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Barley–pea intercropping: Effects on land productivity, carbon and nitrogen transformations

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ABSTRACT

Declining land productivity associated with decreasing soil organic carbon (SOC) and nitrogen (N) are significant issues in monoculture barley production. An intercropping system combining barley and pea may help increase land productivity as well as to maintain SOC and soil mineral N. We grew barley as a monoculture and intercropped with pea without fertilizers in rows of barley:pea 1:1 and 2:1 as well as broadcast arrangements for two years to observe the effects of species ratios and spatial configuration on land productivity, biological nitrogen fixation and transfer, C and N accumulation in aboveground biomass, soil mineral N balance, gross ecosystem photosynthesis (GEP), and net ecosystem productivity (NEP). ^{15}N natural abundance method was used to quantify N fixation and subsequent transfer. Field CO_2 exchange measurements used a dynamic closed transparent chamber connected to a portable CO_2 analyzer.

Intercropping displayed higher land productivity (12–32%) compared to monoculture plots, with 2:1 arrangement producing the highest total land outputs – TLO (5.9 t ha^{-1}) and land equivalent ratio – LER (1.32) values. Intercropped barley showed higher biomass N, grain protein and sequestered higher C in soil compared to monocultured barley. Intercropped pea displayed increased nodulation (27–45%) and symbiotic N_2 fixation (9–17%) compared with monoculture pea resulting in the fixation of 60–78 kg N ha^{-1}. The highest rate of N-transfer (11%), and increased N accumulation (i.e., 200% higher than monocultured barley) in shoot biomass was observed in 1:1 arrangement. However, 2:1 arrangement accumulated higher C (196 g C m^{-2} $year^{-1}$, i.e., 53% higher) in shoot biomass compared to the monoculture barley plots. The 2:1 arrangement also displayed the greatest NEP resulting in the highest soil C sequestration at a seasonal daytime average rate of 229 mg C m^{-2} h^{-1} (i.e., 10% higher than barley monoculture plots). This study demonstrated that intercropping barley and pea is an efficient strategy to increase land productivity, grain and biomass quality, N and C yields, GEP and NEP, and that planting in rows of 2:1 was the most productive arrangement.

1. Introduction

The environmental challenges attributed to agriculture are related primarily to reduced soil, water and air quality often arising from inappropriate nutrient management strategies. Farmers typically use chemically intensive practices to maintain soil productivity combined with other management practices that decrease soil organic matter (SOM) while increasing soil erosion, acidification and salinization (Dumanski et al., 1986). The soil organic carbon (SOC) pools in agricultural systems are currently in disequilibrium with the environment as the losses attributed to decomposition exceed the gains associated with biomass addition (Jarecki and Lal, 2003). Atmospheric CO_2 concentrations have risen from approximately 315 ppm in 1959 to the current average of 401 ppm (UCSD, 2014), and are projected to reach as high as 500–1000 ppm by 2100 (IPCC, 2007). This suggests development of agricultural systems that fix more CO_2 (i.e., greater gross ecosystem photosynthesis, GEP) with the release of less CO_2 (i.e., ecosystem respiration – R_e) which would help balance, and ultimately move to positive CO_2 movement between agricultural ecosystems and the atmosphere, a term referred to as net ecosystem CO_2 exchange (NEE). In addition, sustainable nitrogen (N) management is particularly challenging because of increasing costs of mineral N fertilizers, coupled with N fertilizer's emission of nitrous oxide (N_2O), and nitrate's potential to contaminate both ground and surface water (Ferguson et al., 1999). The nature of these challenges suggests that more effort is needed to develop

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sustainable and ecologically sound nutrient management practices that are scalable to large farms. For small grain production, one strategy that addresses many of these concerns is the inclusion of grain legumes with cereal crops (i.e., intercropping) under organic production practices.

Intercropping, which is defined as growing two or more species simultaneously in the same field during a growing season (Ofori and Stern, 1987), is considered one important strategy in developing sustainable production systems, particularly systems that aim to limit external inputs (Adesogan et al., 2002). Typical species or functional groups used in intercropping include wheat, rye, oats, and barley (i.e., cereals), clover, beans, peas, and vetch (i.e., legumes), and buckwheat, flax, and chicory (i.e., non-leguminous forbs). When one species is nitrogen fixing, the range of ecological services provided by the intercrop expands to include nutrient management. Overall, the range of benefits identified from intercropping two or more species include higher productivity and profitability per unit area (Yildirim and Guvence, 2005), improved soil fertility through nitrogen fixation (Hauggaard-Nielsen et al., 2001, 2009), increased efficiency of resources (Knudsen et al., 2004), reduced damage caused by pests, diseases and weeds (Banik et al., 2006; Sekamatte et al., 2003), improved forage quality (Bingol et al., 2007; Lithourgidis et al., 2007; Ross et al., 2004) and improvements in carbon and nitrogen dynamics (Oelbermann and Echarte, 2011; Dyer et al., 2012).

Pea (*Pisum sativum* L., Fabaceae Lindl.) is one of the most commonly used grain legumes as an intercrop in wheat or barley cropping systems that may provide a new opportunity to develop a production system that fulfills both economic and environmental interests. Specifically, when pea has been intercropped with barley, results included increased yields (Hauggaard-Nielsen et al., 2009), increased land equivalent ratio (Chen et al., 2004; Sahota and Malhi, 2012), improved grain and forage quality (Carr et al., 2004; Lauk and Lauk, 2008), and greater N recovery (Hauggaard-Nielsen et al., 2009). While intercropping barley and pea is not a new concept, the previous research primarily focused on assessing general performance metrics, i.e., land productivity, N yield, disease and pest pressure, crop competition, and weed control (Hauggaard-Nielsen et al., 2001, 2009). The effects of species proportion and their spatial arrangement on N-use efficiency (i.e., biological nitrogen fixation and possible transfer to the companion barley within a season), NEE, GEP, net ecosystem productivity (NEP), and their association with crop performance within an organic production system has not been previously considered. Therefore, a two-year experiment was conducted to assess a designed pairing of barley and pea in spatially unique planting arrangements to identify the spatial arrangements that maximize synergies, as compared to monoculture plots, including biological N fixation and transfers, net ecosystem CO_2 exchange and ecosystem productivity metrics, and to recommend the best combination of practices that are both productive and environmentally sustainable. It was expected that the land productivity, C and N accumulation in aboveground biomass, and ecosystem services are increased in intercrop plots compared to their monoculture counterparts.

2. Materials and methods

2.1. Study site, climate and soil description

This study was conducted at the Centre for Sustainable Food Systems at UBC Farm in Vancouver, BC, during the 2011 and 2012 cropping seasons (May–September). The experimental site was located at 49°15′3″N and 123°14′20″W, at an altitude of 100 m above sea level.

Mean air temperatures for the experimental site during the production seasons (May–September) of 2011 and 2012 was 15.1 °C, with the warmest days in August (17.5–18.2 °C). The mean soil temperature at 20 cm depth ranged from 17.9 to 18.3 °C. Monthly average solar irradiance ranged from 389 to 404 W m^{-2}, with the higher values from June to August. The average monthly precipitation ranged from 32.3 to 42.4 mm. 2012 was dry compared to 2011 with greater levels of solar irradiance associated with lower relative humidity and precipitation.

Four random soil samples from across the whole test site were collected from 0 to 15 cm depth at the time of plot establishment to characterize soil fertility (i.e., pH, organic matter, total N, δ^{15}N, and available P, K, Ca, Mg, Cu, Zn, Fe, Mn and B). The soil was moderately well drained coarse textured sandy loam with low to moderate fertility. Soil was homogeneous with a pH value of 5.9, organic matter content of 117 g kg^{-1}, total N content of 3.5 g kg^{-1}, δ^{15}N of 3.02‰, P of 144 mg kg^{-1}, and K of 183 mg kg^{-1} based on dry soil. Additional soil samples were taken from two different areas within each plot before planting (Spring-2011) and after final harvest (Fall-2012), and sent to an analytical laboratory (Pacific Soil Analysis Inc., Richmond, Canada) to determine soil mineral N (NH_4^+ and NO_3^-) content. The site had not been used for grain production in previous years but had been used for annual vegetable cultivation. The site had been managed under organic vegetable production guidelines for more than 10 years using green manures and compost.

2.2. Experimental details

Barley cv. 'Oxbridge' and pea cv. 'Reward' were selected for intercropping trials based on agronomic performance (i.e., synchronized maturity for combined harvest, yield, and nodulation potential in pea) from cultivar evaluation trials (Chapagain and Riseman, 2012). Plants were grown on the same plots under organic and rain-fed conditions over two years, and managed equally across combinations.

Research plots (4 m × 3 m) were arranged in a randomized complete block design (RCBD) with five treatments and four replications. Treatments consisted of barley cv. 'Oxbridge' and pea cv. 'Reward' grown as monocultures, and intercropped in rows of barley:pea 1:1, 2:1, and broadcast. In monocultures, barley and pea were planted in rows at the recommended plant density targeting 400 and 60 viable plants m^{-2}, respectively. Row and mixed intercropping consisted of planting barley and pea in proportional replacement design in which the combined density of the population varied as the proportions of the species changed (Jolliffe, 2000). The 1:1 arrangement consisted of planting barley and pea in alternate rows targeting 200 and 30 plants m^{-2}, respectively, whereas, 2:1 arrangement targeted 300 barley and 20 pea plants m^{-2}. In broadcast arrangement, seeding densities of barley and pea were reduced by one half of monoculture densities targeting 200 and 30 plants m^{-2}, respectively, and broadcasted and incorporated evenly into the soil. Barley grown as a monoculture was considered the non-N_2-fixing reference plant in analyses. At least 50 cm was kept between each plot to minimize treatment interactions, and 1 m between each block to facilitate plot management.

Pea seeds were inoculated with commercial rhizobia (Garden Inoculant for pea, EMD Crop Bioscience, WI, USA) and planted immediately after inoculation. Barley and pea were sown in mid-May in rows using a hand seeder (Jang Clean Hand Seeder, Jang Automation Co. Ltd., Cheongju-city, South Korea) with adjustable sprockets (Front: 11, Rear: 14), and seed plates (G-12 for barley and N-6 for pea). Sowing depth varied with seed size and ranged from 3–4 cm for barley to 4–5 cm for pea. Research was conducted under rainfed condition without using fertilizers, pesticides or fungicides.