladak’) / orchardgrass (*Dactylis glomerata* L.)-alfalfa/orchardgrass-alfalfa/orchardgrass-soft white winter wheat (cv. ‘Brundage 96’)-spring barley (cv. ‘Bob’) rotation. In the alfalfa forage establishment year, orchardgrass was planted with alfalfa to increase crop competition with weeds. However, as orchardgrass comprised less than 10% of standing biomass in Year 2 and Year 3 alfalfa forage, the three years of alfalfa/orchardgrass cropping in System 1 will be referred to as “establishing alfalfa,” “Year 2
alfalfa,” and “Year 3 alfalfa.” No additional fertility amendment was applied to ORGSYS1 winter wheat, as adequate soil N was expected following the three-year alfalfa forage; however, 2500 kg ha\(^{-1}\) (130 kg N ha\(^{-1}\)) poultry manure was applied to ORGSYS1 spring barley. Organic System 2 (ORGSYS2) was a two-year soft white winter wheat (cv. ‘Brundage 96’)-Austrian winter pea (cv. ‘Windham’) green manure rotation that received no additional fertility inputs. Organic System 3 (ORGSYS3) was a three-year soft white winter wheat (cv. ‘Brundage 96’)-hard red spring wheat (cv. ‘Kelse’) -Austrian winter pea hay (cv. ‘Windham’) rotation, and poultry manure was applied to winter wheat at a rate of 4000 kg ha\(^{-1}\) (200 kg N ha\(^{-1}\)), and to spring wheat at a rate of 4700 kg ha\(^{-1}\) (230 kg N ha\(^{-1}\)). Composted poultry manure was available from a quail farm near the study site, and was broadcast by hand prior to planting. Nutrient analyses of manure samples were obtained from regional testing labs prior to field application. Manure application rates were calculated based on potential crop yield, protein goals, and post-harvest soil inorganic N content following the previous crop as described in regional nutrient management guides by Koenig (2013) for spring and winter wheat (ORGSYST 3) and Mahler and Guy (2007) for spring barley (ORGSYST 1). An 80% mineralization rate was assumed for the poultry manure due to its high N content.

System 4 was a three-year conventional mimic (CONVSYS4) of ORGSYS3, with a soft white winter wheat (cv. ‘Brundage 96’)-hard red spring wheat (cv. ‘Kelse’) -Austrian winter pea hay (cv. ‘Windham’) rotation. System 5 (CONVSYS5) was a three-year grain-intensive conventional soft white winter wheat (cv. ‘Brundage 96’)-hard red spring wheat (cv. ‘Kelse’) -spring pea (cv. ‘Aragorn’) rotation, which is the most common conventional rotation in the area. Conventional winter and spring wheat was fertilized with 56 kg ha\(^{-1}\) starter fertilizer (16-20-0) and topdressed with 112 kg ha\(^{-1}\) urea (46-0-0).
ORGSYS2 winter pea grown as green manure was cut at first- or mid-bloom in mid-June and left on the soil surface. ORGSYS3 and CONVSYS4 winter pea crops were cut for hay with a swather at first- or mid-bloom, baled, and removed from the system. Establishing alfalfa did not accumulate enough biomass to cut for hay, and was mowed to control weeds. ORGSYS1 Year 2 and Year 3 alfalfa in all three system replicates yielded one to two cuttings per year, depending on summer precipitation. Alfalfa hay was swathed, baled, and removed from the system.

As soil erosion is a chronic problem due to the region’s dry climate and steep slopes (Papendick, 1996), reduced-tillage methods were used in this study. All tillage operations were performed to a maximum depth of 10 cm in order to minimize erosion on the slope where this study was located. The seedbed was prepared to a six-inch depth with a sweep plow and a rotary harrow. Crops were planted with a Fabro minimum disturbance double disc drill with 19 cm row spacing (Fabro Enterprises Ltd., Swift Current, SK, Canada). After emergence, all organic grain and hay crops were rotary hoed two to four times to control weeds as needed. Weed control methods used were the same as those described by Gallagher et al. (2010). Weeds in the conventional systems were controlled with the appropriate herbicides.

**Grain and Hay Sampling**

Alfalfa forage (ORGSYS1) and winter pea hay (ORGSYS3 and CONVSYS4) biomass samples were collected just prior to swathing. Hay samples were clipped at the soil surface from three 1000-cm² quadrats per plot, dried in an oven at 55°C, weighed, and ground using a Wiley-Mill (equipped with a 2-mm sieve). Biomass N content was determined with a dry combustion auto analyzer (TruSpec CN Determinator, LECO Corporation St. Joseph, MI). Grain yield was collected with a plot combine (Kincaid Seed Research Equipment, Haven, KS) with a 1.5 m header width for the length (15 m) of the plot. Grain yield was calculated with a Harvest Master
Grain Gage (Juniper Systems, Inc., Logan, UT), and grain samples were collected for quality analysis starting in 2011, and through the end of the study (2014). Seed was cleaned using a Carter-Day dockage tester to separate grain from weed seed and other contaminants. Weed seed was weighed and percent dockage calculated by dividing weed seed weight by the total weight of the sample (grain + weed seed weight). Grain protein was determined by near-infrared spectroscopy (NIRS).

**Soil Sampling and Analysis**

Following grain harvest but prior to fall planting of winter crops, three soil cores were collected from each plot with a 3-cm diameter hydraulic Giddings probe (Giddings Machine Company, Windsor, CO) to a depth of 1.5 m and separated into 0-15, 15-30, 30-60, 60-90, 90-120, and 120-150 cm fractions, and the three cores aggregated. Soil inorganic N was extracted using the KCl extraction method (Maynard and Kalra, 1993) and analyzed with a continuous flow auto analyzer (Quick Chem FIA +8000 Series; Lachat Instruments, Milwaukee, WI). Inorganic ammonium and nitrate were summed to calculate total soil profile inorganic N and converted to Mg N ha\(^{-1}\), assuming an average profile silt loam bulk density of 1.33 Mg m\(^{-3}\) (Borrelli et al., 2014). Soil from the 0-15 cm fraction was air dried and total soil N (TN) and C (TC) determined using a dry combustion auto analyzer. Soil percent TN and TC was converted to weight by multiplying percent TN and TC by 2163 Mg ha\(^{-1}\), the weight of a 15 cm-deep slice of soil using a measured bulk density of 1.44 Mg m\(^{-3}\) (Kahl, 2014). Percent plant-available N was calculated by dividing soil inorganic N by total N values.

**Statistical Analysis**

The organic trial was arranged in a randomized complete block design with 5 blocks. Rotations were replicated and a staggered start was used (ORGSYS1 was initiated three times, in
2008, 2009, and 2010; ORGSYS2 was initiated twice, with each crop present in 2009; ORGSYS3 was initiated twice, in 2009) (Table 1), so that crops within the rotations were replicated in time and space (Posner et al., 2008). The conventional blocks were separated from the organic blocks by a 50-foot-wide buffer to satisfy certified organic production standards. While organic and conventional system plots were not randomized amongst each other due to the USDA National Organic Program (NOP) rules, the systems were located in the same field and soil total C and N content was not different between plots in the organic and conventional blocks at the initiation of the study, enabling accurate comparisons. The conventional systems were replicated using a randomized complete block design with 5 blocks, within the conventional part of the field.

Grain yields and grain protein content of winter and spring wheat, and hay dry matter yields of alfalfa and winter pea, were combined by crop across all years the crop was grown, and compared between cropping systems with ANOVA, using the Mixed Procedure in SAS Version 9.4 (SAS Institute Inc. 2013). Means separations were performed with the Tukey method using an alpha value of 0.05. While yields and soil N and C differed between years, the length of the study provided a number of diverse weather conditions, and year was treated as a random effect. Cropping system was treated as a fixed effect and Block as a random effect. Soil inorganic N and organic N values were square root-transformed to satisfy the assumption of homoscedasticity, and ANOVA performed to compare soil N between systems. As soil was sampled from the same plots year after year, it was possible for soil N values to be auto-correlated within a plot between years. ANOVA was performed with the “repeated” statement in PROC MIXED using an autoregressive covariance matrix to adjust for repeated measures, and BIC values were compared between models with and without repeated measures. The model with the lowest BIC value was
selected. Soil percent organic and inorganic N were transformed using the arcsine square root function to decrease heteroscedasticity (Derksen et al., 1995) where ANOVA was performed.

**Results**

**Grain Yields**

ORGSYS3 winter wheat yields were greater than its conventional check CONVSYS4, as well as the grain-intensive system CONVSYS5 (Figure 1). ORGSYS3 winter wheat yields were also comparable to the Whitman county average for the same time period (2009 to 2014; USDA-NASS), though it was notable that winter wheat yields in both conventional systems were lower than the county average. Winter wheat yields following alfalfa forage in ORGSYS1 were lower than both conventional systems, but greater than ORGSYS2 yields, the winter pea green manure system, which achieved the lowest winter wheat yields of the study. Spring wheat grain yields in ORGSYS3 and both conventional systems were lower than the Whitman County average (Figure 1), but were greater in both conventional systems than in the organic system (ORGSYS3).

**Grain Protein**

Organic winter wheat following alfalfa forage (ORGSYS1) and winter pea green manure (ORGSYS2), had similar mean grain protein levels (Table 2). However, grain protein in organic winter wheat fertilized with poultry manure (ORGSYS3) was greater than winter wheat following green manure (p < 0.001), was similar to its conventional check [CONVSYS4 (p = 0.483)], and greater than winter wheat grain protein in CONVSYS5. Conventionally-grown spring wheat had greater grain protein than organically-grown spring wheat (Table 2) and met the 14% grain protein cutoff required by grain elevators in two of three years grown. Organic spring wheat did not meet the 14% grain protein cutoff in two of the three years grown.
Overall, organically-produced winter wheat contained greater amounts of weed seed in harvested grain than conventionally-produced wheat grain, though the poultry-manured winter wheat (ORGSYS3) contained the least amount of weed seed and was not statistically different from its conventional check (CONVSYS4; Figure 2). However, organic spring wheat in ORGSYS3 contained more than three times the amount of weed seed at harvest than spring wheat from both conventional systems.

Weed seed comprised the greatest percentage (7.5%) of harvested winter wheat grain in the winter pea green manure-only ORGSYS2 (Figure 2). Weed seed dockage was lower in winter wheat following alfalfa forage (ORGSYS1) than following winter pea green manure (ORGSYS2), and was similar to ORGSYS3 winter wheat, but was greater than both conventional systems.

**Soil Inorganic N and Total N**

Despite soil being sampled from plots repeatedly throughout the course of the six-year study, a statistical model taking repeated measures into account did not result in a more parsimonious model according to BIC, and as a result soil N models without the “repeated” statement were used to analyze soil N data. Soil inorganic N levels at the time of winter wheat planting were greatest following winter pea (hay) in ORGSYS3, followed by winter pea (hay) in CONVSYS4 and alfalfa forage in ORGSYS1, which contained similar plant-available N levels (Table 3). Soil inorganic N following spring pea (grain) in CONVSYS5 and winter pea green manure ORGSYS2 were numerically lowest, but comparable to ORGSYS1 and CONVSYS4. A decrease in soil inorganic N over the course of winter wheat growth between planting and harvest was observed in all systems, as expected, though the decrease was small in CONVSYS5 (Table 3).
While organic spring wheat yields were lower than conventional spring wheat yields, soil inorganic N at the time of planting spring wheat was similar among ORGSYS3 and CONVSYS4 and 5 (Table 3). However, following spring wheat harvest, soil inorganic N was greatest in the organic system, compared to the conventional systems, and increased over the course of the spring wheat cropping season, whereas soil inorganic N levels following conventional spring wheat was similar to that measured at the time of planting.

Soil TN (Table 4 and Figure 3) in the alfalfa forage system (ORGSYS1) was greater than ORGSYS2 and both conventional systems, and comparable to ORGSYS3. Of the organic systems, the winter pea green manure system ORGSYS2 contained the least amount of soil TN. Soil inorganic N, as a percent of TN, differed slightly from soil inorganic N content among cropping systems. The high-yielding systems, ORGSYS3 and CONVSYS4, maintained soil inorganic N levels greater than 2% of TN (Figure 3). Additionally, while ORGSYS1 contained a greater quantity of soil inorganic N numerically than CONVSYS5, soil inorganic N made up a significantly lower percentage of TN in the organic system (Figure 3).

**Soil Total C**

Soil TC was greater in all three organic systems than in the conventional systems (Table 4). Of the organic systems, ORGSYS1 contained the most soil TC, but was not significantly different from ORGSYS3. ORGSYS2 contained greater soil TC than both conventional systems, in spite of low biomass accumulation of both crops in the system, over all six years of the study. Soil TC content was similar between CONVSYS4 and 5.

**Discussion**

When fertilized with poultry manure, winter wheat yields were comparable to conventional yields, suggesting that organically-produced winter wheat could produce
comparable yields with conventionally-produced wheat when supplied with sufficient crop nutrients. However, winter wheat following winter pea and alfalfa forage, without additional N supply, yielded only 45% and 60%, respectively, of the conventional winter wheat yields. When mowed and left on the soil surface, winter pea green manure provided average residual inorganic N levels of only 50 kg ha⁻¹, which was not sufficient for satisfactory wheat yields the following year. Supplying N using legumes in conjunction with additional soil fertility inputs can also result in organic winter wheat yields that are comparable to conventional yields. However, lower wheat yields following sole legume crops indicate that organic fertility sources, like animal manures, are necessary to achieve organic wheat yields that compare to conventional yields supplied with N fertilizer sources, similar to the findings of Borrelli et al. (2014).

Winter and spring wheat yields in the conventional systems (CONVSYS4 and 5) at this site were low compared to the county average, likely due to the low soil pH inherent to the site (pH = 5 to 6). Yields of ORGSYS3 winter wheat that received poultry manure were most similar to the county average for conventionally-produced winter wheat. The greater organic winter wheat yields in ORGSYS3 compared to its conventional check were surprising, and may have been due to greater soil pH in the organic system. Soil pH at this same study site was numerically greater in ORGSYS3 (pH = 6.3) than its conventional check (pH = 6.0) in 2013, when soil pH was measured after four years of manure application (Kahl, 2014). The large amounts of poultry manure applied to wheat crops in ORGSYS3 possibly remediated the low soil pH, as application of farmyard manure has been observed to increase soil pH (Whalen et al., 2000).

Organic winter wheat supplied with poultry manure (ORGSYS3) also achieved greater grain protein than winter wheat receiving N solely from legume crops (ORGSYS1 and 2), and
was similar to its conventional check. It is possible that excess quantities of N were present in ORGSYS3 winter wheat as a result of the cumulative effect of poultry manure N mineralization over several years, as a soft white winter wheat grain protein content greater than 10.5% suggests that soil N may have been present in excess of wheat requirements (Hart et al., 2011). Correspondingly, a grain protein level of soft white winter wheat less than 8.5% indicates an N deficiency (Hart et al., 2011). Low soil N availability likely caused the low level of grain protein in ORGSYS2, further supporting the need to supply more N to wheat than the quantities supplied by crop legumes. Results from ORGSYS2 further support that one year of winter pea green manure does not provide sufficient N to support a following winter wheat crop to produce satisfactory yield and grain protein in a dryland organic system. Organic hard red spring wheat in ORGSYS3 achieved satisfactory grain protein (13.5 to 14%) in two of three years grown, though it only reached about 12% in 2011, suggesting that production of high-quality organic hard red spring wheat is possible, though risky, as price discounts are commonly applied to hard red spring wheat if grain does not meet market quality standards. While Ryan et al. (2004) in Australia and Mason et al. (2007) in Canada reported no difference in grain protein content between conventional wheat receiving synthetic fertilizer and organic wheat following 2 to 6 years of legume forage and manure fertilizer, a functional and nutritional wheat quality analysis performed by Park et al. (2015) on the organic spring wheat grain produced in this long-term rotation found that organic grain contained less protein than conventional grain.

Given the low availability of animal manure sources in the region, it would benefit organic growers to identify legume crop species that could provide enough residual soil N to support high yields and grain protein in the following wheat crop. However, neither three years of alfalfa forage (ORGSYS1), nor annual winter pea grown for green manure (ORGSYS2),
resulted in residual soil inorganic N levels similar to that achieved through the application of poultry manure prior to winter wheat planting. The low residual soil inorganic N following winter pea green manure in ORGSYS2 differs from the findings of Borrelli et al. (2012) during the organic transition study performed at the same site in 2003-2007, where 120 kg inorganic N ha\(^{-1}\) was observed following winter pea grown for green manure. These differences may have been due to greater winterkill experienced by winter pea in this study, whereas winter pea stands were more vigorous in the transition study, possibly due to varietal differences between the winter pea cultivars used (Gallagher et al., 2010) or varying weather conditions between years. However, soil inorganic N levels following alfalfa forage were similar to those in both conventional systems. ORGSYS1 winter wheat yields following alfalfa forage may have been limited by weed pressure more than by N availability, as alfalfa has been observed to fix N at levels adequate for corn production (Fox and Piekielek, 1988; Stanger and Lauer, 2008), but volunteer alfalfa proliferated in the winter wheat crop (Tautges et al., 2016). It is possible that soil inorganic N levels following alfalfa forage could have been increased by adjusting the management practices used in this study. On average, 100 kg N ha\(^{-1}\) were exported from ORGSYS1 through the removal of alfalfa forage which, had it stayed in the system, may have accumulated enough soil N to better support the following winter wheat crop. While it is likely difficult for a grower to sacrifice three years of profit during the alfalfa forage production phase, second- and third-year alfalfa forage yielded two cuttings each year it was grown, offering growers a market advantage compared to crops that do not produce well during the organic transition. An organic grower could choose to harvest alfalfa forage only once, and to leave any further accumulation of alfalfa biomass in the field each year. As the second cutting of alfalfa yielded only 30% of the first cutting, the income lost from foregoing the second cutting could be
less than the yield boost in winter wheat the following year, or less than the cost of purchasing additional organic N inputs. Future studies should investigate economic tradeoffs between marketing both cuttings of alfalfa forage versus extra N input from alfalfa biomass left in the system after the first cutting, which has the potential to increase subsequent wheat yields.

Weed seed dockage was greater in winter wheat than spring wheat in both the organic and conventional systems. Weed seed content in harvested grain was greatest in ORGSYS2 winter wheat, where weeds proliferated likely as a result of low soil inorganic N levels, which led to an uncompetitive wheat stand. ORGSYS1 alfalfa forage was highly competitive with weeds (Tautges et al., 2016) and weed seed content in winter wheat following alfalfa forage was lower than ORGSYS2 winter wheat, but greater than in both conventional systems. Much of the weed seed in ORGSYS1 winter wheat was volunteer alfalfa seed, suggesting that dockage could be reduced if more effective termination of alfalfa was achieved (Tautges et al., 2016). ORGSYS3 weed seed content in winter wheat was similar to that of both conventional systems, suggesting that weed seed contamination of organic grain can be comparable to that of conventional winter wheat, if soil fertility levels adequate for winter wheat production are maintained. The same was not true of organic spring wheat, where high soil N levels were maintained but weed seed contamination was greater than in conventional spring wheat, indicating that organic producers would likely struggle more to produce weed seed-free spring wheat grain than winter wheat. Risks of growing winter and spring wheat organically may also include the incursion of additional grain cleaning costs prior to marketing.

The high level of inorganic N available at planting in ORGSYS3, along with high winter wheat yields in that system, suggest that N was less limiting in the poultry-manured organic system than in the green-manured systems. While legume green manure preceded winter wheat
in ORGSYS2 and ORGSYS3, the addition of poultry manure likely sustained N release via mineralization for crop uptake in ORGSYS3, whereas legume-derived N was depleted in ORGSYS2. Interestingly, soil inorganic N decrease over the winter wheat cropping year was similar between ORGSYS3 and CONVSYS4, although N input type differed (manure vs. urea). As grain yields were greater in ORGSYS3, the addition of manure in ORGSYS3 may have provided additional benefits to the crop, such as phosphorus, potassium, or micronutrients that were not measured in this study. Correspondingly, little to no reduction in inorganic N was observed in CONVSYS5, even though winter wheat yields were similar between the two conventional systems. Synthetic fertilizer applications made to CONVSYS5 may have satisfied crop needs, and mineralization of the previous year’s spring pea pulse crop may have maintained high background soil inorganic N levels.

An increase in the soil inorganic N pool was observed over the spring wheat cropping phase (following winter wheat) in ORGSYS3. Such an increase may be the result of consecutive years of poultry manure application, where N mineralization over the previous season resulted in a high soil residual inorganic N level, and suggests that the rate of poultry manure applied to organic spring wheat was likely excessive. It also suggests that the lower yields observed in organic spring wheat, compared to conventional spring wheat, were due to competition from weeds rather than insufficient soil fertility, which is supported by the high levels of weed seed present in organic spring wheat. Further, the 100 kg ha⁻¹ soil residual inorganic N following spring wheat was not ideal for encouraging atmospheric N fixation in the following winter pea crop. However, the cultivation of a winter cover crop in a soil with high inorganic N likely increased retention of the surplus N (Drinkwater and Snapp, 2005) and helped to maintain the
high level of soil inorganic N observed throughout the crop rotation of ORGSYS3, which contributed to the high grain yields and quality observed in that system.

In green manure systems, soil N tends to cycle into soil organic N pools (Tonitto et al., 2006). Consequently, it is expected that green manure systems would have greater soil TN levels than systems receiving fewer organic matter inputs. The three-year alfalfa forage system (ORGSYS1) contained the greatest amounts of soil TN of all cropping systems examined in this study, and was similar to the poultry-manured ORGSYS3 but greater than ORGSYS2, where low biomass accumulation of both the winter pea green manure and winter wheat lead to low soil TN. Although the soil TN content of ORGSYS1 soils was among the greatest observed in the five systems, partitioning of soil N to the inorganic pool, relative to soil TN, was lower than in ORGSYS3 and both conventional systems, suggesting that ORGSYS1 soil TN was likely comprised of more unavailable organic forms of N. The same was likely true of ORGSYS2, which received N inputs only from winter pea green manure. The C:N ratio of the poultry manure applied to ORGSYS3 averaged approximately 6:1, and 80% of total manure N was estimated to mineralize within a season. However, application of poultry manure also resulted in soil TN similar to that of a system with a perennial legume (ORGSYS1), indicating that application of a source of labile N does not necessarily lead to a depleted soil organic N pool.

Soil TC was greatest in ORGSYS1, likely as a result of the high above- and below-ground biomass accumulation of alfalfa forage. Other studies have also reported increased C sequestration in alfalfa, compared to small grain crops (Min et al., 2003), as alfalfa provides perennial cover with minimal tillage and its woody root tissue contains high levels of recalcitrant C compounds that decompose very slowly. While a high C:N ratio can retard SOM mineralization, greater soil TC and SOM levels contribute to soil health (Reeves, 1997). Previous
studies have found that crops following legume green manures obtain 80% of their N from SOM reservoirs (Tonitto et al., 2006), suggesting that the accumulation of SOM is as important as soil inorganic N for achieving high grain yields in organic systems.

ORGSYS2 contained the lowest soil TC levels of the three organic systems as a result of low biomass accumulation. However, all three organic systems contained greater soil C than both conventional systems at the end of the six-year study, though soil TC levels were similar between the organic and conventional plots at the initiation of the study. Wander et al. (1994) also observed accumulation of C in soils receiving organic amendments, whereas no change in soil TC was observed in soils receiving synthetic inputs, after 10 years of organic or conventional management. They also observed that a greater proportion of SOM in manure-amended soils was labile, whereas SOM was more stable in organic soils receiving green manure.

**Conclusions**

Organic winter wheat yields achieved in poultry-manured ORGSYS3 were greater than yields in the conventional check CONVSYS4 and were similar to county average conventional winter wheat yields. The results of this study indicate that organic winter wheat yields and grain protein can meet or exceed grain yield and protein achieved by conventional production systems. Three years of alfalfa forage production, prior to winter wheat, also demonstrated the potential to accumulate soil inorganic N in quantities sufficient for successful winter wheat production, if hay removal is limited and crop residue managed to supply N to the system. Similarly, adequate soil fertility for high-quality organic hard red spring wheat production was achieved when animal manure was applied, but organic spring wheat yields were lower than conventional yields due to weed pressure. One year of winter pea grown for green manure did not accumulate
sufficient soil inorganic N, and is not recommended as a source of N in dryland organic systems without further N input or more than one year of legume cultivation prior to grain cropping. When animal manure is available to achieve sufficient soil N levels, the main constraint to organic hard red spring wheat production in the inland Pacific Northwest may be the ability to control weeds in spring grains.

Soil N dynamics in the poultry-manured ORGSYS3 matched the N dynamics of the conventional systems more closely because the soil inorganic N pool provided a greater proportion of soil TN, compared to the organic green manure systems, and contributed to higher grain yields and quality. However, a more active and labile soil N pool in the poultry-manured organic system, compared to the alfalfa forage-based organic system, did not result in lower soil TN and TC in the long-term. Additionally, all three organic cropping systems, including the unproductive winter pea green manure system, contained greater soil TC than the conventional cropping systems. Organic wheat production systems with poultry manure fertility amendments demonstrated the potential to reach productivity and quality parity with comparable conventional wheat systems, while maintaining long-term soil fertility and quality.
Literature Cited


Table 1. Cropping system designs of three organic and two conventional crop rotations. The “starts” represent the number of times a system was “started,” or replicated. Dashes (—) were placed in years no crop in the rotation was planted; in those years, “placeholder” grain crops were planted.

<table>
<thead>
<tr>
<th>Cropping System</th>
<th>Start</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>ORGSYS 1 Forage rotation</td>
<td>A</td>
<td>Alfalfa* (YR2)</td>
<td>Alfalfa (YR3)</td>
<td>Winter Wheat</td>
<td>Spring Barley (M)</td>
<td>Est. Alfalfa</td>
<td>Alfalfa (YR2)</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>—</td>
<td>Alfalfa (YR2)</td>
<td>Alfalfa (YR3)</td>
<td>Winter Wheat</td>
<td>Spring Barley (M)</td>
<td>Est. alfalfa</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>—</td>
<td>—</td>
<td>Est. Alfalfa</td>
<td>Alfalfa (YR2)</td>
<td>Alfalfa (YR3)</td>
<td>Winter Wheat</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>—</td>
<td>Winter Wheat</td>
<td>Spring Wheat</td>
<td>Spring Pea</td>
<td>Winter Wheat</td>
<td>Spring Wheat</td>
</tr>
</tbody>
</table>

ORGSYS = organic system; CONVSYS = conventional system
Est. = establishing
YR2 = Year 2
YR3 = Year 3
M = poultry manure
GM = green manure
* Alfalfa in ORGSYS2 Start A was established in 2008, not shown here.
Figure 1. Winter wheat (WW) and spring wheat (SW) grain yields from 2009 to 2014. Yields from system replicates (e.g., 1-A, 1-B, etc) were pooled. Lines represent the county average for winter wheat and spring wheat yields from conventional wheat farms in Whitman County, WA, where the field trial was located. Crop rotations are: ORGSYS1 (three-year alfalfa forage-winter wheat-spring barley); ORGSYS2 (winter wheat-winter pea [green manure]); ORGSYS3 (winter wheat-spring wheat-winter pea [hay]); CONVSYS4 (winter wheat-spring wheat-winter pea [hay]); CONVSYS5 (winter wheat-spring wheat-spring pea [grain]).
**Table 2.** Percent wheat grain protein, measured in 2011 to 2014. Dashes (–) were placed in years when wheat was not planted in any system replicates of a cropping system. Bolded p-values from contrasts represent significance at the $\alpha = 0.05$ level.

<table>
<thead>
<tr>
<th>Cropping System</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>Mean</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>% grain protein</td>
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<tr>
<td><strong>Soft White Winter Wheat</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ORGSYS1</td>
<td>8.2</td>
<td>9.2</td>
<td>8.8</td>
<td>–</td>
<td>8.8</td>
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<td>ORGSYS2</td>
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<td>8.6</td>
<td>8.1</td>
<td>8.6</td>
<td>8.4</td>
</tr>
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<td>–</td>
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<td>–</td>
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<td>CONVSYS5</td>
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<td>10.0</td>
<td>10.9</td>
<td>–</td>
<td>10.4</td>
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<td><strong>Hard Red Spring Wheat</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>ORGSYS3</td>
<td>11.9</td>
<td>–</td>
<td>14.1</td>
<td>13.8</td>
<td>13.5</td>
</tr>
<tr>
<td>CONVSYS4</td>
<td>13.2</td>
<td>–</td>
<td>14.6</td>
<td>14.7</td>
<td>14.2</td>
</tr>
<tr>
<td>CONVSYS5</td>
<td>13.7</td>
<td>–</td>
<td>14.6</td>
<td>14.3</td>
<td>14.3</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Contrasts</th>
<th>p-value</th>
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<tr>
<td><strong>Soft White Winter Wheat</strong></td>
<td></td>
</tr>
<tr>
<td>ORGSYS1 vs. ORGSYS2</td>
<td>1.000</td>
</tr>
<tr>
<td>ORGSYS1 vs. ORGSYS3</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>ORGSYS3 vs. CONVSYS4</td>
<td>0.011</td>
</tr>
<tr>
<td>ORGSYS3 vs. CONVSYS5</td>
<td>0.005</td>
</tr>
<tr>
<td><strong>Hard Red Spring Wheat</strong></td>
<td></td>
</tr>
<tr>
<td>ORGSYS3 vs. CONVSYS4</td>
<td>0.027</td>
</tr>
<tr>
<td>ORGSYS3 vs. CONVSYS5</td>
<td>0.014</td>
</tr>
</tbody>
</table>

ORGSYS = organic system
CONVSYS = conventional system
Figure 2. Weed seed dockage (content) of harvested winter and spring wheat grain, calculated as a percentage of total grain harvested on a weight basis.
Table 3. Soil inorganic N at winter and spring wheat planting and harvest. Crops listed within parentheses are the crop preceding wheat in the cropping system’s rotation. Letter groupings represent significant differences at the $\alpha = 0.05$ level within a column (e.g., sampling time).

<table>
<thead>
<tr>
<th>Cropping System</th>
<th>Planting</th>
<th>Harvest</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Soft White Winter Wheat</strong></td>
<td></td>
<td></td>
<td>Mg ha$^{-1}$</td>
</tr>
<tr>
<td>ORGSYS1 (alfalfa forage)</td>
<td>0.062 ab</td>
<td>0.032 cd</td>
<td>-0.030</td>
</tr>
<tr>
<td>ORGSYS2 (winter pea green manure)</td>
<td>0.055 b</td>
<td>0.030 d</td>
<td>-0.025</td>
</tr>
<tr>
<td>ORGSYS3 (winter pea hay)</td>
<td>0.098 a</td>
<td>0.080 a</td>
<td>-0.018</td>
</tr>
<tr>
<td>CONVSYS4 (winter pea hay)</td>
<td>0.078 ab</td>
<td>0.061 ab</td>
<td>-0.017</td>
</tr>
<tr>
<td>CONVSYS5 (spring pea grain)</td>
<td>0.056 b</td>
<td>0.054 bc</td>
<td>-0.002</td>
</tr>
<tr>
<td><strong>Hard Red Spring Wheat</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ORGSYS3 (winter wheat)</td>
<td>0.070 a</td>
<td>0.100 a</td>
<td>+ 0.030</td>
</tr>
<tr>
<td>CONVSYS4 (winter wheat)</td>
<td>0.062 a</td>
<td>0.068 b</td>
<td>+ 0.060</td>
</tr>
<tr>
<td>CONVSYS5 (winter wheat)</td>
<td>0.057 a</td>
<td>0.062 b</td>
<td>+ 0.050</td>
</tr>
</tbody>
</table>

ORGSYS = organic system  
CONVSYS = conventional system
Table 4. Soil total nitrogen (TN) and carbon (TC), averaged over six years of soil sampling following wheat harvest. Letter groupings represent significant differences at the $\alpha = 0.05$ level.

<table>
<thead>
<tr>
<th>Cropping System</th>
<th>Soil TN (%)</th>
<th>Soil TN (Mg ha$^{-1}$)</th>
<th>Soil TC (%)</th>
<th>Soil TC (Mg ha$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.170</td>
<td>3.67 a</td>
<td>2.00</td>
<td>43.3 a</td>
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<tr>
<td>ORGSYS2</td>
<td>0.155</td>
<td>3.35 b</td>
<td>1.89</td>
<td>40.8 b</td>
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<tr>
<td>ORGSYS3</td>
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<td>3.46 ab</td>
<td>1.93</td>
<td>41.8 ab</td>
</tr>
<tr>
<td>CONVSYS4</td>
<td>0.153</td>
<td>3.32 b</td>
<td>1.75</td>
<td>37.9 c</td>
</tr>
<tr>
<td>CONVSYS5</td>
<td>0.155</td>
<td>3.36 b</td>
<td>1.78</td>
<td>38.4 c</td>
</tr>
</tbody>
</table>

ORGSYS = organic system  
CONVSYS = conventional system
**Figure 3.** Soil inorganic N as a percentage of soil total N (TN). Bars indicate the standard error of the mean.
CHAPTER 5
Intercropping Cereals and Pea in Organic Dryland Cereal Production Systems

Abstract

Maintaining soil available nitrogen (N) levels in organically managed soils adequate for producing high-yielding wheat is a challenge in the dryland inland Pacific Northwest. Low mineralization rates during dry, hot summers, alongside a lack of animal manure sources, often result in low inorganic N levels during times of high wheat crop N requirement. Organic producers often rotate cereal crops with pea grown for green manure to build up soil N levels for the subsequent wheat crop, thereby sacrificing a year of revenue and potentially increasing weed pressure. Intercropping pea green manure with cereals harvested for grain could provide additional revenues for organic growers, while increasing crop competition with weeds throughout the rotation. Spring wheat and two varieties of spring triticale, a tall forage variety, and a short-statured grain variety, were monocropped and intercropped with spring pea green manure for two years. Poultry manure was applied to monocrops and intercrops, to compare the N fertility effects of intercropping with manure application. A monocropped spring pea green manure-only control was included to compare intercropping effects with a typical green manure rotation, and the residual soil N effects in a subsequent winter wheat cash grain crop. Intercropped organic wheat yielded 50 to 60%, forage triticale yielded 80 to 105%, and grain triticale yielded 60 to 70%, of monocropped grain yields for each respective cereal crop. Intercropped forage triticale displayed greater resilience to drought than monocropped forage triticale and mono- and intercropped cereals, yielding 9015 kg dry matter ha$^{-1}$ in a dry year. Weed pressure was similar between monocropped and intercropped cereals, but lower than in
monocropped pea green manure. Soil residual available N was greatest following short-statured
grain triticale, and consequently subsequent winter wheat yields following intercropped grain
triticale were greatest, compared to intercropped wheat + pea, intercropped forage triticale, and
monocropped pea green manure. Effects of poultry manure application were not observed in
grain yields the year of application, but were observed in same-year grain protein and subsequent
winter wheat grain yields; however, manure effects were less than intercropping effects.
Intercropping cereals and pea green manure has the potential to increase subsequent grain yields
and protein, and decrease weed pressure, relative to growing pea green manure alone, for dryland
organic wheat producers.
Introduction

Interest is growing in organic agricultural management practices, as reducing or eliminating the use of synthetic chemical inputs is viewed as a way to decrease negative effects of agroecosystems on the environment. Demand for organic products has been steadily increasing, with U.S. organic food sales growing 22% annually between 1999 and 2009 (Carlson and Jaenicke, 2016). However, organic grain production levels in the U.S. have not satisfied growing demand due to the low adoption rate of organic grain production, which has left organic livestock producers struggling to find reliable sources of feed grains (Greene et al., 2009). Primary barriers to converting to certified-organic from conventional production are low yields as a result of increased weed pressure and reduced soil nitrogen (N) fertility, which can result in financial losses (Dabbert and Madden, 1988; Jones et al., 2006; Gallagher et al., 2010). Maintaining soil N levels is major challenge for organic growers in the dryland inland Pacific Northwest (Lorent et al., 2016).

Nitrogen is often the primary limiting nutrient in organic grain production systems (Dawson et al. 2008, Miller et al. 2011), and low soil N levels contribute to reduced grain yields and crop competitiveness with weeds (Sooby et al, 2007; Entz et al., 2001). Historically, legume green manures were the primary source of soil N in intensive cropping systems around the world (Cherr et al., 2006), though commercial inputs in modern conventional systems have replaced green manure use and shortened crop rotations. As organic systems are prohibited from using commercial fertilizers, most organic rotations utilize animal or green manure as primary N sources. In regions like the inland Pacific Northwest, where animal manure is scarce and cost-prohibitive to transport (Gallagher et al. 2010), organic growers often rely on green manures to supply N to subsequent grain crops. Legume green manures contribute N to the system via
fixation of atmospheric N and addition of organic matter to the soil. Mineralization by soil microbes releases N over time, a process which can result in reduced N loss and greater N uptake efficiency in crops compared to conventional chemical fertilizers (Tilman, 1998). However, relying on soil organic matter reserves presents challenges to growers managing crops organically, as N release is often asynchronous with crop N requirements (Stockdale et al. 2002) and organic matter levels following conventional production practices are often insufficient to release adequate levels of N (Clark et al., 1998).

Intercropping techniques, widely utilized in traditional cropping systems, have the potential to provide grain crops with N through the simultaneous cultivation of cereals with an inter-planted green manure crop, and to future crops in the rotation. Intercropping grasses and legumes could contribute to a greater diversity of plant residues in the soil organic matter pool that better sustain fungi, bacteria, and detritivores, which play a large role in soil organic matter mineralization and nutrient cycling (Kibblewhite et al., 2008). Stimulating soil microbial activity could contribute to greater soil organic matter turnover and N availability during certified organic crop production. Intercropping has the potential to stimulate soil organic matter mineralization, improve synchrony between soil N availability and crop uptake, increase crop competitiveness with weeds, and increase the protein content of cereal grains (Hauggaard-Nielsen, 2001).

Intercropping as a management practice, though unusual in the U.S., has been adopted by some organic growers in Europe in cereal production systems. In interviews with organic farmers in five European countries, growers reported that yield stability, weed suppression, and grain quality were the three most important benefits obtained from inter-cropping (Jensen et al., 2006). They also reported high grain protein levels in wheat and barley grown in an inter-cropped
Researchers in Denmark observed increased N uptake, higher grain N content, and increased weed and disease suppression in barley inter-cropped with pea and faba bean (Hauggaard-Nielsen et al., 2008). Intercropping a grain crop with a leguminous green manure crop can increase atmospheric N fixation of the legume, as rapid N uptake by the cereal plants forces the legume to increase its reliance on N$_2$-fixation (Karpenstein-Machan and Stuelpnagel, 2000; Hauggaard-Nielsen et al., 2009). Increased pressure on legumes to fix atmospheric N could have important implications for organic growers in the inland Pacific Northwest, where low soil moisture levels during the summer limit the N fixation potential of green manure crops.

Due to the potential weed control benefits and increased diversity of intercropped systems, intercropping could serve as a strategy uniquely tailored to the needs of certified organic growers. Growing a green manure crop over one to two years, generally field pea, is a common practice in the region (Lorent et al., 2016). Rather than sacrificing a year or more of grain crops and profits to grow green manure crops, organic growers could plant grain crops alongside a legume crop, which could fix atmospheric N and build soil fertility and organic matter during the simultaneous production of a cash grain crop. Cereals are generally more competitive with weeds than pea (Corre-Hellou et al., 2011), and could limit weed pressure in a green manure crop. Alternatively, production of a grass and legume forage mix could afford greater weed control flexibility during the mid-summer hay harvest operation, while including legumes could increase hay quality. While much research has taken place on intercropping cereals and legumes in Europe (Karpenstein-Machan and Stuelpnagel, 2000; Jensen et al., 2006; Hauggaard-Nielsen et al., 2008, 2009; Corre-Hellou et al., 2011), little research has been conducted on this system in the U.S. This study investigates the yield potential of two-year wheat + field pea and triticale + field pea cropping systems as a strategy to produce marketable
grain during certified organic production while promoting the biological processes that increase and maintain soil fertility levels essential for successful organic crop production.

Methods

Site and Cropping System Design

The field study was conducted from 2013 through 2015 at the Boyd Farm, located northeast of Pullman, WA (46°45’6”N; -117°4’56”W), on Palouse silt loam soil (fine-silty, mixed, superactive, mesic Pachic Ultic Haploxerolls). Yearly precipitation ranged from 42 to 45 cm from 2013 to 2015, though the summers of 2014 and 2015 were extremely dry. In years 1 and 2, spring wheat (cv. ‘Kelse’) and two varieties of triticale, a tall forage variety (“forage triticale”; cv. ‘Trical 2700’) and a short grain variety (“grain triticale”; cv. ‘Trimark 118’) were monocropped and intercropped with spring field pea (cv. ‘Aragorn’). A monocropped spring pea green manure control was included to compare the effects of grain cropping with cultivation of a leguminous green manure alone. Poultry manure (4 to 5% N) was applied to one-half of all plots to evaluate its effect on all crops and soil N fertility. Intercropping and monocropping treatments were repeated on the same plots in years 1 and 2, to represent the use of intercropping in place of a two-year spring cereal-legume green manure rotation. In fall of year 2, winter wheat (cv. ‘Amber’) was planted following harvest of spring grains following the second year of the monocropped and intercropped treatments to assess the residual effects of preceding crops on soil N and grain yield and quality. All crops in the study were managed organically. Land was certified organic prior to the addition of the study, and certification was maintained throughout the study’s duration.

Crop Management
In years 1 and 2 of the study, seedbed preparation was performed with a cultivator and harrow, and poultry manure was broadcast at a rate of 1975 kg ha\(^{-1}\) on one-half of plots. The manure application rate was calculated based on potential crop yield, protein goals, and post-harvest soil inorganic N content following the previous crop as described in regional nutrient management guides by Koenig (2005) for spring wheat. Crops were planted with a Monosem NG plus 4 drill (Monosem Inc., Edwardsville, KS) on 25-cm. row spacing. Intercropped treatments were planted by filling alternating seedboxes with wheat, forage triticale, grain triticale, and pea seed, so that the cereal and forage crops were grown side-by-side with pea green manure in alternating rows. Two to three passes were made with a rotary hoe post-emergence, until crops reached about 15 cm in height, to control weeds. Pea green manure was terminated at bloom (early- to mid-July) with sweeps set over the pea rows only, while cereals were left standing to bring to maturity, and monocropped pea green manure was terminated with a rotary mower. Monocropped and intercropped forage triticale was swathed and baled as hay when triticale reached the boot stage, and removed from the field. Wheat and grain triticale were harvested with a combine, and stubble was left standing over the winter until seedbed preparation the following spring. In fall of year 2 following grain harvest, the seedbed was prepared with a cultivator and harrow and winter wheat was planted across the entire trial in late October. No additional manure fertilizer was applied to the winter wheat, which was grown off of residual N from the monocropped and intercropped grains and pea in years 1 and 2. Winter wheat grain was harvested with a combine.

*Plant and Soil Sampling*

Wheat, forage triticale, grain triticale, pea green manure, and weed aboveground biomass were sampled prior to pea green manure termination and hay swathing in early July by
clipping two 0.25-m² quadrats per subplot in all treatments in years 1 and 2. The biomass samples were separated into cereal, pea, and weed samples, dried in an oven at 55°C for 72 hr, and weighed. Forage triticale hay samples were not separated by species, to simulate a hay cutting operation. Dried pea and hay biomass was ground with a Wiley-Mill (Thomas Scientific, Swedesboro, NJ) and pea biomass N content was determined with a dry combustion auto analyzer (TruSpec CN Determinator, LECO Corporation, St. Joseph, MI). Hay was analyzed for crude protein using near-infrared spectroscopy (NIRS). To measure grain yield, wheat and grain triticale were harvested by clipping two 0.25-m² quadrats per subplot, threshing, and weighing the grain. Grain was ground and N content was determined with a dry combustion auto analyzer.

In year 3, 20 flag leaves of winter wheat were collected from each subplot, as grain N content is related to N content and photosynthetic activity of the flag leaf (Gregory et al. 1981). Flag leaves were dried, ground, and analyzed for N content with a dry combustion auto analyzer. Winter wheat grain yield was measured and analyzed as described above for spring wheat and triticale.

Soil was sampled with a 2.5-cm-diameter hand probe at the 0 to 15 cm and 15 to 30 cm depth increments mid-season (early July), prior to pea green manure termination, to measure soil moisture between monocropped and intercropped grains. Gravimetric soil moisture was determined by weighing soil before and after drying in a 60°C oven for 72 hr. In years 1 and 2 following spring grain harvest, two soil cores per subplot were collected with a 3-cm diameter hydraulic Giddings probe (Giddings Machine Company, Windsor, CO) to a depth of 1.5 m and separated into 0-15, 15-30, 30-60, 60-90 cm fractions, and the two cores aggregated. Soil inorganic N was extracted using the KCl extraction method (Maynard and Kalra, 1993) and analyzed with a continuous flow auto analyzer (Quick Chem FIA +8000 Series; Lachat
Instruments, Milwaukee, WI). Inorganic ammonium and nitrate were summed to calculate total soil profile inorganic N.

Statistical Analysis

The field trial was arranged in a randomized complete split-block design with 6 blocks, with whole plot dimensions of 4.5 x 14 m and split plot dimensions of 4.5 x 7 m. The whole plot treatment was the cropping regime (monocropped vs. intercropped cereals and pea), and the split plot treatment was application of poultry manure, or no manure. Grain yield, grain N content, and soil inorganic N content were compared between monocropped and intercropped cereals in years 1 and 2. Pea green manure N content was compared between intercropped treatments and monocropped pea green manure. In year 3, winter wheat flag leaf N content, grain yield, and grain N content were compared between previous cropping treatments. Cropping treatment was treated as a fixed whole-plot factor, poultry manure was treated as a fixed split-plot factor, and block was treated as a random factor. Means comparisons were performed with ANOVA, using PROC MIXED in SAS Version 9.4 (SAS Institute Inc. 2013). Means separations were performed with the Tukey method using an alpha value of 0.05.

Weed biomass was standardized between treatments by computing relative weed biomass, where relative weed biomass (%) is equal to the weight of weed biomass divided by the weight of total aboveground biomass (weed + crop). Relative biomass percentages were transformed using the arcsine square root function to decrease heteroscedasticity (Derksen et al., 1995), and ANOVA was performed on transformed relative weed biomass data.

Results and Discussion

Grain, Hay, and Green Manure Yields
Grain yields were high in year 1 due to favorable weather and precipitation, even under organic management. Grain yields were greater (p < 0.001) in monocropped wheat and triticale, compared to intercropped cereals. Intercropped spring wheat and triticale yields were 2720 kg ha\(^{-1}\) and 2250 kg ha\(^{-1}\), respectively, and were 60% of monocropped grain yields in year 1 of the study (Figure 1). In year 2, grain yields were substantially lower than in year 1 due to a spring and summer drought, and monocropped grain yields were greater (p < 0.001) than intercropped yields. Intercropped spring wheat and triticale yielded only 1290 kg ha\(^{-1}\) and 1285 kg ha\(^{-1}\), respectively. In year 2, the proportion of intercropped spring wheat grain yields to monocropped grain yields was 55%, similar to year 1, but were greater in triticale, where yields were 70% of monocropped triticale (Figure 1).

Mid-season soil moisture was greater (p = 0.032) in intercropped wheat and grain triticale (10.9%) than when monocropped (9.4%) in year 1, the wet year, likely due to lower soil water uptake by pea and no further water uptake by intercropped wheat and triticale. No difference in mid-season soil moisture was observed between monocropped and intercropped forage triticale (9.5%), suggesting soil water use to be similar between mono- and intercropped forage crops. No differences in mid-season soil moisture were observed in year 2 between mono- and intercrops (soil moisture ranged from 8.9 to 9.3%), indicating that soil water use was similar between monocropped and intercropped cereals, forages, and pea in a drought year. However, as soil moisture was measured only at planting and once mid-season, it is possible that differences in soil water use between monocrops and intercrops may not have been observed, if they occurred at an earlier point in the season. No effect of the poultry manure application was observed in grain yields in years 1 or 2. While mineralization of manure N was not measured, it is likely that the dry, hot conditions that followed shortly after manure application limited manure N.
availability and mineralization to the cereal crops, or that mineralization of manure N was not well synchronized with crop N requirements.

As the intercropped cereals were planted to only half of the seeding rate of the monocropped cereals on a land area basis, intercropped grain yields greater than 50% of monocropped grain yields indicate a yield advantage from intercropping, per unit land area planted. In both years of intercropping treatments, intercropped cereals achieved yields greater than 50% of monocropped grains. Intercropped triticale may have been able to access more soil moisture or soil N compared to monocropped triticale in a dry year, when competition for soil moisture was high. As pea generally uses less water than cereals (Angadi et al., 2008), less intraspecific competition between cereal plants for soil moisture in the intercropped treatments may have led to greater yields in intercropped triticale in year 2 of the study, proportionally to monocropped triticale. Increased availability of soil moisture to cereals intercropped with a crop with lower water use, like pea, could reduce risk and increase cereal yields in drought years.

In contrast to lower yields observed in wheat and grain triticale, forage triticale hay yields in year 2 were greater than in year 1, in spite of the drought in year 2. In year 1, hay yields were greater \( p = 0.043 \) in monocropped triticale than in intercropped triticale, because triticale produces more biomass than pea. However, in year 2, yields were greater \( p = 0.019 \) in intercropped \( (9015 \text{ kg dry matter ha}^{-1}) \) than in monocropped \( (8040 \text{ kg dry matter ha}^{-1}) \) triticale hay (Figure 1), although spring precipitation was very low and crops in the area experienced drought conditions. No effect of the poultry manure on hay yields was observed in either year. Similar to what was observed in triticale grown for grain, intercropping forage triticale may buffer the risk of yield loss in a dry year due to less intraspecific competition for soil moisture.
Additionally, the hay crop displayed greater resilience to drought conditions, compared to the cereal crops.

Monocropped pea green manure biomass accumulation was greater in year 2 than in year 1, which is surprising given that pea is sensitive to low soil moisture and high temperatures prior to flowering, conditions which occurred in year 2 (Table 1). However, better weed control achieved through rotary hoeing, in conjunction with the drought, limited weed pressure in pea green manure, likely resulting in greater pea biomass accumulation than in year 1. Pea green manure biomass accumulation was similar among grain triticale + pea, forage triticale + pea, and monocropped pea green manure in year 1, but was greater in wheat + pea (p = 0.026) (Table 1). Greater competitive ability for soil water in triticale, compared to wheat (Salmon et al., 2004), may have limited the pea crop’s ability to access soil water when intercropped with triticale, whereas soil water was more available to pea when intercropped with wheat. Monocropped pea green manure biomass accumulation was likely limited by weed pressure. In year 2, pea biomass accumulation was greatest in monocropped pea green manure, was similar between forage triticale + pea and spring wheat + pea intercrops, and lowest in the grain triticale + pea intercrop (Table 1). In a drought year where soil moisture was more limiting, monocropped pea likely accumulated more biomass than intercropped pea, which competed for soil water with cereal crops. Monocropped pea in year 2 likely also accumulated more biomass as a result of greater weed control achieved in year 2 than in year 1. The trend observed in pea biomass in the grain triticale + pea intercrop complements the yields observed in intercropped grain triticale in year 2, which were more similar to monocropped grain triticale than in year 1. During a drought, intercropped grain triticale yielded more similarly to monocropped grain triticale, at the expense of pea biomass accumulation, when competition for soil water was high. Increased crop diversity
and use of multispecies systems has been observed to buffer the negative impacts of climate variation, like drought, in agricultural systems (Lin 2011). The greater yields observed in intercropped, compared to monocropped, forage triticale in this study demonstrates the ability of multispecies cropping to be more productive than monocrops in the face of drought.

**Grain, Hay, and Pea Green Manure Quality**

In year 1, both the intercropping (p < 0.001) and manure (p = 0.005) treatments had a significant effect on grain N content, but there was no interaction between intercropping and manure fertilizer. The addition of manure raised grain N by only one-tenth of a percent, which translates into an additional 0.6 percent grain protein (N x 5.7) (Kindred et al., 2008).

Intercropping wheat and triticale resulted in an additional 0.3 percent grain N (1.5% protein) (Table 2). In year 2, the addition of manure again raised grain N, but the effect was greater in year 2, as manure resulted in an additional 0.22 percent grain N (1.3% protein) (Table 2). Cumulative mineralization of year 1 and 2 manure applications may have resulted in a greater effect in year 2. Also in year 2, wheat grain N content was similar between monocropped and intercropped wheat grain, but intercropping triticale resulted in an additional 0.3 percent grain N (1.9% protein). Growing pea green manure alongside either cereal increased grain protein similarly to, or more than, the addition of manure, which is surprising given the amount of N applied through manure application. Wheat grain N is increased when cereal crops are under stress (Gooding et al., 2003), which includes drought and heat stress. In a drought year like year 2 of the study, the effect of water stress on wheat grain N may have been greater than the effect of intercropping supplying additional N to the wheat during the season, though the effect of intercropping was observed in triticale consistently in both years. The effect of intercropping on grain protein could be extremely valuable in organic systems, as organic wheat producers in the
inland Pacific Northwest have reported struggling to achieve grain protein levels sufficient for bread-quality wheat, which is a lucrative market for organically-produced grain. Growers could increase grain protein through intercropping and sell their grain for a higher price, which could possibly offset the decreased yields observed in intercropped cereals.

In both years, crude protein levels were greater (p < 0.003) in intercropped triticale + pea (10 to 13%) than monocropped triticale alone (8 to 12%). Intercropped triticale had 15% greater crude protein levels than monocropped triticale in both years, which is unsurprising given the greater N content of pea, compared to triticale. Higher quality triticale hay that meets a “premium” quality standard commands prices $10-30 greater than a “good” quality classification (USDA-AMS, 2016), which could be achieved by mixing triticale with pea. While monocropped triticale yielded greater than intercropped in year 1, intercropped triticale + pea hay could result in similar or greater returns because of a higher price for higher-quality hay.

In year 1, pea N content was greatest in monocropped pea green manure (p = 0.019), compared with pea intercropped with grains (Table 1), suggesting that competition for soil N was greater in intercropped cereals. In year 2, no differences were observed in pea N content between intercrops and monocrops. The dry summer in year 2 of the study may have caused pea growth and pea N accumulation to be limited by soil moisture, rather than soil N availability. High temperatures and low soil moisture have also been shown to reduce N\textsubscript{2} fixation in legumes (Zahran, 1999). Additionally, no effect of poultry manure application was observed in pea N content in either year, although fertilization of legumes has been reported to reduce N\textsubscript{2} fixation (Van Kessel and Hartley, 2000). Low mineralization rates during summer of the spring-applied poultry manure likely resulted in little increase of available soil N in years 1 and 2, causing pea to rely on N\textsubscript{2} fixation rather than soil inorganic N. While intercropping pea green manure with
cereals reduced pea green manure N content in year 1, greater pea green manure aboveground biomass accumulation in intercropped wheat and pea led to similar total N inputs into the system (32.8 kg N ha\(^{-1}\)) between wheat + pea green manure and monocropped pea green manure. However, grain triticale + pea green manure resulted in only 23.4 kg N ha\(^{-1}\), likely due to triticale’s greater competitive ability for soil moisture and N, compared to wheat. In year 2, pea green manure biomass accumulation and total N input was lower than in year 1 (Table 2), due to higher temperatures and drought conditions early in the season.

**Weed Biomass**

In years 1 and 2, weed biomass was greatest in monocropped pea green manure and lowest in monocropped forage triticale (Figure 2), which was tall in stature and highly competitive for soil moisture. No effect of poultry manure on relative weed biomass was observed in either year. Relative weed biomass in monocropped and intercropped wheat was statistically similar in both years 1 and 2, but relative weed biomass was greater in intercropped compared to monocropped grain triticale in year 2 (Figure 2). The substitution of pea for cereal crop in alternating rows decreased soil surface shading by the crop, and weeds emerged in the pea row, between cereal rows. While the differences in relative weed biomass between intercropped and monocropped cereals were not large, there was an upward trend in weed biomass in intercropped cereals from year 1 to year 2, in spite of the drier summer in year 2, suggesting that weed pressure may increase over time in cereals intercropped over consecutive years. However, intercropping pea green manure with cereals decreased weed biomass by 20 to 50% compared with monocropped pea green manure, and producing intercropped triticale + pea hay decreased weed biomass 50 to 60%, relative to monocropped pea green manure. Including a cereal in a green manure or cover crop with pea has been found to suppress weeds to a greater
extent than pea alone (Akemo et al., 2000). Therefore, intercropping pea green manure with cereals harvested for grain could lead to long-term benefits in weed suppression during the green manure phase of a rotation, as well as short-term increases in profits.

*Soil Residual Inorganic N*

In year 1, despite no detection of the effects of poultry manure in crop productivity or quality parameters, soil residual inorganic N was greater in poultry-manured soils, compared to unfertilized soils, and there was an interaction between manure and cropping treatment (p = 0.0153) (Table 3). Soil residual inorganic N was lowest following both manured and non-manured monocropped wheat and non-manured intercropped wheat. By contrast, soil residual inorganic N was greatest following manured intercropped wheat and manured monocropped grain triticale (Table 3). High soil inorganic N following these crops is likely due to the low grain yields in these systems (Figure 1), and suggests that release of N via manure mineralization was not well synchronized with crop N uptake. Conversely, the low soil residual inorganic N levels observed following non-manured intercrops (Table 3) suggests that N release from pea green manure was utilized by the grain crop, remained tied up in pea residues, or was released but immediately immobilized by soil microbes.

In year 2, the effect of cropping treatment on soil residual inorganic N was not significant at the α = 0.05 level (p = 0.094), though there was a consistent trend for greater residual soil inorganic N following intercropped, compared to monocropped, cereals (Table 3). Manured soils contained 25 kg N ha⁻¹ on average more than non-manured soils, and residual soil inorganic N was greater following the year 2 crop harvest than year 1 (Table 3), suggesting some soil N accrual occurred. Greater soil N levels in year 2 may have supported greater hay yields in year 2 of the forage system, in spite of the drought. Soil N levels were numerically greatest following
two years of intercropped grain triticale, followed by intercropped forage triticale and
intercropped wheat, and were lowest following monocropped wheat and grain triticale (Table 3).
Interestingly, pea biomass accumulation and pea green manure N input were lowest in both years
in intercropped grain triticale (Table 1), which would suggest that low N accumulation would be
achieved in the system. However, N withdrawals from the system via removal of the triticale
grain were comparatively low, as grain yields were low in that system, especially in year 2
(Figure 1). Diversity of plant residues in that system may have increased the diversity of carbon
substrates available to soil microbes, which can stimulate microbial activity and organic matter
mineralization (Sanchez et al., 2001), leading to high levels of soil inorganic N. Differences in
soil organic matter mineralization may have been a driving factor for the trend of greater soil
inorganic N following the intercropped systems, compared to monocropped pea green manure.
Future studies should investigate the impact of intercropping on soil microbial activity, as it
correlates to soil organic matter turnover and nutrient cycling, important features of a healthy
organic system (Mader et al., 2002).

Year 3 Winter Wheat

The effect of previous cropping system on winter wheat flag leaf N was not significant at
the $\alpha = 0.05$ level ($p = 0.148$), but a greater trend of flag leaf N was observed following
intercropped wheat + pea, intercropped forage triticale + pea, and monocropped pea green
manure (3.5, 3.3, and 3.2% N, respectively). Flag leaf N was lowest following monocropped
wheat and grain triticale (2.9% N). The effect of manure applied the previous two years was
significant ($p = 0.017$) and increased N by 10% (data not shown). Nitrogen effects observed from
the manure and not from the intercropping treatments suggests that manure-N may have been
supplying N at the time of flag leaf development in the subsequent winter wheat crop, and not
green manure-N. Application of manure during the previous two years also increased winter wheat grain yields by 20% (680 kg ha\(^{-1}\)), compared to non-manured systems (Figure 3), as predicted by flag leaf N. However both previous cropping system (p < 0.001) and manure treatment (p = 0.008) exerted an effect on subsequent winter wheat yields. The effect of poultry manure application on subsequent organic winter wheat grain yields highlights the benefits of manure to productivity in organic systems and confirms that incorporation of manure into soil fertility management programs can increase productivity, and profitability if the manure is accessible and affordable. However, intercropping cereals with pea green manure increased subsequent winter wheat grain yields by 1060 to 2880 kg ha\(^{-1}\) on average, compared to monocropped pea green manure (Figure 3). By comparison, applying manure to monocropped cereals resulted in of 850 to 2250 kg ha\(^{-1}\) greater yields in the subsequent winter wheat crop, compared to monocropped pea green manure (Figure 3). Non-manured intercropped triticale + pea hay resulted in 1015 kg ha\(^{-1}\) greater subsequent yields, compared to monocropped pea green manure. Intercropping cereals and green manure could have greater benefits for subsequent productivity, compared to manure, and could prove more economical.

Winter wheat grain yields were greatest following intercropped grain triticale and were lowest following monocropped green manure, likely due to the buildup of weed pressure in that system (Figure 2; personal observation) (Figure 3). High yields following intercropped grain triticale were likely the result of high N availability in that system, as inorganic N levels observed prior to planting winter wheat were greatest following intercropped grain triticale (Table 3). While grain yields in triticale the previous two years were not high (2000 to 4500 kg ha\(^{-1}\), on average), the 1000 kg ha\(^{-1}\) increase in winter wheat yields following triticale, relative to following other monocropped or intercropped cereals, will likely prove more profitable for
growers. Alongside the buildup of soil residual N, intercropped grain triticale suppressed weeds similarly to other intercropped and monocropped cereals, and more than monocropped pea green manure, satisfying both goals of the green manure phase of an organic grain production system. However, this study tested only one variety of grain triticale, and higher-yielding varieties of triticale may withdraw more N and other nutrients from the system and result in lower residual soil available N. The study should be repeated using different cereal varieties to ascertain whether residual soil N effects are dependent on cereal variety.

Conclusions

Adding cereal crops that were harvested for grain to the green manure fertility-building phase of the rotation did not reduce the N available to the subsequent winter wheat cash crop, but rather increased subsequent yields and protein content by limiting weed pressure in pea, a less competitive crop. Additionally, intercropped triticale + pea hay increased subsequent winter wheat yields, compared to monocropped pea green manure and displayed greater resilience and yields during drought conditions than intercropped cereals harvested for grain. Intercropped triticale + pea hay also contained greater crude protein than monocropped triticale hay and, given production levels, could potentially be more profitable than intercropped cereals. Applying poultry manure the two years prior increased winter wheat yields, but no effect from manure was observed in grain yields in years 1 and 2, suggesting that investing in spring-applied manure in organic grain production systems will not be effective in the short term.

Intercropped pea green manure resulted in N inputs of up to 32.8 kg N ha⁻¹, and after termination did not interfere with grain harvest. Termination of pea green manure mid-season was effective at killing the pea crop, but may not be necessary if a short-statured pea variety is used. Future studies should investigate management strategies for intercropping cereals and
legumes grown for green manure with the goal of reducing additional labor and costs associated with managing the green manure crop, such as using a short-statured pea variety. A shorter pea cultivar may not require termination, but will dry down to a height over which a combine can cut during grain harvest. Belowground competitive interactions for soil water and nutrients between intercropped cereals and green manure should be investigated, with the goal of pairing intercrops to minimize direct competition. Additionally, the fate of N released from the green manure should be traced to determine the timing of availability and uptake for cereal crops. This study demonstrated the potential of intercropping cereals and pea green manure in dryland organic systems to increase the productivity and quality of organic cereals, which has the potential to improve revenues for organic growers.
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Figure 1. Grain yields in monocropped and intercropped spring wheat and grain triticale (Grain Trit), and forage yields in forage triticale (For Trit), in a) 2013, a wet year, and b) 2014, a dry year, at the Boyd Farm site. Forage yields depicted are in kg dry matter ha$^{-1}$. Error bars depict the standard error of the mean.
Table 1. Pea aboveground biomass accumulation, pea tissue N, and pea green manure (GRNM) total N input to the systems in years 1 (2013) and 2 (2014) at the Boyd Farm site. Means displayed are averaged across manured and non-manured treatments.

<table>
<thead>
<tr>
<th></th>
<th>Pea Biomass (kg ha(^{-1}))</th>
<th>Pea Tissue N (%)</th>
<th>Pea GRNM N Input (kg N ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>StdErr(^{†})</td>
<td>Mean</td>
</tr>
<tr>
<td><strong>Monocropped Pea GRNM</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Year 1</td>
<td>1015</td>
<td>210</td>
<td>3.21</td>
</tr>
<tr>
<td>Year 2</td>
<td>1965</td>
<td>305</td>
<td>2.20</td>
</tr>
<tr>
<td><strong>Intercropped Pea GRNM + Wheat</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Year 1</td>
<td>1380</td>
<td>175</td>
<td>2.79</td>
</tr>
<tr>
<td>Year 2</td>
<td>575</td>
<td>55</td>
<td>2.22</td>
</tr>
<tr>
<td><strong>Intercropped Pea GRNM + Grain Trit</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Year 1</td>
<td>965</td>
<td>160</td>
<td>2.70</td>
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<tr>
<td>Year 2</td>
<td>395</td>
<td>60</td>
<td>2.16</td>
</tr>
<tr>
<td><strong>Intercropped Pea GRNM + Forage Trit</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Year 1</td>
<td>960</td>
<td>105</td>
<td>2.96</td>
</tr>
<tr>
<td>Year 2</td>
<td>815</td>
<td>95</td>
<td>2.00</td>
</tr>
</tbody>
</table>

\(^{†}\) standard error of the mean
Figure 2. Relative weed biomass, as a percent of total aboveground biomass (crop + weed), in monocropped and intercropped spring wheat, forage triticale (For Trit), and grain triticale (Grain Trit) in a) 2013 and b) 2014 at the Boyd Farm site. Error bars depict the standard error of the mean.
Table 2. Grain percent N in mono- and intercropped spring wheat and triticale in years 1 (2013) and 2 (2014) at the Boyd Farm site.

<table>
<thead>
<tr>
<th></th>
<th>Monocropped</th>
<th>Intercropped</th>
<th>Cropping Treatment Effect $^§$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No Manure</td>
<td>Manure $^¥$</td>
<td>No Manure</td>
</tr>
<tr>
<td>----------------------------------% grain N----------------------------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wheat</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Year 1</td>
<td>1.77</td>
<td>1.84</td>
<td>2.05</td>
</tr>
<tr>
<td>Year 2</td>
<td>2.13</td>
<td>2.37</td>
<td>2.25</td>
</tr>
<tr>
<td>Grain Trit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Year 1</td>
<td>1.99</td>
<td>2.05</td>
<td>2.23</td>
</tr>
<tr>
<td>Year 2</td>
<td>1.61</td>
<td>1.80</td>
<td>1.99</td>
</tr>
</tbody>
</table>

$^¥$ The effect of manure was significant ($\alpha = 0.05$) in both years 1 and 2

$^§$ Means comparisons ($\alpha = 0.05$) for cropping effect, comparing mono- and intercropped cereals
Figure 3. Winter wheat grain yield in year 3, following two years of monocropping and intercropping. Dark gray bars represent the increase in yield from applying poultry manure the previous two years, compared to no manure or application of other fertilizer. Different letters represent significant differences among cropping treatments at the $\alpha = 0.05$ level. GRNM = green manure, WT = Wheat, GRTrit = grain triticale, ForTrit = forage triticale variety.
Table 3. Residual soil available N (NH$_4^+$ + NO$_3^-$) following harvest of spring cropping treatments in year 1 (2013) and year 2 (2014) of the intercropping phases. GRNM = green manure, Grain Trit = grain triticale, For Trit = forage triticale variety

<table>
<thead>
<tr>
<th>Cropping Treatment</th>
<th>Year 1</th>
<th>Year 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No Manure</td>
<td>Manure</td>
</tr>
<tr>
<td>Monocropped Pea GRNM</td>
<td>63 abc $^\dagger$</td>
<td>71 abc</td>
</tr>
<tr>
<td>Monocropped Wheat</td>
<td>33 c</td>
<td>26 c</td>
</tr>
<tr>
<td>Intercropped Wheat</td>
<td>34 c</td>
<td>89 ab</td>
</tr>
<tr>
<td>Monocropped Grain Trit</td>
<td>34 c</td>
<td>92 a</td>
</tr>
<tr>
<td>Intercropped Grain Trit</td>
<td>47 abc</td>
<td>65 abc</td>
</tr>
<tr>
<td>Monocropped For Trit</td>
<td>54 abc</td>
<td>63 abc</td>
</tr>
<tr>
<td>Intercropped For Trit</td>
<td>39 bc</td>
<td>80 abc</td>
</tr>
</tbody>
</table>

$^\dagger$ In year 1, there was an interaction between cropping and manure treatments. Different letters correspond to differences at the $\alpha = 0.05$ level among interacting treatments.

$^\S$ In year 2, the main effects of cropping and manure treatments were significant, but there was no interaction. Different letters correspond to differences at the $\alpha = 0.05$ level among cropping systems.
APPENDIX

Summary Report


Introduction

While many growers have reported dissatisfaction with the lack of information and resources available to organic farmers, few surveys have been conducted about the organic grower population by public institutions to inform research and Extension services tailored towards organic farming. The Organic Farming Research Foundation (OFRF) has conducted four nationwide organic producer surveys, which included questions concerning the amount and type of products produced, marketing practices, organic prices, and research priorities (Walz, 2004). The U.S. Department of Agriculture (USDA) performed surveys of organic growers nationwide in 2009 and 2011, in which growers were asked to report land use, value of sales, crops harvested, and marketing practices. While these surveys were very valuable in terms of identifying research priorities for organic agricultural research nationwide (Sooby et al., 2007) and quantifying the extent and value of organic production in the U.S. (USDA-NASS, 2012), little to no questions were asked about tillage implements, weed control, and soil fertility management.

In the Pacific Northwest, a survey was conducted in 2006 through a joint effort of the WSU Wheat Breeding Program and the Department of Community and Rural Sociology targeting Washington wheat growers (Jones et al., 2006). While most respondents were
conventional growers, questions were included to gauge interest in growing organic grains, as well as to identify the perceived primary barriers to organic small grains production. More recently, surveys of certified organic producers in Washington and Idaho were conducted that addressed motivations to farm organically, marketing practices, sources of information, and challenges faced by organic growers (Goldberger, 2008; Goldberger et al., 2010). Because these surveys targeted all organic producers and the character of vegetable, small grains, and livestock operations are often quite different, information pertaining specifically to large-scale organic management practices was still lacking.

To gain a better understanding of organic growers’ use of tillage implements, weed control, and soil fertility management practices in the northwestern U.S., a survey of certified organic producers of alfalfa, grass hay, cereal crops, pulses, livestock, and dairy cows was conducted from February to May 2014. The survey was performed to supplement findings from field trials and to inform outreach efforts and future research on applied management practices as part of a USDA-funded, multi-state, six-year project examining weed control, soil management, and crop rotation practices in dryland organic production systems. Goals of the survey were to identify 1) barriers to producing organic grains in the northwestern U.S., 2) weed control practices, 3) soil fertility management practices, 4) the most problematic weeds for organic farmers in the region, and 5) research and Extension needs of organic producers in the northwestern U.S. in the areas of weed control and soil management.

Methods

Survey recipients were identified and addresses were obtained from the 2012 List of Certified USDA Organic Operations from the USDA (http://apps.ams.usda.gov/nop/), a national database searchable by state, products produced, and other parameters. The survey was
conducted by the Social and Economic Sciences Research Center (SESRC) at Washington State University from February to May 2014 using the Tailored Design Method (Dillman et al., 2009), during which survey recipients received four mailings, including an introductory letter, questionnaire, reminder postcard, and replacement questionnaire. Survey recipients had the option to complete the survey via the paper questionnaire or on the web. Survey questionnaires were sent to 432 certified organic producers in Idaho, Montana, Oregon, Utah, and Washington and consisted of 36 questions presented in a mix of close-ended and open-ended formats. The questionnaire was divided into three sections: (1) the character of individual farm operations and experiences of growers producing organic crops, (2) production practices concerning weed and soil fertility management and research needs of organic producers, and (3) respondents’ demographics and farming experience.

Results

Of the 432 surveys mailed, 157 completed questionnaires (via mail and the web) and 1 partially completed questionnaire were returned, for a response rate of 38%. Respondents were 86% male and 14% female. Average age was 55 years. Respondents had been involved in farming as an owner, manager, or primary decision maker for 1 to 60 years, with an average of 28 years. The majority (90%) of respondents were not the first person in their family to farm, but 83% were the first person in their family to produce certified organic products. A majority of respondents completed some post-secondary education as their highest level of formal education, with 23% reporting having completed some years of college without finishing the degree, 13% completed a two-year degree, and 31% having obtained a four-year college degree. Only 16% of respondents reported a high school diploma or less as the highest level of formal education completed.
The National Organic Standards and the USDA Organic Seal were established in 2002; prior to this time, growers were certified organic by smaller, independent, state or regional certification agencies. When the USDA established a uniform set of national standards, responding to growth in demand for organic certification, many of these state and regional agencies became accredited by USDA to certify organic operations under the national program. Over a third of respondents reported operating certified organic farms prior to 2002, which were certified organic mostly by state agencies (e.g., Washington State Department of Agriculture), which have since received accreditation by USDA. After 2002, the greatest number of new organic certifications took place in 2006 and 2007 (Figure 1), after which the number of new certifications declined among the grain crop and livestock producer population surveyed.

Seventy-nine percent of survey respondents had transitioned some of their conventional acreage to certified organic acreage; however, only 29% of respondents still operated some conventional acreage, indicating that the majority of operations produced only organic products. Respondents operated 1,338 certified organic acres, on average, with respondents in Montana and Utah operating more certified organic acres than growers in Idaho, Oregon, and Washington (Table 1). Grass hay was the most common organic product produced by survey respondents, followed by alfalfa, barley, and beef cattle. When asked in an open-ended question what their primary reason was for farming organically, respondents most commonly mentioned financial or economic factors, followed by the belief that growing organically was better for the environment. Concerns about corporate agriculture and chemicals, the health of their family and workers, and animal welfare were also motivating factors mentioned by respondents.

When presented with a list of potential problems associated with farming organically, survey respondents were asked to rate the extent that each factor had been a challenge to the
success of their organic farming operation in the past five years. The “high cost of organic inputs” was rated as the most challenging, with 63% of respondents rating it as a “moderate” or “considerable” challenge. “Weed-related production losses” and “variable or low yields” were the second and third most challenging factors faced by organic growers in the northwestern U.S (Table 2). The majority (66%) of respondents reported having used irrigation on their farms in the past five years, and of those respondents, 63% reported having no trouble accessing sufficient irrigation water during the past five years. However, in the list of primary challenges to operating a successful organic farm, “lack of irrigation water” was rated as a “moderate” or “considerable” challenge by 30% of respondents, implying that access to water is a major issue for those few operations that require irrigation and experience limited access. Despite these challenges, 98% of all respondents planned on maintaining their organic certification over the next five years, and of those, 41% planned to increase production (Figure 2).

When asked to select the product that represented the largest portion of growers’ gross income earned from certified organic products, alfalfa (23%) and dairy cows (milk and other dairy products) (21%) were the top two products chosen. Given the diversity of the operations surveyed, many other products were selected as the most profitable (Figure 3). Only 15% of respondents reported developing value-added products from certified organic crops, meat, and eggs produced on their operations. Increased income and access to markets were mentioned by these respondents as reasons for producing value-added products. Certified organic products made up the majority of farm sales for most respondents, as these products made up greater than 75% of total farm sales for 68% of respondents (Figure 4). Similarly, 65% of respondents were able to sell greater than 75% of their certified organic products at an organic price premium.
A majority (66%) of respondents rated the importance of being able to sell their certified organic products at a price premium as “somewhat important” or “very important” to the success of their operation, but 21% rated it as “very unimportant” (Figure 5). Interestingly, more growers who produced only certified organic products rated the importance of organic price premiums as “very unimportant” compared with growers who produced both types of products, suggesting that price premiums are not crucial for the survival of all organic operations. However, those who rated price premiums as “somewhat important” or “very important” included growers who produced only certified organic products and growers who produced both organic and conventional products, indicating that even growers who operate in both types of markets depend on price premiums for certified organic products.

Weed Management

Seventy-one percent of respondents used at least one type of tillage implement to control weeds on their certified organic acreage, and 53% used more than one type of mechanical tillage. As some tillage implements are appropriate to use in only certain crops, mechanical tillage use responses were disaggregated by type of crops produced (grain crops vs. forage crops). Grain crop producers used, on average, more mechanical tillage implements compared with forage crop producers, likely because many forage crops are perennials, and don’t require annual tillage before and after planting. Grain crop producers used pre-plant tillage (78%) and a rod weeder (43%) for mechanical weed control, and forage crop producers used pre-plant tillage (43%) and a tine weeder (15%) for mechanical weed control (Table 3). The cultural controls used by the most respondents to control weeds were crop rotation (89% of grain crop and 59% of forage crop producers) and an increased seeding rate (71% of grain crop and 46% of forage crop producers) (Table 3). A majority (65%) of grain crop producers reported having used cover crops. When
asked which weeds have proven difficult to control on certified organic acreage and/or have negatively impacted their certified organic products, growers most often mentioned Canada thistle (*Cirsium arvense*) and field bindweed (*Convolvulus arvensis*), followed by mustard (Brassicaceae) and pigweed (*Amaranthus*) species (Figure 6).

**Soil Fertility**

A majority (78%) of respondents conducted soil sampling and/or soil tests to monitor the nutrient status of their soils, and of those, 89% of growers who operated both conventional and certified organic acreage performed soil sampling/tests on both types of acreage. Sixty-nine percent of respondents reported having applied livestock and/or poultry manure on their farm, of which 76% applied manure only on their organic acreage. Additionally, 74% of those who applied manure reported that the manure was generated on-farm.

Fifty percent of respondents reported having grown cover crops and 55% of respondents grew green manure crops on their certified organic acreage to supply nitrogen to their soil. The cover crops most commonly mentioned were peas (38%) and oats (29%) followed by wheat (19%), barley (16%), triticale (16%), and vetch species (16%). Rates of the use of green manure between the five states were comparable, with the lowest in Oregon (48%) and greatest in Montana (67%). Growers were asked about their fertility management strategies, and green manure was the most common soil fertility management tactic employed by respondents. Growers also reported applying compost (36%), natural fertilizer from animals (e.g., blood meal, fish emulsion, bone meal) (45%), and green waste (18%). These rates of use were comparable between grain crop and forage crop producers. When asked what soil fertility issues they would like to see addressed by public researchers and Extension agents, growers most often mentioned the development of affordable soil fertility amendments or products (16%) and cover crops.
research (13%). Growers also mentioned strategies to achieve sufficient levels of plant-available nitrogen (12%) and phosphorus (10%).

Conclusions

While the survey results indicate that the rate of adoption of organic agriculture is slowing in the northwestern U.S. among small grains and livestock producers, they also show that those operating certified organic acreage have little intention of giving up on organic management. Financial factors proved to be the strongest motivator for certified organic producers; however, their strong convictions in organic farming leading to the improved health of their families and a lower impact on the environment likely lower the possibility that certified organic growers in the northwestern U.S. will return to conventional farming, even if returns from organic products decrease. In written comments many respondents expressed their belief that organic agricultural practices were better for their families and customers, and did not want to use chemicals on their operations. However, the number of organic small grains, forage, and livestock producers in the northwestern U.S. is low compared to other regions, such as the Midwest (USDA-NASS, 2012); consequently, these growers struggle with problems that result from the organic market being relatively small and undeveloped, such as feeling underserved by public researchers and the agricultural industry as a whole.

Responses indicated alfalfa and dairy to be the most profitable certified organic products produced, followed by beef cattle, suggesting that meat and dairy products are likely more profitable for growers than are certified organic commodity cash grains such as winter and spring wheat, and other small grains. Such a finding suggests that certified organic grain producers may find that marketing their organic small grains for feed may be more profitable than growing for food-grade markets.
While other surveys have identified low yields to be a challenge for organic growers (Goldberger, 2008) and a perceived barrier to adopting organic production practices (Jones et al., 2006) in the northwestern U.S., certified organic growers still reported struggling with weed and pest control issues, which indicates little progress has been made in controlling pests without the use of chemicals. The persistence of yield losses due to weeds and pests points to the need for public researchers and Extension agents to use survey findings to inform the design of organic production studies, while listening to the needs of growers and taking current management practices into account. Currently, most growers reported having used mechanical tillage but relied mostly on cultural methods to control weeds, especially pre-plant tillage, crop rotation, and increased seeding rates, which have not proven successful in ameliorating pressure from the perennial weeds Canada thistle and field bindweed.

Similarly, field studies of organic management practices often focus on cultural controls, as they are an integral part of the organic agricultural paradigm; however, research on larger-scale, technology-based tactics for weed and pest control, such as precision guidance systems for tillage implements in performing weeding operations, could greatly benefit organic growers operating on large acreages. Research efforts to help organic field crop growers control weeds would likely contribute to the sustainability of these operations, as several growers reported weeds as limiting their crop choices and endangering the survival of their organic operations. Enabling the practice of organic agriculture on large acreages could also extend the ecological benefits derived from organic agriculture to a greater land area, as opposed to researchers focusing on small organic vegetable farms operating on few acres. The findings of this survey identify a group of organic growers operating on a comparable scale to conventional producers with similar, but underserved, research needs. Publicly supported efforts to improve weed
control and soil fertility efforts on these operations could benefit the availability of organic products, increase financial returns for growers, and result in measurable benefits to agroecosystems on a landscape scale.
Literature Cited


Figure 1. Histogram of organic certifications received by operations of respondents after 2002, adhering to the National Organic Standards established by USDA in 2002.
Table 1. Mean and median certified organic acreage reported by survey respondents in five states.

<table>
<thead>
<tr>
<th>Certified Organic Acres Operated</th>
<th>Mean</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>Idaho</td>
<td>536</td>
<td>260</td>
</tr>
<tr>
<td>Montana</td>
<td>3,770</td>
<td>1,398</td>
</tr>
<tr>
<td>Oregon</td>
<td>581</td>
<td>320</td>
</tr>
<tr>
<td>Utah</td>
<td>5,376</td>
<td>5,086</td>
</tr>
<tr>
<td>Washington</td>
<td>328</td>
<td>170</td>
</tr>
<tr>
<td>All States</td>
<td>1,338</td>
<td>350</td>
</tr>
</tbody>
</table>
### Table 2. Challenges faced by certified organic operations in the northwestern U.S.

<table>
<thead>
<tr>
<th>Challenge</th>
<th>Mean Score*</th>
</tr>
</thead>
<tbody>
<tr>
<td>High cost of organic inputs</td>
<td>2.74</td>
</tr>
<tr>
<td>Weed-related production losses</td>
<td>2.67</td>
</tr>
<tr>
<td>Variable or low yields</td>
<td>2.44</td>
</tr>
<tr>
<td>Lack of affordable fertility sources</td>
<td>2.32</td>
</tr>
<tr>
<td>Lack of organic price information</td>
<td>2.14</td>
</tr>
<tr>
<td>Difficulty in obtaining organic inputs</td>
<td>2.10</td>
</tr>
<tr>
<td>Lack of public research focused on organic production</td>
<td>2.05</td>
</tr>
<tr>
<td>Production losses due to pests or diseases</td>
<td>1.99</td>
</tr>
<tr>
<td>Lack of irrigation water</td>
<td>1.98</td>
</tr>
<tr>
<td>Lack of animal manure resources</td>
<td>1.91</td>
</tr>
<tr>
<td>Low prices received for products</td>
<td>1.81</td>
</tr>
<tr>
<td>Unstable organic prices</td>
<td>1.77</td>
</tr>
<tr>
<td>Limited distribution opportunities</td>
<td>1.77</td>
</tr>
<tr>
<td>Inability to find enough farm labor</td>
<td>1.72</td>
</tr>
<tr>
<td>Lack of crop varieties suited for organic production</td>
<td>1.71</td>
</tr>
<tr>
<td>Limited demand for organic products</td>
<td>1.67</td>
</tr>
<tr>
<td>Lack of access to processing facilities</td>
<td>1.56</td>
</tr>
<tr>
<td>Lack of access to equipment</td>
<td>1.50</td>
</tr>
<tr>
<td>Pesticide or herbicide drift</td>
<td>1.30</td>
</tr>
</tbody>
</table>

* Mean score on a scale from 1 = “Not at All,” 2 = “Minimal,” 3 = “Moderate,” 4 = “Considerable.”
Figure 2. The percentage of respondents planning to decrease, maintain, or increase current level of organic production, of those respondents who plan to maintain their organic certification over the next five years.
Figure 3. Certified organic products representing the largest portion of gross income.

Respondents were asked to select the one product that represented the largest portion of the gross income earned from their operations’ certified organic products in the previous year (2013). The “dairy” category includes milk and other dairy products; the “sheep” category includes sheep-derived products; the “chickens” category includes eggs and meat; the “other poultry” category includes eggs and meat, and the “other products” category includes certified organic crops, animals, or animal products not on the list provided.
Figure 4. Percentage of total farm sales derived from certified organic products, including certified organic value-added products.
Figure 5. Importance of receiving a price premium for certified organic products. Survey recipients were asked to rate the importance of being able to sell their certified organic products at a price premium to the success of their operation. Responses shown above are displayed according to the type of operation. “Both certified organic and conventional” refers to operations with both certified organic and conventional acreage, and “only certified organic” refers to operations with certified organic acres only.
Table 3. Percentage of respondents who reported using selected implements for mechanical weed control. Percentages shown include those who used these implements only on their certified organic acres, and those who used them on both their certified organic and conventional acres.

<table>
<thead>
<tr>
<th>Weed Control Practice</th>
<th>Grain Crop Producers(^a) (%)</th>
<th>Forage Crop Producers(^b) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mechanical Controls</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-plant tillage</td>
<td>78</td>
<td>43</td>
</tr>
<tr>
<td>Rod weeder</td>
<td>43</td>
<td>19</td>
</tr>
<tr>
<td>Tine weeder</td>
<td>32</td>
<td>22</td>
</tr>
<tr>
<td>Inter-row cultivator</td>
<td>30</td>
<td>11</td>
</tr>
<tr>
<td>Root undercutter</td>
<td>22</td>
<td>13</td>
</tr>
<tr>
<td>Rotary harrow</td>
<td>17</td>
<td>15</td>
</tr>
<tr>
<td>Rotary hoe</td>
<td>11</td>
<td>4</td>
</tr>
<tr>
<td><strong>Cultural Controls</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crop rotation</td>
<td>89</td>
<td>59</td>
</tr>
<tr>
<td>Increased seeding rate</td>
<td>71</td>
<td>46</td>
</tr>
<tr>
<td>Cover crop</td>
<td>65</td>
<td>35</td>
</tr>
<tr>
<td>Selection of competitive varieties</td>
<td>64</td>
<td>41</td>
</tr>
<tr>
<td>Residue mulch</td>
<td>45</td>
<td>18</td>
</tr>
<tr>
<td>Relay- or inter-crop</td>
<td>32</td>
<td>18</td>
</tr>
</tbody>
</table>

\(^a\) Includes respondents who produced winter wheat, spring wheat, beans (dry), barley, chickpeas, oats, triticale, peas, and/or lentils, and not the crops in the forage category (see footnote b).

\(^b\) Includes respondents who produced alfalfa, grass hay, and/or silage, and not the crops in the grain crop category (see footnote a).
Figure 6. Weeds mentioned in response to an open-ended question, asking survey recipients to list weeds that were difficult to control on their organic acreage and/or have negatively impacted their certified organic products. Weeds mentioned by less than 4% of respondents are not shown.