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Transition cropping system impacts on organic wheat yield and quality

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Abstract

Organic wheat and small grains are produced on relatively few acres in the inland Pacific Northwest. The objective of this study was to examine how the nitrogen (N) dynamics of cropping systems (CSs) produced during the transition phase impacted organic wheat yield and protein levels in the first 2 years of certified organic production. Certified organic spring wheat (SW) was produced in 2006 and winter wheat (WW) in 2007 following nine, 3-year transitional cereal, small grain and legume-intensive CSs. SW and WW following perennial alfalfa + oat/pea forage or 3 years of legume green manure tended to be more productive than wheat that followed systems that contained a small grain crop for at least 1 year during the transition. In addition to increasing soil N, well-established stands of forage and green manure provided adequate cover to reduce weed establishment prior to organic production. Effective weed control strategies were as important as increasing soil inorganic N levels for improving organic wheat production. Choice of crop type, cultivar and rotation is important in organic wheat systems and in this study, WW had better stand establishment, competition with weeds and higher overall yield than SW and would be a better-suited class of wheat for organic production in situations where spring weeds are the dominant problem. Regardless of CS or crop type, supplemental soil fertility (primarily N) during the organic production phase will be necessary to maintain high soil N levels and wheat yields in these dryland systems.

Key words: organic wheat, legume green manure, mixed forage, soil inorganic N, organic weed control

Introduction

Washington State crop producers have been very successful at achieving high yields of dryland spring and winter wheat (WW) (*Triticum aestivum* L.) using conventional practices[1], but only produce 1.4% of the total amount of organic wheat grown in the USA.[2] A local survey documented that many Washington wheat growers are interested in organic production; however, only a few actually practice organic agriculture[3]. Reliance on inputs to manage soil fertility and weeds make organic grain farming in the region difficult and, often, economically unsustainable. Inadequate fertility inputs as well as weed and pest control methods can reduce crop yields and grain quality, and are often cited as the main reasons that growers are reluctant to adopt organic practices[3–7]. In the inland Pacific Northwest, organic growers are constrained beyond federal organic regulations[8] by sparse livestock production and the concern of soil erosion[9,10]. As a consequence, grower options for adopting mechanical and animal-based methods to manage weeds and soil fertility are limited[11]. Given the potential constraints associated with organic dryland wheat production, cropping systems (CSs) that aid growers in (1) successfully transitioning to organic production and (2) achieving certified organic yields and protein levels comparable to those in conventionally managed systems, must be identified for the dryland region of the inland Pacific Northwest.

Organic CSs rely on crop rotations, tillage, changes in seeding dates and rates, intercropping, use of green manures and varietal selection to build soils and control pests[5,12,13]. Legumes have the ability to supply a renewable source of nitrogen (N) to agricultural soils through biological N-fixation, providing a viable option for organic growers to deliver N to non-leguminous crops and reducing off-farm N inputs[14–16]. The benefits of including legumes as green manures in rotations with cereal crops as a source of N[5,14,15,17,18] and in mixed-CSs for forage production[4,19–21] are well documented.

Organic production practices do not necessarily reduce grain yields or protein levels[5,7,22,23]. Maximum yields of organic grain crops were higher than conventional grain yields during the transition and the first year of organic production[24] and when compared to long-term averages for conventional yields[4]. Cavigelli et al.[25] found that organic crops produced higher yields and had lower risks than conventional systems, despite increased management challenges. In many cases, organic grain crops have also demonstrated a greater tolerance to environmental stresses, such as drought and heat, when compared to conventionally grown crops[5,7,22,26]. However, many authors warn that environmental conditions in combination with poor soil fertility or crop competitive properties can negatively impact organic grain yields[12,22,27,28].

Despite the challenges of organic production, demand for organic food products remains high and US sales of organic foods have sustained a relatively stable 20% growth rate since 2000[7,29–31]. The need for organic feed grains and forage is particularly great, due to the expansion of the dairy and beef industries in the Pacific Northwest, and increased price premiums for these products[7,31]. In 2003, Washington State imported 85% (US$328.6 million) of the organic grain feed it consumed from the Mid-west and Canada due to production deficiencies of these products in the inland Pacific Northwest[31]. Recognition of available markets, along with increased interest by growers in producing organic products in the inland Pacific Northwest[32,33] emphasizes the need for continued research of organic dryland CSs in this region.

The current experiment is a continuation of research reported by Gallagher et al.[11] and Borrelli et al.[34] Gallagher et al.[11] examined the agronomic performance, and Borrelli et al.[34] the N dynamics, of nine diverse CSs managed under reduced tillage during the 3-year transition to certified organic wheat production in Eastern Washington State. Key objectives of Gallagher et al.[11] were to design and evaluate organic transition CSs that did not rely on inversion tillage and that supplied N fertility to the following organic cereal crops through the use of legume grain, green manure and perennial forage crops in rotation. Gallagher et al.[11] found that spring crops experienced poor stand establishment, did not produce sufficient biomass, experienced weed pressure, and often failed as transition crops. Alternatively, the perennial forage and winter legume green manure performed more suitably as transition crops because they produced ample biomass and suppressed weeds. When examining the N balances of the transition systems, Borrelli et al.[34] found that because perennial forage and winter legume green manure crops were competitive with weeds and increased residual soil inorganic N in the final year of the transition, they demonstrated the greatest potential for enhancing soil fertility during organic production[34]. The objective of the current experiment was to examine how the N dynamics of CSs produced during the transition phase impacted organic wheat yield and protein levels in the first 2 years of certified organic production.

Materials and Methods

Site description

The experiment was conducted in Whitman County, near Pullman, WA (46°45′N; −117°4′W) on a Palouse silt loam soil type (fine-silty, mixed, superactive, mesic Pachic Ultic Haploxerolls). The regional climate is subhumid and the annual average precipitation is approximately 55–65 cm[1,35] with 60% of the precipitation occurring between November and March and 11% from July to September[36].

Transition systems

Nine transitions systems (2003–2005; Table 1) were designed to represent possible systems ranging from grain cash crop-intensive to legume-intensive CSs under dryland conditions typical of Eastern Washington. Detailed agronomic conditions and management practices of the crops grown during the transition phase were reported thoroughly by Gallagher et al.[11]. The CSs included various combinations of cereal crops [spring wheat (SW), WW or spring barley (*Hordeum vulgare* L.; SB)], legume crops [spring pea (*Pisum sativum* L.; SP), winter pea (WP) or bell bean (*Vicia faba* L.; BB)] and a perennial alfalfa (*Medicago sativa* L.), oat (*Avena sativa* L.) and SP forage mixture. Whenever present, cereal crops (WW, SW and SB) were harvested as grain cash crops. Cropping system 1 was a cereal-intensive system that had no legume crops and represented a rotation common to Eastern Washington, and acted as a control. Cropping systems 2 and 3 were grain-intensive rotation systems of SP and WW or SW, respectively. Spring pea was harvested as a cash grain crop (CSs 2, 3, 4 and 5 in 2003; CSs 2 and 3 in 2005) with the intention that it would still contribute N to these systems from fixation even with grain removal, as suggested by Kirkegaard et al.[14] and Peoples et al.[15]. When SP plots had 50% or greater weed cover, they were considered a crop failure and flail mowed[11]. Bell bean (CSs 6, 7 and 8) was intended to be grown as a green manure throughout the experiment and was flail mowed at 75% flower initiation in 2003[11]. However, due to poor stand establishment and overall poor growth in 2003[11], BB was replaced by WP as a green manure legume in 2004 and 2005. In 2005, all WP legume crops (CSs 4, 5, 6, 7 and 8) were grown as green manure. Cropping system 8 was a legume-intensive system and the legumes were grown as green manure every year. Green manure crops were mowed once per

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Table 1. Rotation sequences for the organic transition CSs.

CS	Transition phase			Certified organic phase[1]	
	Year				
	2003	2004	2005	2006	2007
			Control rotation		
1	SW	WW	Spring barley	SW	WW
			3 years of grain cropping		
2	Spring pea	WW	Spring pea	SW	WW
3	Spring pea	SW	Spring pea	SW	WW
			2 years of grain cropping + 1 year green manure		
4	Spring pea	WW	Winter pea GM	SW	WW
5	Spring pea	SW	Winter pea GM	SW	WW
			1 year of grain cropping + 2 years green manure		
6	Bell bean GM	WW	Winter pea GM	SW	WW
7	Bell bean GM	SW	Winter pea GM	SW	WW
			3 years green manure		
8	Bell bean GM	Winter pea GM	Winter pea GM	SW	WW
			Legume/grass forage		
9	Alfalfa + oat/pea	Alfalfa + oat/pea	Alfalfa + oat/pea	SW	WW

[1] Each SW plot was split to a hard red (cv. 'Tara 2002') and soft white (cv. 'Alpowa') wheat variety.

year (early to mid-July in 2003 and 2004; early June in 2005). The perennial legume–grass forage mixture (CS 9) was broadcast-seeded to alfalfa at the start of the transition phase. Alfalfa establishment was supplemented by drilling an oat/SP mixture into the stand each of the transition years[11]. The annual oat and SP crops helped alfalfa compete with early-season weeds, but the forage stand was primarily dominated by alfalfa as the season progressed. Perennial forage was cut for hay once per year (mid-July in 2003 and 2004; mid-June in 2005), baled and removed from the system each year. Termination of the forage without herbicides or tillage was an initial concern, but a fall sweep plow and rotary harrow system successfully terminated it at the end of the transition phase[11]. Repeated mowing with a low-disturbance rotary hoe, harrow and under-cutter sweep was necessary to control fall weed growth following crop failure or harvest and to prevent germination of spring weeds. Failure to control weeds would have impeded both winter and spring crop development. Weed control methods varied slightly depending on CS each year and detailed descriptions of timing, method and frequency are discussed in specific detail by Gallagher et al.[11].

Crop management during the organic phase

The certified organic phase of the project began in 2006 and continued through 2007. During this phase, wheat was grown in all plots each year. In 2006, the 9 by 15 m plots were split, with half hard red (HR) SW (cv. 'Tara 2002') and half to soft white (SW) SW (cv. 'Alpowa'). In 2007, all plots were planted to the same variety of WW (cv. 'Madsen'). Crop management practices followed the USDA National Organic Program (NOP) regulations throughout the duration of the experiment, with a few exceptions as explained by Gallagher et al.[11].

Spring and WW were established without the use of inversion tillage methods. Pre-plant soil preparation generally included one pass with a sweep plow followed by one (WW) or two (SW) passes with a rotary harrow to control pre-season weeds. Crops were direct-seeded using a 2.2 m wide Fabro® no-till drill with 19 cm row spacing (Fabro Enterprises Ltd., Swift Current, SK, Canada). Both varieties of SW were seeded on May 2, 2006 and WW on October 2, 2006. Supplemental fertilizer (in 2006, BioGro® 7N–7P–2K; Bio-Oregon, Inc., Warrenton, OR and in 2007, Nature's Intent 9N–3P–4K; Pacific Calcium Inc., Tonasket, WA) supplied 18 and 23 kg ha^{-1} of N to SW and WW, respectively, as a starter fertilizer in addition to any plant-available N that may have been supplied by the preceding crop rotation during the transition phase. In-crop weeds were partially controlled with three to five passes of a rotary hoe. Wheat was harvested at maturity using a Wintersteiger® plot combine (Wintersteiger Inc., Salt Lake City, UT) with a 1.2 m wide harvesting head. Spring wheat was harvested on August 23, 2006 and WW on August 7, 2007. Protein was determined by near-infrared spectroscopy (NIR) according to the Approved Method 39–10[37] as a wheat quality indicator. A Carter-Day dockage tester was equipped with a No. 2 plastic riddle, no sieve in top carriage location, and two No. 2 [1.98-mm (5/64-in)] round-hole sieves in the middle and bottom sieve locations, to quantify all matter other than the wheat that can be

Table 2. Soil inorganic nitrogen (N) levels (0–1.5 m) following nine, 3-year CSs transitioning to organic production (Spring 2006) and following organic production of SW (Fall 2006) and WW (Fall 2007).

CS	Transition phase crop rotation	Soil inorganic *N*		
		Spring 2006	Fall 2006	Fall 2007
		----------kg ha^{-1}----------		
1	SW–WW–SB	120 a[1]	84 e	55 cd
2	SP–WW–SP	107 a	88 e	66 abc
3	SP–SW–SP	103 a	84 e	50 d
4	SP–WW–WP	122 a	113 bc	73 ab
5	SP–SW–WP	110 a	113 bc	79 a
6	BB–WW–WP	118 a	104 cd	74 ab
7	BB–SW–WP	120 a	122 ab	70 ab
8	BB–WP–WP	111 a	130 a	76 a
9	For–For–For	127 a	97 de	62 bcd
P value		0.2685	0.0001	0.0018

SW, spring wheat; WW, winter wheat; SB, spring barley; SP, spring pea; WP, winter pea; BB, bell bean and For, perennial forage.
[1] Means followed with the same letter within a column are not significantly different at the 5% level based on Fisher's LSD level of separation.

removed from the original sample of grain. The feed control was set on 6 and the air control was set on 4 as prescribed in the Federal Grain Inspection Service (FGIS) Grain Inspection Handbook for Wheat (Grain Inspection Packers and Stockyard Administration[38]).

Sample collection and processing

In spring 2006, soil samples were collected from each plot prior to applying fertilizer or planting SW in order to provide a baseline value for soil inorganic N. Post-harvest soil samples were collected again in fall 2006 and 2007. At each sampling time, three soil samples were collected from each plot to a depth of 1.5 m using a 2 cm diameter soil probe. Samples were separated by depth (0–15, 15–30, 30–60, 60–90, 90–120 and 120–150 cm) and the three samples combined for analysis.

Soil inorganic N was determined using a potassium chloride (KCl) extraction method described by Mulvaney[39] and analyzed colorimetrically with a continuous flow auto analyzer (Quick Chem FIA + 8000 Series; Lachat Instruments Milwaukee, WI). Inorganic N values were converted from concentration (mg l^{-1}) to content (kg ha^{-1}) by assuming 2,000,000 lb of soil in an acre furrow slice (approximately 2.2 million kg ha^{-1}, at 15 cm depth) based on an approximate silt loam soil bulk density of 1.33 g cm^{-3}. Crop and weed biomass samples were collected once, mid-season and prior to flowering, removed at ground level and pooled from three, randomly selected 0.33 m^2 subsamples from each plot. Weeds were separated and samples of crop and weed biomass dried for 3 days at 55°C and weighed to determine total biomass. Crop and weed biomass samples were analyzed for total N using a dry combustion auto analyzer (TruSpec CN Determinator; LECO Corporation St. Joseph, MI).

Statistical analyses

The experimental design was a randomized complete block design with nine treatments (CSs) and five replications. Statistical analyses were performed using the PROC GLM procedure in SAS at 95% confidence levels using Fishers's protected LSD method of comparison (SAS Institute, Cary, NC) with block as the random effect and system as the fixed effect. In 2006, plots were split between two cultivars of SW. Data for SW yield, protein and dockage were analyzed as a split-plot design to examine interactions between cultivar and system and differences between cultivars. Soil samples in 2006 were not analyzed separately based on SW cultivar, but compiled and analyzed as a randomized complete block design as stated above.

Results

Soil inorganic N

Soil inorganic N levels were similar among transition phase systems in spring 2006 (mean = 115 kg ha^{-1}; Table 2). Following organic SW production in fall 2006, post-harvest soil inorganic N levels were higher following CS 7 (122 kg ha^{-1}) and CS 8 (130 kg ha^{-1}; Table 2) than other systems. CSs 1, 2, 3 and 9 (84, 88, 84, and 97 kg ha^{-1}, respectively) had the lowest soil inorganic N levels following organic SW. Soil inorganic N levels decreased in all systems following WW production in 2007 but varied depending on CS during the transition phase (Table 2). The highest amounts of soil inorganic N were in CS 8 (76 kg ha^{-1}) and CS 4 to 7 (mean = 74 kg ha^{-1}). CSs 1 (55 kg ha^{-1}), 3 (50 kg ha^{-1}) and 9 (62 kg ha^{-1}) had the lowest soil inorganic N levels following organic WW.

Table 3. Yield and grain protein levels for organic hard red spring wheat (HRSW; cv. 'Tara 2002') and soft white spring wheat (SWSW; cv. 'Alpowa') in 2006 following nine, 3-year CSs during the transition to organic production.

CS	Transition phase crop rotation	'Tara 2002' HRSW yield[1]	'Alpowa' SWSW yield	'Tara 2002' HRSW protein	'Alpowa' SWSW protein
		------------------kg ha^{-1}-----------------		--------------------%--------------------	
1	SW–WW–SB	1990 d[2]	1560 e	10.0 b	8.8 c
2	SP–WW–SP	2810 cd	2450 cde	10.8 b	9.6 c
3	SP–SW–SP	2740 cd	2080 de	10.1 b	9.2 c
4	SP–WW–WP	3060 bc	2500 bcde	12.6 a	11.7 a
5	SP–SW–WP	2570 cd	1980 de	12.5 a	11.2 ab
6	BB–WW–WP	3480 abc	3210 abc	12.6 a	11.3 ab
7	BB–SW–WP	3120 bc	2630 bcd	12.7 a	11.6 a
8	BB–WP–WP	3870 ab	3420 ab	12.4 a	11.3 ab
9	For–For–For	4290 a	3820 a	12.2 a	10.8 b
P value		0.0024	0.0004	0.0001	0.0001

SW, spring wheat; WW, winter wheat; SB, spring barley; SP, spring pea; WP, winter pea; BB, bell bean and For, perennial forage.
[1] Average 2006 SW yields for Whitman County, WA[40] were 3290 kg ha^{-1} and average regional protein levels were 13.3% for HRSW and 10.5% for SWSW[41].
[2] Means followed by the same letter within a column are not significantly different at the 5% level based on Fisher's LSD level of separation.

2006 spring wheat

Transition systems by wheat class/cultivar interactions were not significant for 2006 organic SW yields and protein levels. However, wheat class/cultivar did significantly impact grain yield and protein. Protein has a big impact on sale price when hard wheat is sold, whether or not it is organic, due to its critical role in gluten strength for bread and other products. Protein does not generally affect the price of soft wheat. Because crop yield and quality differ between hard and soft classes of wheat and influence market values, results are presented for each wheat class separately in Table 3.

'Tara 2002' HRSW was higher in yield (mean = 3100 kg ha^{-1}) and protein content (mean = 11.8%) than 'Alpowa' SWSW (mean = 2630 kg ha^{-1} and 10.6%, respectively). Average 2006, SW yield for Whitman County, WA[40] was 3290 kg ha^{-1} and average regional protein levels were 13.3% for HRSW and 10.5% for SWSW[41]. Thus, yields of both varieties were lower than the county average and protein of HRSW was lower.

'Tara 2002' HRSW yield was the highest following CS 9 (4290 kg ha^{-1}), which was similar to the grain yields following CS 6 (3480 kg ha^{-1}) and CS 8 (3870 kg ha^{-1}; Table 3). Hard red SW yields were the lowest following CS 1 (1990 kg ha^{-1}), and were similar to yields following CS 2 (2810 kg ha^{-1}), CS 3 (2740 kg ha^{-1}) and CS 5 (2570 kg ha^{-1}). Yields following CSs 4 and 7 were intermediate with other transition phase systems (3060 and 3120 kg ha^{-1}, respectively). Similarly, HRSW grain protein levels were significantly higher following legume-intensive and forage systems during the transition phase (CSs 4 to 9; mean = 12.5%) compared to grain-intensive cash crop systems (CSs 1 to 3; mean = 10.3%; Table 3).

The effects of CSs on grain yields and protein for 'Alpowa' SWSW followed a pattern very similar to 'Tara 2002' and were the highest following CS 9 (3820 kg ha^{-1}), which were comparable to yields following CS 6 (3210 kg ha^{-1}) and CS 8 (3420 kg ha^{-1}; Table 3). Grain yields were the lowest following CS 1 (1560 kg ha^{-1}), CS 3 (2080 kg ha^{-1}) and CS 5 (1980 kg ha^{-1}). Soft white SW grain following CSs 2, 4 and 7 had intermediate yields compared to those following other transition systems (mean = 2530 kg ha^{-1}). Protein levels for SWSW were the highest following CS 4 (mean = 11.7%) and CS 7 (mean = 11.6%) and lowest following CSs 1 to 3 (mean = 9.2%). Soft white SW protein following CS 9 (mean = 10.8%) was lower than CSs 4 and 7 and higher than CSs 1 to 3. CSs 5, 6 and 8 (mean = 11. 3%) had SWSW protein levels that were intermediate to CSs 4, 7 and 9.

Because no significant interaction was found between SW cultivar and the transition system for SW and weed biomass measurements or grain dockage (Table 4), data for both cultivars are combined. Wheat class/cultivar did have a significant impact on all of these components individually, and 'Tara 2002' HRSW had higher biomass production, lower occurrence of weeds and lower dockage than 'Alpowa' SWSW (Table 4).

Transition system significantly impacted SW and weed biomass yields (Table 4). Weed biomass was not determined for individual weed species, but the most prominent weed species observed at this location were wild oat (*Avena fatua* L.), field bindweed (*Convolvulus arvensis* L.), prickly lettuce (*Lactuca serriola* L.) and Canada thistle (*Cirsium arvense* (L.) Scop.). Spring wheat biomass was the lowest following CS 1 (1290 kg ha^{-1}) and the highest following CSs 6 and 7 (mean = 2390 kg ha^{-1}), CS 8 (3140 kg ha^{-1}) and CS 9 (3140 kg ha^{-1}).

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Table 4. Mid-season SW biomass, weed biomass and grain dockage in 2006 following nine, 3-year crop rotations during the transition to organic production.

CS	Transition phase crop rotation	SW biomass[1]	Weed biomass[2]	Grain dockage
		--------------------kg ha^{-1}--------------------		----%----
1	SW–WW–SB	1290 c[3]	650 a	3.6 ab
2	SP–WW–SP	2080 b	380 b	3.2 abc
3	SP–SW–SP	1600 b	500 ab	2.9 abc
4	SP–WW–WP	2260 b	450 ab	2.8 abc
5	SP–SW–WP	1710 bc	640 a	3.0 abc
6	BB–WW–WP	2390 ab	270 bc	2.6 abc
7	BB–SW–WP	2400 ab	380 b	4.0 a
8	BB–WP–WP	3140 a	120 cd	2.4 bc
9	For–For–For	3140 a	20 d	2.1 c
P value		0.0001	0.0001	0.0489
	Wheat class[3]			
	'Alpowa' SWSW	1930 b	450 a	3.6 a
	'Tara' HRSW	2520 a	300 b	2.3 b
P value		0.0001	0.0002	0.0001

SW, spring wheat; WW, winter wheat; SB, spring barley; SP, spring pea; WP, winter pea; BB, bell bean and For, perennial forage.
[1] Because no significant interaction was found between SW cultivar and transition CS for SW biomass, weed biomass or SW grain yield, data for both cultivars are combined.
[2] Weed biomass was not determined for individual species, but the most prominent weed species at this location were wild oat (*Avena fatua* L.), field bindweed (*Convolvulus arvensis* L.), prickly lettuce (*Lactuca serriola* L.) and Canada thistle (*Cirsium arvense* (L.) Scop.).
[3] Means followed by the same letter within a column are not significantly different at the 5% level based on Fisher's LSD level of separation.

Generally, SW following legume-intensive transition phase systems produced more crop biomass than the following CS 1. Weed biomass was inversely related to crop biomass and grain production (Fig. 1A and B) and was the lowest following CS 9 (20 kg ha^{-1}; Table 4). Cropping system 8 had similar weed biomass yields as CS 9 (120 kg ha^{-1}), whereas CSs 1 to 7 had higher weed biomass levels, up to 650 kg ha^{-1} in CS 1. Dockage of SW differed slightly depending on the transition system (Table 4). Cropping system 7 (4.0%) had higher dockage than CS 8 (2.4%) and CS 9 (2.1%). CS 1 (3.6%) also had higher dockage than CS 9 and all other systems were intermediate. Wild oat was the main contaminant contributing to dockage among the systems.

2007 winter wheat

Organic 'Madsen' WW yields in 2007 were the highest following legume-intensive systems CSs 4 to 7 (mean = 4330 kg ha^{-1}) and CS 8 (4010 kg ha^{-1}). Cropping system 5 (4070 kg ha^{-1}) and CS 8 were not different from CS 3 (3190 kg ha^{-1}) or CS 9 (3920 kg ha^{-1}). Winter wheat yields were lowest following CSs 1 to 3 (mean = 3080 kg ha^{-1}; Table 5). Winter wheat yields following CS 9 (3920 kg ha^{-1}) were similar to systems with the highest and lowest yields, and protein levels were among the lowest (8.9%), and were comparable to grain cash crop-intensive systems (CSs 1 to 3; mean = 8.6%). Winter wheat following green manure in CSs 4 to 8 had the highest protein levels (mean = 10.0%). Protein levels would not be expected to affect crop prices for soft white WW, as previously mentioned, but represent an indicator of soil N fertility. Average 2007 WW yields were 5050 kg ha^{-1} in Whitman County, WA[40] and regional average protein levels were 9.8% for WW[42].

Winter wheat biomass yields differed depending on transition phase systems (Table 6) but were much higher than SW biomass (Table 4). Winter wheat following CS 1 produced the lowest crop biomass yields (3540 kg ha^{-1}), which were similar to CS 2 (3660 kg ha^{-1}), CS 3 (3950 kg ha^{-1}) and CS 8 (4670 kg ha^{-1}). Transition phase system did not affect weed biomass (mean = 120 kg ha^{-1}) or grain dockage (mean = 4.6%; Table 6).

Discussion

Nitrogen dynamics of transition systems can impact the production of dryland organic grains. However, management does not solely depend on external N inputs, and must focus on utilizing multiple cultural practices to ensure sustainability of organic CSs. Producing a perennial alfalfa + oat/pea forage or green manure-intensive CS prior to wheat production is a viable option for growers who are interested in transitioning from

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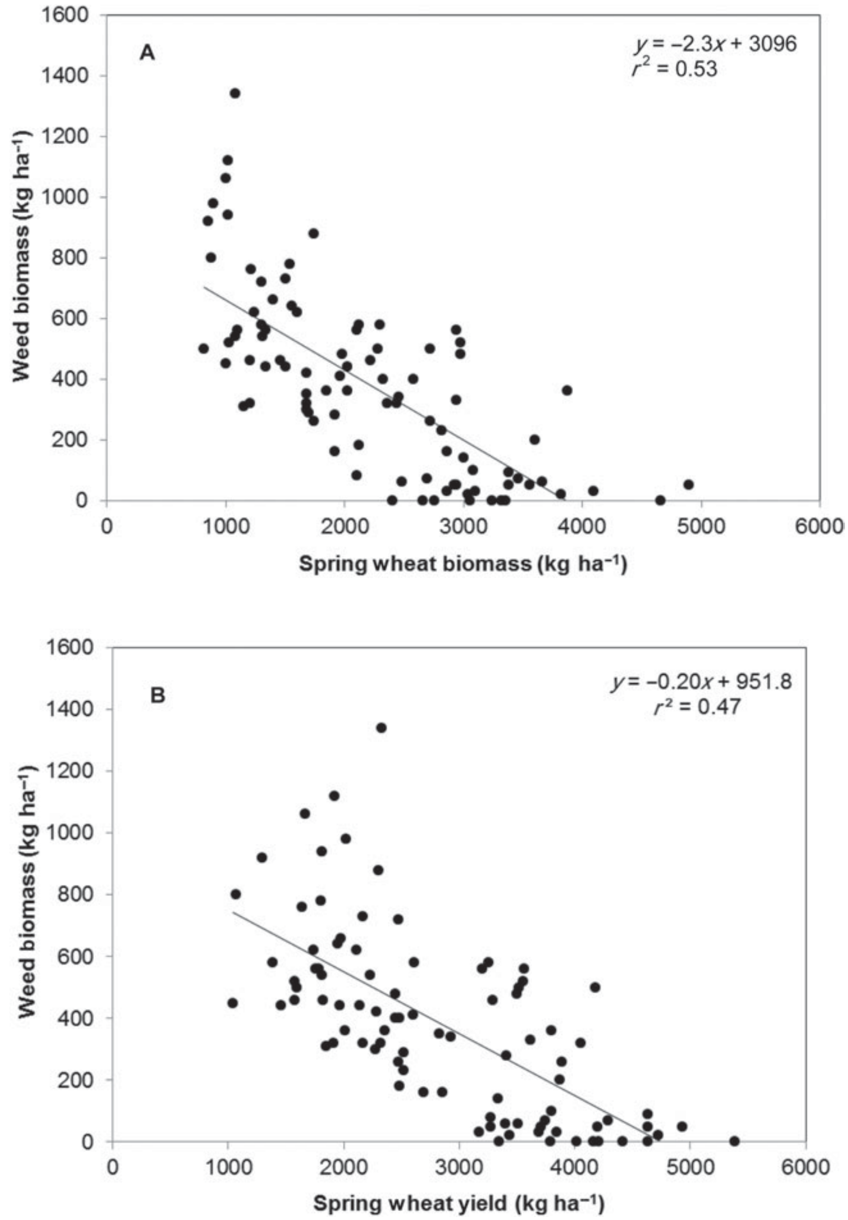

Figure 1. Comparison of total SW and weed biomass (A) and SW grain yield and total weed biomass (B) in 2006.

conventional to organic cereal production in the inland Pacific Northwest. Forage was cut and baled as hay each year. As a consequence biomass N was removed from the field and Borrelli et al.[34] reported a relatively low overall N balance for this system. However, soil inorganic N levels remained relatively high and high HR and SWSW yields and protein levels were observed following perennial forage compared to the other transition systems, indicating that more N was being mineralized from soil organic matter than was found in other systems. Many producers in Manitoba and Saskatchewan, Canada also found yield benefits for crops following perennial forage when moisture was adequate to support crop growth[43]. In a long-term experiment, Hoyt et al.[21] demonstrated that wheat produced after alfalfa and an alfalfa + bromegrass (*Bromus* sp.) mix had significantly higher yields for several years than wheat following a fallow–wheat control or bromegrass alone. Root biomass in the perennial forage system may have enhanced soil organic matter and N mineralization rates, which could provide adequate amounts of inorganic N to SW throughout the season. Rapid turnover of legume roots and nodules through rhizodeposition is recognized as an important contributor, along with biological N-fixation, to increased N availability under growing legumes[15,18,20,21,44,45]. Several authors estimated that 20–36% of the total N derived from different species of legumes resided below-ground[46–48] confirming that in addition to N fixation, below-ground biomass is an important source of N in CSs that include legumes.

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Table 5. Yield and grain protein levels for organic soft white WW (cv. 'Madsen') in 2007, in the second year of cereal production following nine, 3-year CSs during the transition to organic production.

CS	Transition phase crop rotation	'Madsen' WW yield[1] (kg ha^{-1})	'Madsen' WW protein (%)
1	SW–WW–SB	2970 d[2]	8.6 b
2	SP–WW–SP	3070 cd	8.7 b
3	SP–SW–SP	3190 bcd	8.4 b
4	SP–WW–WP	4400 a	9.8 a
5	SP–SW–WP	4070 ab	10.1 a
6	BB–WW–WP	4410 a	9.9 a
7	BB–SW–WP	4440 a	10.2 a
8	BB–WP–WP	4010 abc	10.1 a
9	For–For–For	3920 abcd	9.0 b
P value		0.0096	0.0001

SW, spring wheat; WW, winter wheat; SB, spring barley; SP, spring pea; WP, winter pea; BB, bell bean and For, perennial forage.

[1] Average 2007 WW yields for Whitman County, WA[40] were 5050 kg ha^{-1} and average regional protein levels were 9.8% for WW[42].

[2] Means followed by the same letter within a column are not significantly different at the 5% level based on Fisher's LSD level of separation.

By 2007, post-harvest soil inorganic N levels in CS 9 had decreased substantially (Table 2) following SW production. Winter wheat had some of the highest grain yields following CSs 4 to 8 (Table 5). Winter wheat protein levels following these transition systems were also high and comparable to local averages, while WW protein levels following CS 9, or CSs 1, 2 and 3, were below the local average (Table 5). Regardless of the CS produced during the transition phase, average WW yields were well below the 2007 county average. Because weed biomass following CS 9 was low in both years, it can be assumed that weed competition did not reduce crop available N in this system. Rather, organic N contribution from forage roots was not substantial enough to continually provide plant available N and sustain high grain yield and protein for more than one growing season. This point is supported by observations that N contribution from mineralization of lupine below-ground biomass was 40% in the first year but only 15% in the second year[48]. Jensen[45] also found that soil N deposition from pea and barley roots decreased over time.

Higher WW yield and protein levels in 2007 following CSs 4 to 7 could also be attributed to greater mineralization of green manure biomass in the second year. Some authors suggest that mineralization of legume biomass occurs rapidly, and that organic N becomes depleted by the second year of crop production[49,50]. It is apparent from the soil inorganic N levels following WP green manure crops (Table 2) that systems in the current experiment did not become N depleted. Instead, soil inorganic N was present at higher levels for 2 years, and in some cases increased even after 1 year of cereal production (CSs 5, 7 and 8). Higher amounts of soil inorganic N, as well as high WW yield and protein levels, demonstrate that biomass from a high-yielding green manure legume crop can provide soil benefits from mineralization.

Providing sufficient N to achieve high yields and grain protein levels using legumes as the only fertility source is a substantial challenge, and considerable depletion of soil inorganic N was apparent by fall 2007 (Table 2). Although perennial forage in CS 9 provided many plant and soil benefits following the transition to organic production, findings from this research indicate that soil N should be supplemented after 1 year of organic cereal production to maintain high organic wheat yields and grain protein levels in the inland Pacific Northwest. After 2 years of cereal production, soils should be amended with an organic fertilizer source to sustain cereal production, particularly if higher, hard wheat protein goals are to be met. Murphy et al.[28] recommend using N sources in combination with cultivars that have high N use efficiency in dryland cereal-based CS in order to obtain organic grain yields comparable to those of conventional growers. Campbell et al.[51] further suggest that although legumes provide a source of N, they will not sustain production for extended periods of time because they do not provide other plant nutrients, such as phosphorus.

In comparison to CS 9, CSs 2 and 3 had poor SP establishment and development during the last year of the transition[11], but also had high N balances and inorganic N levels comparable to other CSs prior to organic grain production[34]. Although low N uptake by the SP crop during the transition phase resulted in high mineralization of soil organic N and residual plant available N (Table 2), organic SW had some of the lowest grain yields and protein levels following these grain cash crop-intensive systems. Because SP was relatively unsuccessful, we can assume that any observed N benefits did not result from including a legume, and the consideration that the SP was grown as a cash crop and not a green manure during the transition was inconsequential. Inorganic soil N following CSs 2 and 3 was minimal in fall 2006 and depleted rapidly by crop uptake because, unlike CS 9, N inputs from the SP were not sufficient to provide enough mineralizable organic matter to sustain WW production in 2007. The grain cash crop-intensive systems (CSs 1 to 3) had low crop yields in 2005 that resulted in little removal of soil inorganic N prior to going into organic production[34]. Low grain yields and protein levels in both classes of SW following CSs 1 to 3 (Tables 3 and 4) further indicate that grain-intensive cash crop systems do not return enough N to the soil to sustain wheat production after the transition phase. Badaruddin and Meyer[19] similarly found that unfertilized wheat yields were lower following either unfertilized or fertilized wheat as compared to wheat yields that followed legume green manure crops in rotation. The authors attribute the yield advantage to greater efficiency and utilization of N following green

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Table 6. Mid-season means of WW biomass, total weed biomass and grain dockage in 2007 following nine, 3-year crop rotations during the transition to organic production.

CS	Transition phase crop rotation	WW biomass	Weed biomass	Grain dockage
		-----------------------------kg ha^{-1}-----------------------------		----------------------------%----------------------------
1	SW–WW–SB	3540 d[1]	50 a	4.1 a
2	SP–WW–SP	3660 cd	110 a	4.4 a
3	SP–SW–SP	3950 bcd	60 a	4.1 a
4	SP–WW–WP	5230 a	180 a	4.6 a
5	SP–SW–WP	5090 ab	340 a	4.5 a
6	BB–WW–WP	4830 abc	60 a	4.2 a
7	BB–SW–WP	5380 a	100 a	4.1 a
8	BB–WP–WP	4670 abcd	140 a	5.6 a
9	For–For–For	4860 abc	50 a	5.9 a
P value		0.0336	0.3229	0.2143

SW, spring wheat; WW, winter wheat; SB, spring barley; SP, spring pea; WP, winter pea; BB, bell bean and For, perennial forage.
[1] Means followed by the same letter within a column are not significantly different at the 5% level based on Fisher's LSD level of separation.

manure crops. In a related study, the same authors found comparable results when using legumes for grain crops in rotation rather than as green manure[17]. Entz et al.[4] also improved HRSW yields by following alfalfa or sweet clover instead of oat. Yield benefits could also be associated with underground and rotational benefits of legumes such as alfalfa.[52,53].

Although including legumes in crop rotations can improve availability of soil N to subsequent crops, soil inorganic N levels following the transition phase were similar across all systems, regardless of which crops were included in the rotation (Table 2). However, organic wheat yields and grain protein levels varied by CS during the organic production phase. This can be attributed to the amount of mineralizable soil organic matter as a source of N, as was evident when SW followed perennial forage instead of cereal or grain crops in the transition. However, systems that produced WP green manure during the last year of the transition (CSs 4 to 7), which would also be expected to have relatively labile N contributions to the subsequent wheat crop[49,50,54], did not reliably produce high SW yields. The amount of plant-available soil N provided by the CS during the transition phase is, therefore, not the only factor contributing to higher organic wheat yields and grain protein levels.

Organic SW following perennial forage and green manure-intensive systems had some of the highest yields and protein levels as well as a low occurrence of weeds, suggesting that more competitive transition-phase rotations can reduce the incidence of weeds during organic production[7,55]. Better crop establishment increased crop competition with weeds throughout the transition phase, and repeated, mid-season cuttings removed wild oats and other weeds before they went to seed each year[11]. In contrast, including small grain crops in rotations allowed weed growth to increase weed density throughout the transition phase, and thus decrease the overall effect that mid-season mowing of well-established green manure stands in CSs 4 to 7 had on weed control. Effective weed control is a necessary factor for successful organic cereal production, and maintaining low weed production is important not only for the in-season crop but also throughout establishment of the CS[7,55,56].

Lower weed competition in 2007 compared to 2006 suggests that WW is more competitive with weeds in the inland Pacific Northwest environment than SW for obtaining plant-available resources. Lemerle et al.[57] suggest that genotypes and morphological traits can cause wheat cultivars to vary in their ability to compete with weeds. In relation, 'Alpowa' SWSW is well known to be a slow-developing cultivar and was an uncompetitive SW choice for this organic system. 'Alpowa' was reported to harbor the highest quantity of weed biomass, compared to 63 cultivars[58]. Identifying crop cultivars that have a competitive advantage to achieve high grain yields and minimize weed seed production is important for successful organic management.[5,28,59]. High variations in weed pressure and limited efficacy of individual organic weed control methods make combined strategies of direct and indirect weed control tactics necessary to reduce competition[7,55,43,57].

Summary

It is challenging to produce wheat yield and protein levels in organic, reduced-tillage systems that are comparable to conventionally managed wheat systems in the inland Pacific Northwest, and multiple management factors must be taken into consideration. Findings from this study supported the hypothesis of Gallagher et al.[11] that producing intensively managed legume crops during the transition to organic production can result in higher cereal yields and grain protein levels during the certified organic

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production phase, while producing intensively managed cereal and grain cash crops during the transition phase can lower organic cereal production and quality. Gallagher et al.[11] assumed that transition-phase rotation benefits would mainly come from the soil fertility (N) contributions of legume crops. However, intensive management of perennial legumes and green manure throughout the transition phase also enhanced weed management, which would improve organic cereal crop production as much as soil N. Perennial alfalfa + oat/pea forage and green manure-intensive transition systems appeared to be the best in this regard, because crop canopy coverage and mowing management in these systems improved competition with weeds, while the presence of legumes increased soil inorganic N. Although including a green manure in the final year of the transition improved soil inorganic N levels in the second year of organic production, small grain crops produced during the first 2 years of the transition were not competitive enough with weeds to relieve weed pressures during organic production. Winter crops were better adapted to the region during the transition phase[11,34] and organic WW developed better stands, higher yields and better weed control than the SW cultivars chosen for this experiment. During 2006 and 2007, SW and WW yields were often lower than local averages, regardless of the preceding CS. It is therefore necessary for growers to choose cultivars and cereal types that are well-suited to organic production, where resource availability is often low and competition from weeds is high. Managers must also eventually supplement crops with additional soil fertility sources, such as animal manure, in addition to legumes in order to sustain production of organic cereal crops over time and to maintain high yields and protein levels.

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