Agriculture, Ecosystems and Environment 264 (2018) 63–72

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Intensified dryland crop rotations support greater grain production with fewer inputs

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ARTICLE INFO

Keywords:
Cropping system intensification
Arbuscular mycorrhizal fungi
Potentially mineralizable nitrogen
Net farm income
Fertilizer and herbicide use

ABSTRACT

Rising use and costs of agri-chemical inputs to support agricultural production have placed an economic burden on farmers while contributing to environmental and human health issues. Ecologically based nutrient and weed management – the use of ecological processes to replace external chemical inputs – may represent a strategy to support crop growth while achieving positive environmental and economic outcomes. In dryland agroecosystems around the world, farmers are increasingly transitioning toward no-till and intensified cropping systems, in which unvegetated fallow periods are replaced with crops. This study seeks to determine if cropping system intensification represents an ecologically based strategy for managing nutrients and weeds relative to traditional crop-fallow systems, and to understand the implications for crop production and profitability. We quantified total and potentially mineralizable nitrogen (N), arbuscular mycorrhizal fungal (AMF) colonization of wheat roots and implications for plant phosphorus (P) uptake, 6 years of crop yields, fertilizer and herbicide use, and net operating income across dryland, no-till cropping systems in the semi-arid High Plains, USA. Three levels of cropping system intensity were represented ranging from wheat-fallow (unvegetated fallow every other year) to continuous cropping (no fallow years). After accounting for variability due to environment and site characteristics, total and potentially mineralizable N were 12% and 30% greater in continuous rotations relative to wheat-fallow, respectively. Mid-intensity (fallow every 2 or 3 years) and continuous rotations had roughly 2 and 3 times more AMF colonization than wheat-fallow, respectively, and AMF colonization was positively correlated with wheat plant P concentration. Farmers practicing continuous cropping applied 22 and 34 $kg\,ha^{-1}$ less N fertilizer per crop compared to wheat-fallow and mid-intensity, respectively, despite similar and 60% greater annualized crop production than mid-intensity and wheat-fallow rotations, respectively. Additionally, farmers who practiced continuous cropping used less than half the total herbicide used by wheat-fallow farmers. Net operating incomes of continuous and mid-intensity rotations were an estimated 47 $USD\,ha^{-1}\,yr^{-1}$ (80%) and 42 $USD\,ha^{-1}\,yr^{-1}$ (70%) more than wheat-fallow, respectively. These results suggest that cropping system intensification, and especially continuous cropping, represents an opportunity to achieve more grain production while managing weeds and nutrients with fewer agri-chemical inputs, leading to greater profitability and improved environmental outcomes in no-till agroecosystems.

1. Introduction

Global agricultural production has risen steadily over the past several decades, but with extensive environmental impacts. The environmental footprint of agriculture is growing in part because rising nutrient requirements associated with increasing crop production have largely been addressed through greater additions of synthetic fertilizers (Tilman et al., 2001). Production practices that suffer nutrient losses and rely on external chemical inputs simultaneously threaten ecosystem function and economic performance (Carolan, 2016; Hunter et al., 2017). Increasing use and costs of nitrogen (N) and phosphorus (P) fertilizer, in addition to rising herbicide use, place an economic burden on farmers, reflected in the widening disparity between low commodity prices and high input costs (Liebman et al., 2001; Fuglie et al., 2007; Carolan, 2016). Meanwhile, synthetic N and P fertilizer and herbicides continue to exact high environmental and human costs, evidenced by oceanic dead zones, groundwater contamination, and degradation of natural ecosystems due to atmospheric N deposition and pesticide pollution (Galloway et al., 2003). Reducing the need for external inputs could reduce impacts on environmental health and increase farmer

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https://doi.org/10.1016/j.agee.2018.05.017
Received 11 December 2017; Received in revised form 13 May 2018; Accepted 18 May 2018

profits if yields could be sustained. However, N and P are often the most limiting nutrients in agricultural production (Chapin III et al., 1986), and the onset of herbicide resistant weeds is driving greater use of even more expensive herbicides with higher levels of toxicity (Mortensen et al., 2012). The challenge, then, is to identify an alternative strategy for maintaining or increasing agricultural production while sustainably managing nutrients and weeds. Ecologically based nutrient and weed management – the deployment of ecological processes to replace external chemical inputs – may represent such a strategy (Anderson, 2003; Drinkwater and Snapp, 2007).

The need for ecological alternatives to external inputs is particularly urgent in the semi-arid dryland cropping systems of the US High Plains, just one of many semi-arid regions around the world that are undergoing a profound shift in cropping system management (Smith and Young, 2000; Maaz et al., 2018). The rise of no-till over the past several decades has enabled sufficient water savings to reduce the need for year-long fallow periods, called summer fallow, that have traditionally characterized dryland cropping systems (Hansen et al., 2012). Still, while eliminating summer fallow can increase overall grain production (Peterson and Westfall, 2004), it remains a prevalent practice in the High Plains in part due to trade-offs with crop yields (Lyon et al., 2007), and possible effects on input requirements. Traditionally, tillage has been used to maintain these unvegetated fallow periods, but no-till requires the use of increasingly expensive herbicides (Anderson, 2003). Additionally, researchers have suggested that even a slight increase in cropping system intensity may increase fertilizer requirements. For example, Kolberg et al. (1996) estimated that in the High Plains, intensifying from the traditional winter wheat (*Triticum aestivum*)-fallow system (WF) to a mid-intensity (MID) system like wheat-corn (*Zea mays*)-fallow increases the N requirement by 44%. Nutrient requirements may be even greater for continuous cropping systems (CON) that have eliminated summer fallow altogether (Grant et al., 2002). As tens of millions of acres in semi-arid regions around the world are intensifying, including millions in the High Plains (Smith and Young, 2000; Hansen et al., 2012; Maaz et al., 2018), there is a need to determine the impact of cropping system intensity on herbicide and fertilizer use in no-till systems.

Meeting rapidly increasing crop nutrient requirements while mitigating environmental harm necessitates an ecologically based nutrient management strategy. Despite theoretically higher nutrient requirements, cropping intensification may represent such a strategy, as it is associated with greater crop production and subsequent soil carbon (C) inputs, which offer the opportunity to recouple C and N cycles (Drinkwater and Snapp, 2007). Cropping system intensification can increase crop production and residue returns to soil by up to 100% (Peterson and Westfall, 2004), which leads to larger stocks of soil C and N (Halvorson et al., 2002; Sherrod et al., 2003; Rosenzweig et al., 2018). Reservoirs of organic N are released more slowly over time compared to pulse additions of highly mobile mineral N applications, and thus intensified systems that accrue organic N may be able to meet plant N needs more efficiently (Gardner and Drinkwater, 2009).

Intensified cropping systems may also stimulate plant uptake of N and P relative to WF through changes in soil microbial communities. WF is a highly simplified cropping system reliant on only one crop and 14 months of fallow every other year. During the long summer fallow period, C limitations are imposed on the microbial community that may inhibit its growth and activity. We recently observed that microbial biomass was 20% and 35% greater in MID and CON systems in the High Plains relative to WF, respectively (Rosenzweig et al., 2018), and we suspect that the alleviation of C limitation through cropping system intensification has significant impacts on plant nutrient availability via impacts on the microbial community. In particular, arbuscular mycorrhizal fungi (AMF) can increase plant nutrient uptake, but are susceptible to "long fallow syndrome" wherein populations of AMF are drastically reduced in the absence of a host plant (Thompson, 1987; Harinikumar and Bagyaraj, 1988). AMF form a symbiotic relationship with most crop types, in which AMF colonize the host plant's roots and trade water and nutrients in return for C (Augé, 2001; Allen, 2007). AMF are particularly effective at increasing their host plant's access to immobile nutrients like P, and higher colonization rates have been attributed to increased plant P concentrations and grain yields in semi-arid cropping systems (Al-Karaki et al., 2004). Increasing the availability of C substrates through cropping system intensification may increase populations of AMF and associated benefits to nutrient accessibility, and potentially provide a means of reducing dependence on P fertilizer.

In addition to the potential impacts of less intensive and diverse agroecosystems on fertilizer dependency, a lack of crop production and diversity may also foster herbicide dependency (Anderson, 2003). No-till systems, in particular, require high rates of herbicide application, a reality that is only becoming more severe as weeds continue to develop herbicide resistance (Young, 2006). However, the combination of no-till and cropping intensification maintains surface residue and increases plant competition with weeds, which can suppress weed productivity and seed germination (Bastiaans et al., 2008; Anderson, 2009; Nichols et al., 2015). Additionally, cropping system intensification is often associated with greater crop diversity, which disrupts the weed community pattern of emergence (Anderson, 1994; Derksen et al., 2002). Anderson (2005) estimated that the combined effects of no-till and diversified rotations on weed seed emergence and survival, disrupted weed life cycles, and weed/crop competition could reduce weed management costs by 50% by providing an ecological alternative to synthetic herbicide.

Despite its potential benefits, there are serious tradeoffs with risk and yield associated with cropping system intensification in water-limited environments. For example, CON systems eliminate summer fallow before wheat, which can incur a substantial wheat yield penalty and increase the risk of crop failure (Nielsen and Vigil, 2005; Holman et al., 2016). Thus, a wide suite of soil health, yield, and economic impacts of cropping system intensification need to be elucidated so farmers can be fully informed when making difficult crop management decisions. We coupled detailed management and yield data with a suite of soil analyses on working dryland, no-till farms and long-term experiment stations in the High Plains states of Colorado and Nebraska to address the following objectives: 1) Quantify cropping system intensity effects on microbially-mediated nutrient cycling, specifically AMF colonization and potentially mineralizable N (PMN), 2) Quantify cropping system effects on herbicide and fertilizer use; 3) Quantify cropping system intensity effects on crop yields and estimate implications for profitability. We hypothesized that intensification would increase the nutrient supplying capacity of soil and reduce herbicide use, resulting in greater crop production with fewer inputs, increasing profitability.

2. Methods

2.1. Cropping systems

WF has traditionally been the dominant dryland cropping system in the semi-arid High Plains (Hansen et al., 2012). This system consists of growing winter wheat *(Triticum aestivum)* from September to July, followed by a non-vegetated fallow period for 14 months (summer fallow) until the next wheat planting. No-till farmers in this region often reduce summer fallow frequency from one out of two years (WF), to one out of three or four years (MID), by rotating winter wheat with crops like corn (*Zea mays*), sorghum (*Sorghum bicolor*), proso millet (*Panicum miliaceum*), peas (*Pisum sativum*), or sunflowers (*Helianthus annuus*). They may also eliminate summer fallow altogether via continuous cropping (CON), most often through a diverse crop rotation. MID rotations present in this study included wheat-corn-fallow, wheat-sorghum-fallow, wheat-millet-fallow, wheat-corn-sorghum-fallow, and wheat-corn-millet-fallow. CON rotations present in this study included wheat-millet, wheat-corn-millet, wheat-corn-peas, wheat-corn-