Review

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Cropping Systems Diversification as an Approach to Enhancing Crop Productivity

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Review

Cropping Systems Diversification as an Approach to Enhancing Crop Productivity: A Review

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Abstract: Agricultural intensification increased crop productivity but simplified production with lower diversity of cropping systems, higher genetic uniformity, and a higher uniformity of agricultural landscapes. Associated detrimental effects on the environment and biodiversity as well as the resilience and adaptability of cropping systems to climate change are of growing concern. Crop diversification may stabilize productivity of cropping systems and reduce negative environmental impacts and loss of biodiversity, but a shared understanding of crop diversification including approaches towards a more systematic research is lacking. The current review highlights the use of Cropping Systems Diversification as an Approach to Enhancing Crop Productivity. Crop diversification can be considered as an attempt to increase the diversity of crops through, e.g. crop rotation, multiple cropping or intercropping, compared to specialized farming with the aim to improve the productivity, stability and delivery of ecosystem services. It can be one measure to develop more sustainable production systems, develop value-chains for minor crops. Crop diversification practices can include higher crop diversity, more diverse crop, mixed cropping; cultivation of grain legumes in otherwise cereal dominated systems, perennial leys or grassland and regionally adapted varieties or variety mixtures. Crop diversification and/or additional diversification measures like variation of seeding time or changing cropping patterns have the potential to lead to higher and more stable yields, increase profitability and lead to greater resilience of agro-ecosystems in the long term. These practices have the potential to make cropping systems more diverse in space, time and genetics. Through a balanced portfolio approach to agricultural sustainability, cropping system performance can be optimized in multiple dimensions, including food and biomass production, profit, energy use, pest management, and environmental impacts.

Keywords: diversification; intercropping; crop rotation; productivity; sustainable agriculture

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1. Introduction

Widespread uptake of sustainable practices in agriculture and food supply chains is essential to meet current and future threats to food security and environmental resilience. The global food system does not yet provide adequate calories or nutrition to everyone on the planet, yet it enables some populations to over-consume (Urruty *et al*., 2016). In the coming decades, global agriculture must produce more food to feed a growing population while adapting to climate change, an increasing threat to agricultural yields. Food needs are projected to double by 2050. It is a global imperative to meet this growing demand for food in a manner that is socially equitable and ecologically sustainable over the long term. Current practices are undermining the ecological foundation of the global food system through overuse and the effects of agricultural pollution, thereby enhancing degradation, reducing ecosystem capacity to generate sustainable yields and threatening food security. While modern, industrialized agricultural systems in theory produce sufficient food to feed the world's current population, they have accomplished this feat with significant ecological and social externalities (Hazell, 2003).

The green revolution brought with mass production of staple cereals (wheat, rice, and corn) to solve the problem of feeding a growing population (Martin-Guay *et al*., 2018). Worldwide, countries have devoted natural resources to cropping those grains, at times without proper planning to avoid indiscriminate losses of biodiversity (Foley *et al*., 2005). Despite the profit gained from agricultural development in the last 65 years, problems such as a lack of equity, stability, and sustainability still remain major concern. The advance of scientific knowledge focused on agricultural purposes (crop genetics, water-use efficiency, fertilizers, technological devices, intelligent algorithms, and so forth), as well as prices becoming more affordable to consumers, are without doubt intrinsic benefits of advances made during this time. However, land-use change, soil degradation, soil salinity, chemical pollution, groundwater depletion, and climate change emerge as the consequences of irrational cultivation (Tilman *et al*., 2002).

A multitude of driving forces led to lower diversity of cropping systems like, e.g., concentration of breeding efforts on the economically most important crops and these processes supported a higher genetic uniformity within crop species (Kahiluoto *et al*., 2019), less crop species in rotations (Barbieri *et al*., 2017 and Stein and Steinmann, 2018) and higher uniformity within agricultural landscapes with large field sizes (Bianchi *et al.,* 2006 and Rusch*et al.,* 2016). Moreover, it caused environmental problems such as nitrate pollution of water, eutrophication of ecosystems, climate-relevant emissions of greenhouse gases (Bommarco *et al*., 2013; Therond *et al*., 2017 and Bowles *et al*., 2018) and an overall loss of habitats and biodiversity (Bommarco*et al*., 2013; Buhk *et al*., 2017 and Therond *et al*., 2017). The current scenario not only demands that crop productivity must be increased, but that it should be done in a sustainable way that promises greater social, economic, and environmental security (Germer *et al*., 2011).

Simplification of farming systems and growing environmental problems led to concerns about the future functionality of today's cropping systems with regard to resilience, adaptability to climate change, multifunctionality of agricultural landscapes, provisioning of ecosystem services and biodiversity. Consequently, attention is now being directed toward the development of crop production systems with improved resource use efficiencies and more benign effects on the environment. How can such costs be minimized at the same time that food production is increased? In one sense the answer is simple: crop and livestock production must increase without an increase in the negative environmental impacts associated with agriculture, which means large increases in the efficiency of nitrogen, phosphorus and water use, and integrated pest management that minimizes the need for toxic pesticides. In reality, achieving such a scenario represents one of the greatest scientific challenges facing humankind because of the trade-offs among competing economic and environmental goals, and inadequate knowledge of the key biological, biogeochemical and ecological processes (Rusch *et al*., 2016).

Crop diversification can be considered as an attempt to increase the diversity of crops through, e.g. crop rotation, multiple cropping or intercropping, compared to specialized farming with the aim to improve the productivity, stability and delivery of ecosystem services (Wezel *et al*., 2014 and Garbach *et al*., 2017). It can be one measure to develop more sustainable production systems, develop value-chains for minor crops (Meynard *et al*., 2018) and contribute to socio-economic benefits (Feliciano, 2019). Crop diversification practices can include higher crop diversity (Renard and Tilman, 2019), more diverse crop rotations (Reckling *et al*., 2016), mixed cropping (Bedoussac *et al.*, 2015), cultivation of grain legumes in otherwise cereal dominated systems (Watson et al. 2017), perennialleys or grassland (Phelan *et al*., 2015; Weißhuhn, *et al*., 2017 and Haughey *et al*., 2018) and regionally adapted varieties or variety mixtures (Yang *et al*., 2019; Vijaya *et al*., 2019). Crop diversification and/or additional diversification measures like variation of seeding time or changing cropping patterns have the potential to lead to higher and more stable yields, increase profitability and lead to greater resilience of agro-ecosystems in the long term (Liu *et al*., 2019; Rosa-Schleich *et al*., 2019 and Meynard *et al*., 2018). These practices have the potential to make cropping systems more diverse in space, time and genetics. Consequences of diversification are temporal shifts and ranges of phenological stages (relevant for biodiversity and adaptation to climate change), more frequent or continuous soil cover and more diverse management strategies, i.e., 'tillage', 'sowing dates', 'fertilization', 'irrigation', 'harvesting' and also reducing labour peaks and economic risk (Urruty*etal*., 2016 and Renard and Tilman, 2019).

Rotation systems also foster spatial diversity, since different crops within the rotation sequence are typically grown in different fields on a farm in the same year. Diversification through crop rotation can be an especially useful strategy in farming systems that integrate crop and livestock

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production. The addition of forage crops, including turnips and clovers, to cereal-based systems enhanced nitrogen supply through fixation by legumes, and increased nutrient cycling due to greater livestock density and manure production. These changes allowed the intensification of both crop and livestock production and increased yields substantially (Grigg, 1974). Integrated crop– livestock systems remained widespread and in recent years, there has been interest in reintegrating crop and livestock systems as a strategy for reducing reliance on fossil fuels, minimizing the use of increasingly expensive fertilizers, and limiting water pollution by nutrients, pathogens, and antibiotics (Magdoff *et al*., 1997).

This review aims therefore, to highlight the current use of crop diversification and define it as 'a process that makes a simplified cropping system more divers in time and space by adding additional crops.

2. Cropping System Diversification

The vast majority of diversified cropping is through introducing a 'new' crop into the baseline cropping system: either by temporal diversification (Table1)—expanding continuous cropping of a single crop or a simple crop rotation—or by spatial diversification (Table 1) of a pure stand on a single field through, e.g., intercropping, mixed cropping or companion cropping (Raseduzzaman and Jensen, 2017). Maintaining diversity across scales through diversified farming system practices not only enhances these ecosystem services but promotes their resilience in the face of disturbances such as drought, deluge, or pest infestations. Intercropping is thought to promote over-yielding because different crops grown together can utilize more of the available resources (e.g., crops with different rooting depths can access a larger fraction of spatially stratified nutrients and water) or because one crop facilitates the growth of the other (Lin, 2011).

Table 1. Measures of Crop Diversification and its Characterization.

Measure of crop diversification	**Characterization**
Temporal crop diversification	
Crop rotation	Growing of two or more different crops in consecutive growing seasons
Double to multiple cropping	Growing of two or more different crops in one growing season
Catch crops	Minor crops planted before, between or after a major crop
Relay cropping	The seeding of one crop into another standing crop and thus growing two crops simultaneously for a certain time
Spatial crop diversification	
Alley cropping	The simultaneous growing of arable and perennial crops in different broader strips
Intercropping	Simultaneous growing of at least 2 crops in different yet proximate rows
Mixed cropping	Simultaneous growing of at least two crops
Companion crops	Special form of mixed cropping. Simultaneous sowing of at least two crops. One of it is used in the year(s) after sowing
Variety mixtures	Growing of two or more varieties of one species
Bee plants	Mixture of commercial and noncommercial crops on the same field (to support insects, etc.)

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Trap crops	Mixture of commercial and noncommercial crops on the same field to control pests or diseases

Source: Raseduzzaman and Jensen, (2017).

2.1. Multiple Cropping or Poly-cropping:

Growing two or more crops on the same piece of land in one calendar year is known as multiple cropping. It is the intensification of cropping in time and space dimensions i.e., more number of crops within a year and more number of crops on the same piece of land at any given period. It includes inter-cropping, mixed cropping and sequence cropping.

Types of Inter-Cropping:

a. Mixed intercropping: Growing two or more crops simultaneously with no distinct row arrangement.

b. Row intercropping: Growing two or more crops simultaneously where one or more crops are planted in rows.

c. Strip Inter-cropping: Growing two or more crops simultaneously in different strips wide enough to permit independent cultivation but narrow enough for the crops to interact ergonomically.

d. Relay inter-cropping: Growing two or more crops simultaneously during part of the life cycle of each. A second crop is planted after the first crop has reached its reproductive stage but before it is ready for harvest.

Inter cropping and its Objectives

Intercropping was originally practiced as an insurance against crop failure under rainfall conditions. At present the main objective of intercropping is higher productivity per unit area in addition to stability in production. Intercropping systems utilizes resources sufficiently and their productivity is increased. Yield is taken as primary consideration in the assessment of the potential of intercropping practices. Intercropping was originally practiced as an insurance against crop failure under rainfall conditions (Tsubo *et al.*, 2005).

The objectives of Intercropping Systems are:

1. Increase in total productivity per unit land area.
2. Insurance against main crop failure under aberrant weather conditions or pest epidemics.
3. Judicious utilization of resources such as land, labour and inputs.

2.2. Benefits of Intercropping for Productivity and Yield Stability

Increased crop productivity is among the most important and frequently cited benefits of intercropping. Over yielding occurs when the productivity of an intercrop is increased relative to the average of each component species grown in a monoculture. This is the most common way that crop productivity is increased with intercropping, and is often driven by resource partitioning. Transgressive over yielding is when the productivity of an intercrop is increased relative to the highest-yielding component species grown in monoculture. This occurs less frequently and is typically the result of facilitation, rather than simply resource partitioning. In addition to increased productivity, there are other benefits that intercropping can provide, including yield stability, pest suppression, and soil health. Intercropping has been shown to decrease the risk of crop failure by increasing the crop yield stability over time and across locations (Bybee-Finley, 2016 and Raseduzzaman, and Jensen, 2017).

The crop yield stability can be increased by reducing the variation over years at the same site, or by increasing the production consistency throughout the year. For example, growing a mixture of cool and warm season perennials for forage can counter seasonal slumps in production (Williamson, 2018). Crop yield stability can also be increased spatially by reducing the variability in production within fields (e.g., wet spots) and by maintaining production across different fields. The coefficient of variation (CV) is a metric used to evaluate the production consistency across space and over time. This is calculated by dividing the standard deviation of crop biomass in each treatment by the mean

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biomass of that treatment. It is a measure of dispersion with a lower number, indicating greater yield stability.

A meta-analysis of 69 intercropped systems found greater yield stability in grass-grain legume intercrops compared to those crops in monoculture, with CVs of 0.25, 0.30, and 0.19 for the grass monocultures, legume monocultures, and intercrops, respectively (Bybee-Finley, 2016 and Raseduzzaman, and Jensen, 2017). Another study with nine site-years which compared four annual species in monoculture and five intercropping treatments of those species found that the four-species mixture had similar yields to the highest-producing grass monoculture, but greater yield stability (Bybee-Finley, 2016). Despite the lack of transgressive overyielding in that study, the average CVs were 0.55, 0.47, and 0.36 for the monocultures, three-species mixtures, and the four-species mixture, respectively (Bybee-Finley, 2016).

2.3. Benefits of Intercropping for Pest Reduction

Intercropping has been shown to reduce the risk of weeds, insects, and diseases, a benefit that partially explains the increased yield and yield stability. Typically, intercrops can more effectively utilize available resources (e.g., light, water, nutrients) than if crops were grown separately, thus reducing the amount of resources that are available to weeds. In a review by Liebman and Dyck (1993), a cash crop intercropped with a "smother" crop had lower weed biomass in 47 out of 51 cases (Liebman, and Dyck, 1993). Trends were similar when the intercrop was composed of two cash crops, but not to the same degree (Liebman, and Dyck, 1993). A recent meta-analysis of 34 articles about cash crops (e.g., corn or forage) intercropped with legume companion crops containing 476 experimental units (site × year × cash crop × legume companion plant species × agricultural practices) determined that intercropping decreased weed biomass by 56% relative to non-weeded monoculture treatments (Verret *et al.*, 2017).

More generally, intercrops can diminish the damage by pests and diseases by reducing the number of susceptible hosts (dilution effect), resistant plants acting as a physical barrier to susceptible plants (barrier effect), inducing resistance by increasing the diversity of pests and diseases, reducing the speed by pest adaption through disruptive selection, and compensation of one species that performs poorly (Tonhasca and Byrne, 1994). A meta-analysis of 21 agroecosystem studies of diversified cropping systems showed a moderate reduction in herbivorous insect populations compared to more simplified cropping systems that served as the controls (Tonhasca and Byrne 1994). Another meta-analysis of 43 studies found that increasing the complexity of plant architecture resulted in a significant increase in predator and parasitoid natural enemies, mainly driven by increased plant detritus in intercropped systems (Langellotto and Denno, 2004). In a review of more than 200 studies of foliar fungi, intercropped systems had, on average, a 73% reduction of disease compared to their respective monocultures (Boudreau, 2013).

Trap crops that attract pests away from main crops as well as crops that repel pests can be intercropped for enhanced pest management. One of the most well-known examples using trap and repellent crops together is the push-pull system that is used to manage corn stemborers (Busseolafusca Fuller) and weeds like Striga spp. (Khan *et al.*, 2011). The strip intercropping method involves planting corn (the cash crop), a "pull" crop, like Napier grass (Pennisetum purpureum Schumach.) that uses semi-chemicals to attract corn stemborers, and a "push" crop like the legume Desmodium spp. planted between rows to repel corn stemborers from the corn (Figure 1) (Eigenbrode *et al*., 2016). The Desmodium spp. also elicits a fatal germination response from the parasitic weed Striga spp., reducing weed density and competition with the corn. A review article by Khan *et al*. (2011), stated that the push-pull system increased corn yields from below 1 to 3.5 t ha^{-1} largely in smallholder farms in east Africa (Khan *et al.*, 2011).

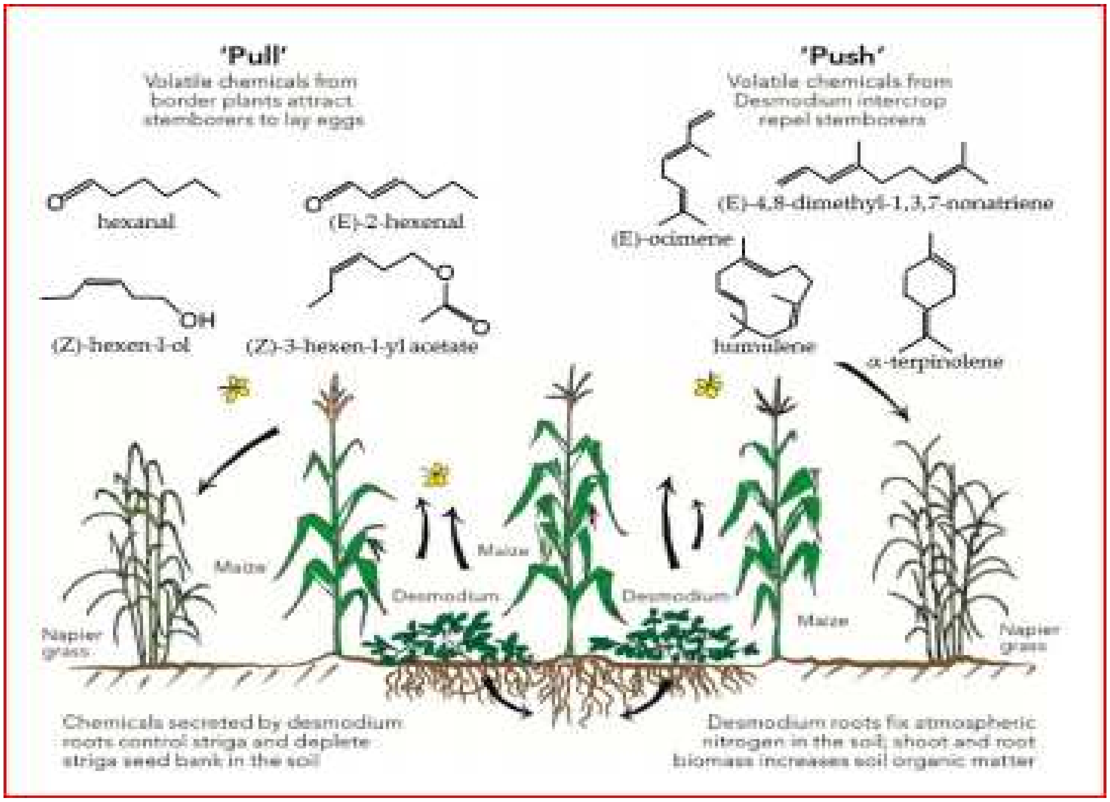

Figure 1. Scheme developed by the African Insect Science for Food and Health at the International Centre of Insect Physiology and Ecology (ICIPE) of the push-pull system in corn which illustrates the semiochemical ecology of attracting or detracting the corn stemborer and suppressing weeds. Adapted from: ICIPE, (2007).

2.4. Maize Based Rotation Crop Yields and Net Profitability

Davis *et al*. (2012), conducted rotation experiment for 9 years. Cropping system diversification in this study included both crop species and management practices. In contrast to the 2-yr rotation, with two species, both of the 3-yr and 4-yr rotations included four crop species. In the 4-yr rotation, further temporal diversification was achieved by including a perennial-only crop phase (alfalfa hay) for one quarter of the rotation sequence. The experimental cropping system treatments included a conventionally managed 2-yr rotation (maize/soybean) that received agrichemicals at rates comparable to those used on commercial farms in the region, and more diverse cropping systems - a 3-yr rotation (maize/ soybean/small grain + red clover green manure) and a 4-yr rotation (maize/soybean/small grain + alfalfa/alfalfa hay) – managed with reduced N fertilizer and herbicide inputs. The results showed productivity gains associated with greater diversity in system-level harvested crop mass and maize and soybean seed yields. they also observed increased stability of profit, with similar long-term means, in the 3-yr and 4- yr rotations compared to the 2-yr rotation (Davis *et al*., 2012).

The cropping system diversification enhanced yields of maize and soybean grain and system-level harvested crop mass (grain, straw, and hay) while maintaining economic returns. Over the 2003 to 2011 period, maize grain yield was on average 4% greater in the 3-yr and 4-yr rotations than in the 2-yr rotation (means for the 2-yr, 3-yr and 4- yr rotations are hereafter referred to as μ_2, μ_3 and μ_4, respectively; μ_2= 12.360 Mg ha^{-1}; μ_3= 12.760 Mg ha^{-1}; μ_4= 12.960 Mg ha^{-1}; pre-planned 1 d.f. contrast of system: $F_{1,7}$= 8, P = 0.03), and similar in the 3-yr and 4-yr rotations (Figure 2a). Soybean grain yield during the same period was on average 9% greater in the 3-yr and 4-yr rotations than in the 2-yr rotation (μ_2= 3.46 Mg ha^{-1}; μ_3= 3.860 Mg ha^{-1}; μ_4= 3.860 Mg ha^{-1}; $F_{1,7}$= 11.3, P = 0.01) and similar in the 3-yr and 4-yr rotations (Figure 2b). Harvested crop mass, averaged over the various crop phases

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comprising each cropping system, followed a similar pattern to maize and soybean grain yields. Mean crop biomass for 2003 to 2011 was 8% greater in the 3-yr and 4-yr rotations than in the 2-yr rotation (μ_2= 7.960 Mg ha^{-1}; μ_3= 8.560 Mg ha^{-1}; μ_4= 8.660 Mg ha^{-1}; system: t 6= 5.1, P = 0.002), and similar in the 3-yr and 4-yr rotations (Figure 2c) (Davis *et al*., 2012).

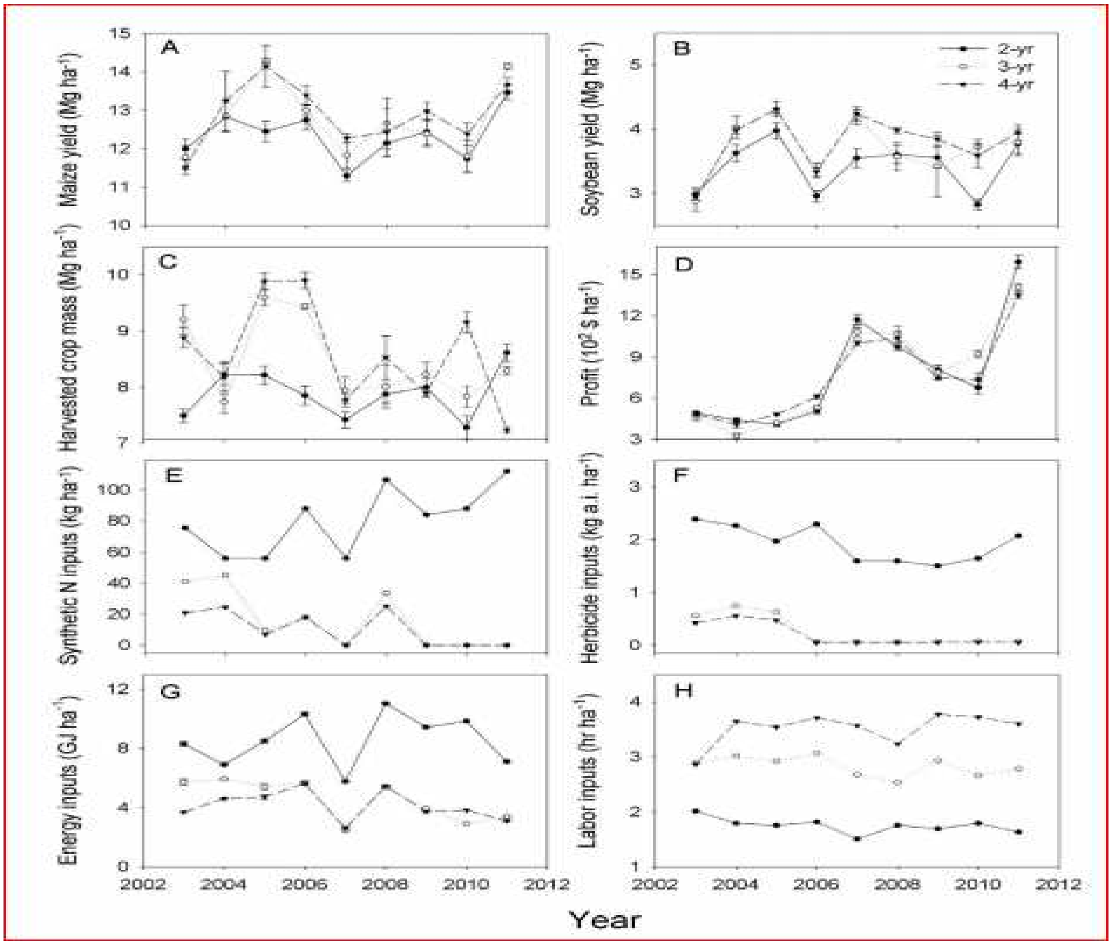

Figure 2. Cropping system performance over time. Annual performance of maize-soybean (2-yr), maize-soybean-small grain/red clover (3-yr), and maize-soybean-small grain/alfalfa-alfalfa (4-yr) cropping systems in Boone, IA, from 2003 to 2011. Performance metrics included: a) maize yield, b) soybean yield, c) rotation-level harvested crop mass, d) net returns to land and management, e) manufactured N fertilizer application rate, f) herbicide application rate, g) fossil energy use, and h) labor requirements. Symbols represent the mean 6 SEM of four replicate experimental blocks (N = 36 per cropping system). **Source**: adapted from Davis *et al*. (2012).

2.5. Grain Productivity and Protein Yield of Wheat Based Rotation Systems

St. Luce M, *et al*. (2020) conducted a study on crop rotation as: F-W-W (fallow-wheat-wheat); GM-W-W (lentil green manure-wheat-wheat); F-W-W-W (fallow-wheat-wheat-wheat); ContW (continuous wheat) and W-C-W-P (wheat-canola-wheat-pea) for 12 years. They found that, on average across the 12-yr period, grain and protein yields were 14 to 38% and 33 to 66% higher, respectively, for W-C-W-P than the other systems. Annualized grain yield followed the order of W-CW-P >ContW> F-W-W-W > GM-W-W = F-W-W, while the order for protein yield was W-C-W-P >ContW> GMW-W = F-W-W-W > F-W-W (Table 2). The W-C-W-P system produced higher grain yield than ContW in 8 of 12 yr. Annualized grain yield for ContW was higher than the other systems (except for W-C-W-P) in 4 yr. Also, the protein yield was higher for W-C-W-P than all other systems

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in all years except in 2012, when it was similar to ContW (Table 2). The ContW system produced more protein than the two fallow systems in 4 yrs (St. Luce M, *et al*., 2020).

Table 2. Annualized grain and protein yields in five long-term crop rotations at Swift Current, Saskatchewan, Canada from 2004 to 2015.

	F-W-W[a]	GM-W-W	F-W-W-W	ContW	W-C-W-P	Mean
Year	Grain yield		kg ha^{-1}			
2004	2297b[b]	2522b	2485b	3074a	3204a	2716A
2005	1586c	1543c	1732bc	1848b	2363a	1814DE
2006	1506a	1150b	1539a	1563a	1659a	1483G
2007	1406a	896b	1348a	1323a	1491a	1293H
2008	1448c	1655bc	1635bc	1859ab	1986a	1716EF
2009	1529ab	1295b	1566a	1545a	1666a	1520G
2010	1333d	1729c	1558cd	2010b	2410a	1808DE
2011	2123c	2311c	2213c	2801b	3049a	2499B
2012	1400b	1566b	1517b	1816a	1927a	1645F
2013	2001d	2264bc	2069cd	2434b	3069a	2368C
2014	1710b	1597b	1725b	1790b	2448a	1854D
2015	1230c	1351bc	1354bc	1536ab	1659a	1426G
Mean	1631d	1656d	1728c	1967b	2244a	
Year	Protein yield		kg ha^{-1}			
2004	304c	358b	314c	394b	500a	374A
2005	203b	219b	222b	228b	396a	254EF
2006	232bc	197c	238b	258b	327a	250EFG
2007	251b	168c	242b	249b	318a	246FG
2008	217c	278b	252bc	288b	380a	283CD
2009	216b	194b	227b	229b	296a	233GH
2010	184d	247bc	215cd	274b	405a	265DE
2011	268c	332b	277c	348b	441a	333B
2012	171d	223bc	195cd	255ab	270a	223H
2013	232d	289bc	251cd	308b	418a	300C
2014	204c	215bc	215bc	251b	395a	256DF
2015	203c	221bc	224bc	260b	322a	246FG
Mean	224d	245c	239c	279b	372a	

[a]F-W-W, fallow-wheat-wheat; GM-W-W, lentil green manure-wheat-wheat; F-W-W-W, fallow-wheat-wheat-wheat; ContW, continuous wheat; W-C-W-P, wheat-canola-wheat-pea. [b]Values followed by the same lowercase letters within rows and uppercase letters within columns are not significantly different ($P > .05$). **Source:** St. Luce M, *et al*. (2020).

The higher annualized grain yield of the W-C-W-P than ContW was partly due to the fact that wheat yields in the W-C-W-P system averaged 20 to 25% higher than that of ContW (Figure 2); this more than compensated for the lower canola and field pea grain yields. The increase in annualized grain and protein yield as fallow frequency decreased was in agreement with previous studies (Gan *et al*., 2015; Smith *et al*., 2017 and Rosenzweig *et al*., 2018), and was mostly related to the absence of a crop during the summer fallow and GM phases. Differences in protein yield among rotation system is a partial reflection of the specific crops within the rotations. The inclusion of field pea in the W-C-W-P rotation increased overall protein yield compared to the other systems. Pulse crops, such as field pea, have a much higher seed N concentration, and often produce equivalent or greater seed yield than cereals and oilseeds, as observed in this study. In addition, wheat following field pea in the W-C-W-P system had 15 to 18% higher protein yield than wheat grown on stubble in the fallow and ContW systems (Table2). The inclusion of pulses in cropping systems can help to improve soil and human health by providing adequate protein for human consumption (Lal, 2017). Canola in the W-C-W-P system had similar protein yield to wheat grown on stubble in the fallow and ContW systems, further contributing to the higher annualized protein yield for W-C-W-P. Although canola is primarily grown for its oil content and there's a direct inverse relationship between oil and protein content, meal from canola oil extraction can be used to produce protein-rich human and animal food (Wanasundara *et al*., 2016; Hossain *et al*., 2019 and St. Luce *et al*., 2020).

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The diversified cropping systems which include pulses in the rotation can more consistently produce high grain and protein yields, without relying on substantial synthetic N fertilizer inputs than a continuous cereal monoculture system and fallow systems in the semiarid prairies, regardless of growing conditions. The low N fertilizer use and high FUE of the diversified system can potentially minimize the negative environmental consequences associated with N fertilizers. In semiarid regions, where moisture availability is a major constraint to agricultural productivity, traditional summer fallow systems, within the context of the parameters considered in this study, may be warranted going forward, but only if the subsequent crop yields more than compensates for the yield loss in the fallow year. With the need to meet the demands of a rapidly growing world population and future technological developments, such as the genetic enhancements of cultivars for improved heat and drought tolerance, coupled with improved farming practices, the use of continuous cropping over fallow systems, and extended and diversified over monoculture systems is favored (St. Luce *et al.*, 2020).

2.6. Yield Stability of Rotation Systems

The GM-W-W system had below-average grain and protein yields in low-yielding conditions, and near-average protein yield in high-yielding conditions (Figure 3a, 3b). Annualized grain and protein yields were lowest in the GM-W-W system in dry and hot years, and when the previous year was also hot and dry. The fallow systems had mostly below-average grain and protein yields, with a few exceptions (Figure 3a, 3b), and their slopes (< 0.8) were significantly (P < .05) less than 1 (Figure 3c, 3d). More specifically, the fallow systems generally produced above- or near-average grain and protein yields only in very low-yielding conditions (Figure 3a, 3b). Interestingly, the gap between the fallow systems and the average site yield increased as grain and protein yield progressed from low to high-yielding conditions (St. Luce *et al.*, 2020). The ContW system produced near or above-average grain yields, which increased from low-yielding to high-yielding conditions (Figure 3a), and had a slope > 1 (P < .05; Figure 3b). For protein yield, however, the ContW system produced average or above-average yield across all conditions, with a slope close to 1 (P > .05). The W-C-W-P system had low yield stability with slopes significantly > 1 (P < .05; Figure 3d), and consistently had above-average grain and protein yields across all conditions (St. Luce M, *et al.*, 2020).

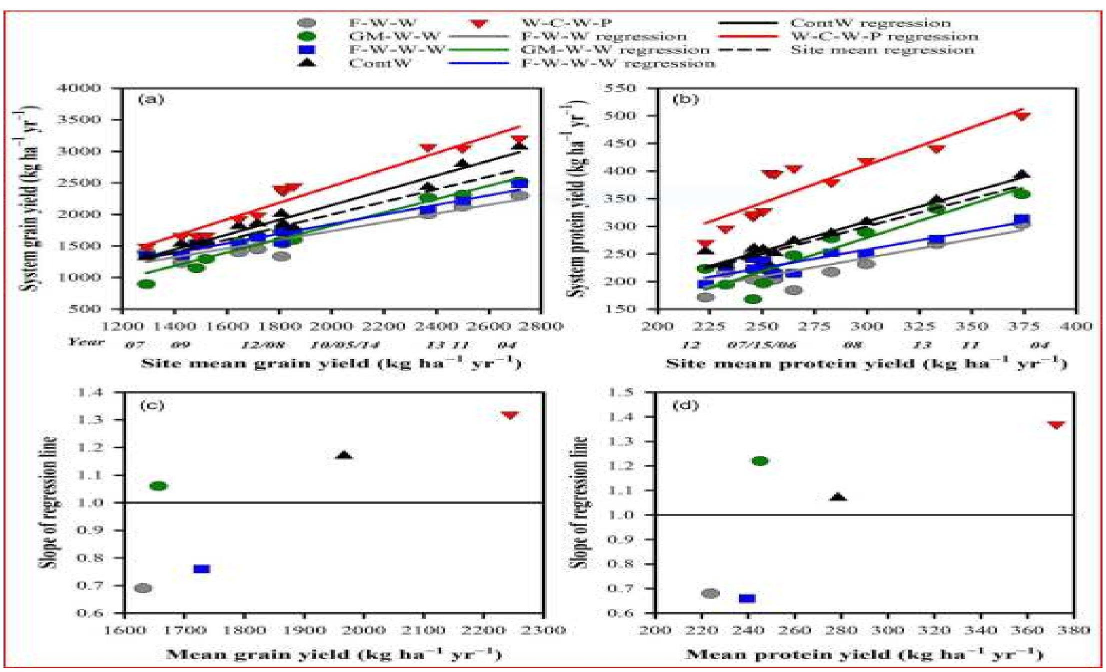

Figure 3. Stability of five long-term cropping systems at Swift Current, Saskatchewan, Canada over a 12-yr period (2004–2015). Relationship between cropping system mean yield (a) and site mean yields

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(b), and relationship between regression coefficient and cropping system mean yield (c, d). F-W-W, fallow-wheat-wheat; GM-W-W, lentil green manure-wheat-wheat; F-W-W-W, fallow-wheat-wheat-wheat; ContW, continuous wheat; W-C-W-P, wheat-canola-wheat-pea. **Source:** St. Luce M, *et al*. (2020).

3. Long-Term Impacts of Crop Rotation and Farming Practices on Yield

There is increasing pressure on agriculture with imperative to produce more food, reduce negative environmental impacts, prevent yield decline and adapt to climate change. Yield decline and stagnation reported by investigations on global crop production (Ray *et al*., 2015) as well as the challenges brought by climate change (Lobell *et al*., 2011 and Bindi and Olesen, 2011) call for the development of adaptive crop production systems. St-Martin *et al*. (2016), in their experiments, investigated the long-term effect of diverse crop rotation compared to monoculture and its contribution as climate change adaptation. They provided evidence of whether diversification of agriculture might be such a strategy and its contribution to crop yield. They compared diversification in crop-livestock, diverse stockless and specialized cropping systems.

3.1. Diversification of Cropping Systems on Crop Yields

St-Martin *et al*. (2016), in their experiment, investigated how diversification in cropping systems and in crop rotations contributed to cereal yields throughout 8 Long Term Experiments (LTE) covering experimental periods ranging between 20 and 55 years. They found that crop-livestock and stockless systems were equal in delivering high yield in the long-term. This suggests that stockless diversification provides a valid alternative to crop-livestock systems to maintain high yields. Diversification provides an opportunity for land managers to increase crop productivity and secure continued high yields, even under conventional management. Investigations of the CV and stability analysis suggest that conventional management with application of inorganic fertilizer protect cropping systems in the face of environmental variability (St-Martin *et al*., 2016).

It should be noted that the stability of each cropping system is very much dependent on the other systems included in the analysis. This means that the outcome could have been different if other cropping systems had been included. An extension to investigation of how a specialized cropping system compared with diverse systems and whether a crop-livestock system provided added benefits compared to a stockless diverse system in terms of yield and stability would be to evaluate the stability of each cropping systems for all the crops included in each system, not limiting it to one crop type. Another extension would be to include an analysis of profitability parallel to the yield analysis (St-Martin *et al.,* 2016).

On overall yield response of contrasting cropping systems, they investigated how cropping systems 'crop-livestock', 'specialized', and 'diverse', and associated management practices affected yield response. They found that diversification enhance crop yield both at the cropping system level as well as at the level of the crop rotation and yields in specialized system and in monoculture were lower than in diverse cropping systems or diverse crop rotations (St-Martin *et al.,* 2016) and (Figs. 4, 5, 6, 7 and 8). When examining the development over time in the LTE from 6 LTEs across Europe showed management with diverse crop rotation contribute to maintaining high yield (St-Martin, 2017) (Figure 4).

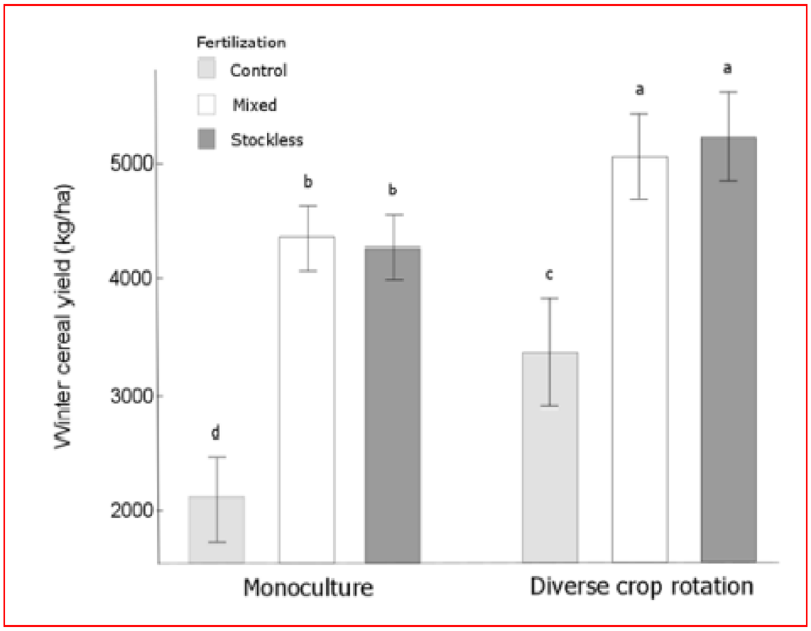

Figure 4. Effect of crop rotation and fertilization in 6 LTEs across Europe. Error bars represent 95% confidence interval. Bars with identical letters are not significantly different t p<0.05 (Tukey, HSD). **Source**: St-Martin, (2017).

When examining 6 LTEs, he found that yields in monoculture underwent a slower increase over time than did yield in diverse crop rotations (Fig.5) (St-Martin, *et al.*, 2016).

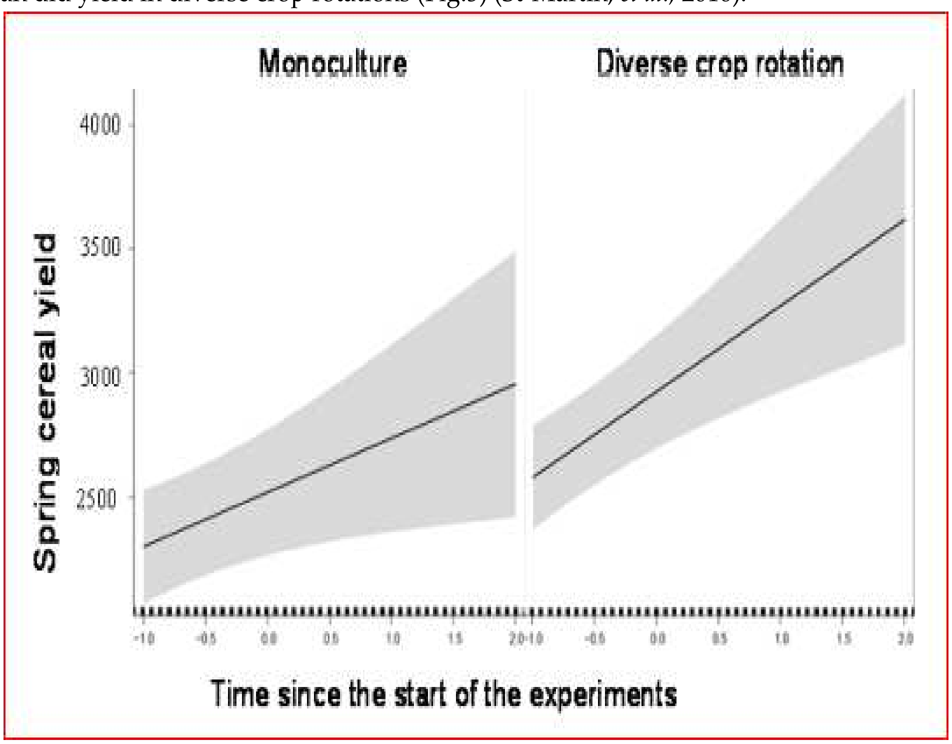

Figure 5. Effect of crop rotation on spring cereal yield development in 6 LTE across Europe. Shaded areas around the lines represent 95% confidence interval. **Source**: St-Martin, A. (2017).

3.2. Yield Effect of Crop-Livestock System Compared to Stockless Diversification

When investigating diversification options at the cropping system level, crop-livestock and stockless diverse systems are both equal at delivering high cereal yield, with a tendency of crop-livestock to deliver higher yield for spring cereals (St-Martin, 2017). The 6 LTEs showed mixed fertilization (combining manure with mineral fertilizer) associated with crop-livestock system does not provide added yield benefit compared to stockless fertilization relying exclusively on mineral fertilizer (Figure 6) and that the yield gain from fertilizer was greater under stockless fertilization (St-Martin, 2017).

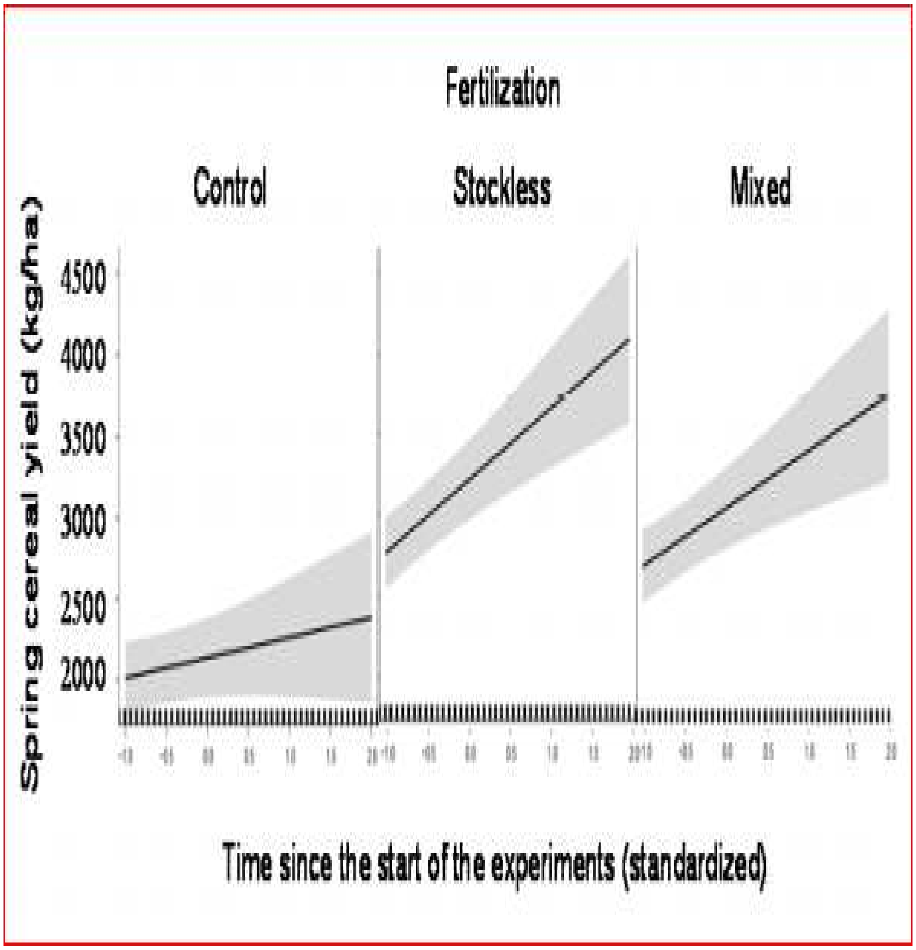

Figure 6. Effect of fertilization on spring cereal yield development in 6 LTE across Europe. Shaded areas around the lines represent 95% confidence interval. **Source**: St-Martin, (2017).

Investigating the effect of year-to-year variation on yield of contrasting cropping systems in Borgeby, St-Martin, (2017), found that the three cropping systems were equally stable with regards to winter wheat. The crop-livestock system tended to deliver higher yield in high-yielding years for spring wheat (Figure 7) (St-Martin *et al.*, 2015 and St-Martin, 2017). Interestingly, diverse cropping systems and diverse crop rotation provided yield benefits even under high mineral fertilization (St-Martin, 2017). When investigating the yield response in contrasting crop rotations to the range of temperature and precipitation encountered in 7 LTEs across Europe, they found a positive effect of increasing growing season precipitation and a negative effect of increasing growing season temperature on spring cereal yields (St-Martin *et al.*, 2016 and St-Martin, A. 2017).

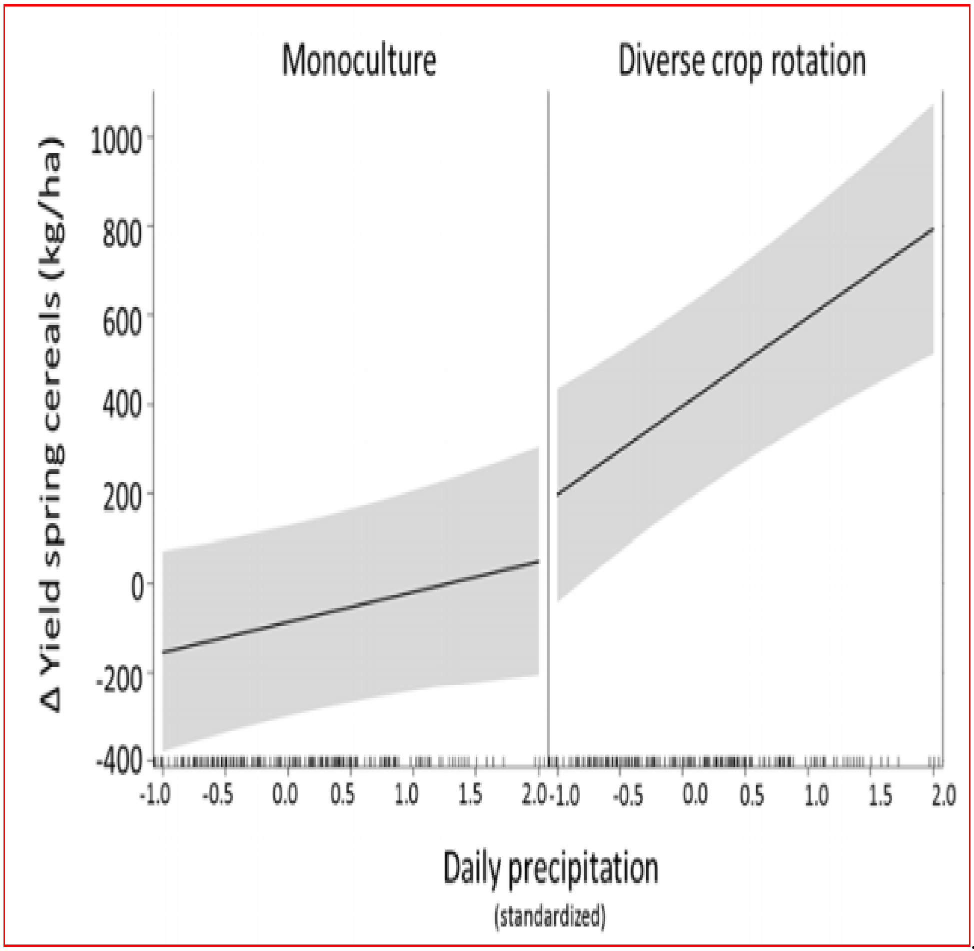

Figure 7. Change in yields and daily precipitation over the growing season for spring cereals grown in monoculture and in diverse rotation in 5 LTEs. Shaded areas around the lines represent 95% confidence interval. **Source:** St-Martin, A. (2017).

In northern latitudes where spring cereals are grown, the positive effect of precipitation was more pronounced in diverse crop rotation than in monoculture (Figure 8). Data from 5 LTEs suggests that diverse crop rotation is a potential adaptation to expected climate change for northern latitudes. They found a negative effect of both increasing temperature and precipitation during the growing season on winter cereal yields (St-Martin *et al.*, 2016 and St-Martin, 2017). In Southern latitudes, where winter cereals are grown, the positive effect of decreasing precipitation during the growing season tended to be more pronounced in diverse crop rotation than in monoculture (Figure 8). Data from 3 LTEs suggests that diverse crop rotation is a potential adaptation to expected climate change for southern latitudes (St-Martin, 2017).

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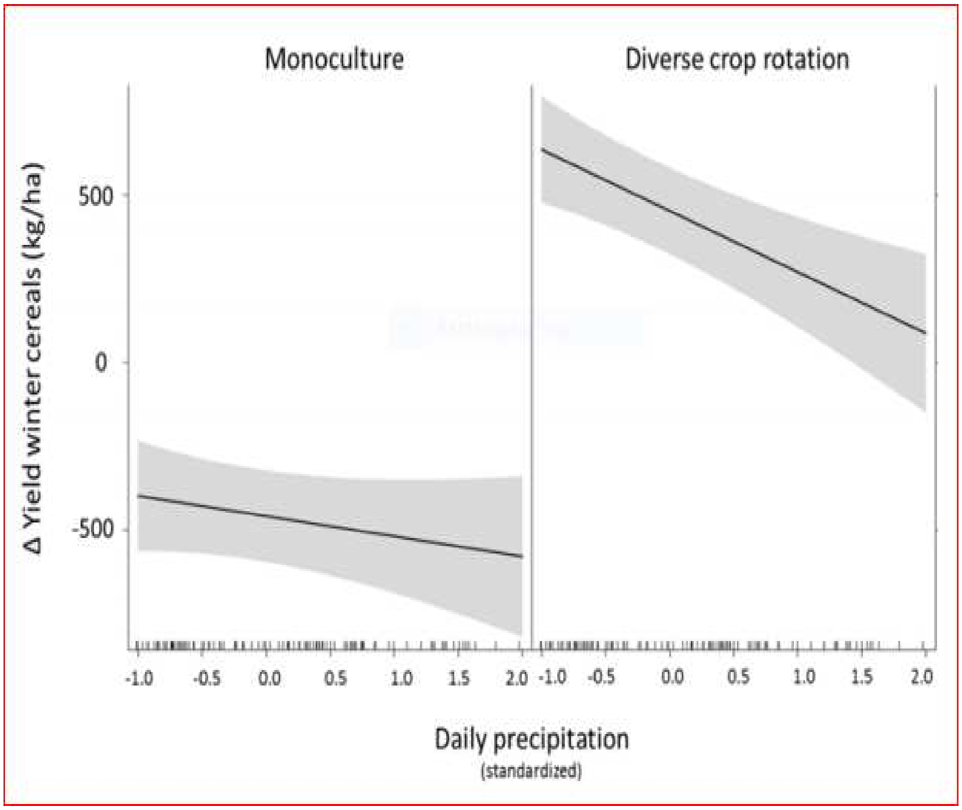

Figure 8. Change in yields and daily precipitation over the growing season for spring cereals grown in monoculture and in diverse rotation in 5 LTEs. Shaded area around lines represent 95% confidence interval. **Source**: St-Martin, A. (2017).

3.3. Diversification of Crop Rotation and Fertilization

Rotation systems have been used for millennia to maintain soil fertility and productivity and to suppress pests, and can increase yields even in situations where substantial amounts of fertilizers and pesticides are applied (Varvel, 2000). In 6 LTEs located across Europe covering an experimental period ranging between 20 and 55 years, Naylor *et al*. (2005) found that yield benefits of diverse crop rotation on long-term cereal yields. Both stockless and mixed fertilization delivered high cereal yield in the long-term. The results further suggest that diverse crop rotation gives added benefits under high mineral input. Diversification through crop rotation can be an especially useful strategy in farming systems that integrate crop and livestock production. The addition of forage crops, including turnips and clovers, to cereal-based systems enhanced nitrogen supply through fixation by legumes, and increased nutrient cycling due to greater livestock density and manure production. These changes allowed the intensification of both crop and livestock production and increased yields substantially. Through diversification of farm activities, integration of crop-livestock has been identified to mitigate the effects of price fluctuations on crop or input (Ryschawy *et al*., 2012).

3.4. Diversification Crop Rotation and Climate Change

St-Martin *et al.* (2016), investigated how yields from monoculture and diverse crop rotations in multiple long-term experiments have responded to past climatic variation provides an important step in understanding how these practices are likely to respond to projected future climates. The observed year-to-year variation in 7 LTEs across Europe was much greater than the observed trend in climate (St-Martin, 2017). Therefore, they estimated yields reacting to, for example, an increase in growing season temperature and how crop rotation affected this response. It was found that, at northern latitudes, where precipitation and temperature is expected to increase, and at southern latitudes

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where precipitation is expected to decrease, diversifying crop rotation represents an adaptation strategy for enhancing cereal yields. Climatic extremes can have larger effects than average conditions (Lesk *et al*., 2016 and Lobell and Field, 2007). Crop-livestock systems have also been found to mitigate the effect of climate variability on farm performance due to the flexibility gained from the production of a wider range of agricultural products (Bell *etal*., 2014). In recent years, there has been interest in reintegrating crop and livestock systems as a strategy for reducing reliance on fossil fuels, minimizing the use of increasingly expensive fertilizers, and limiting water pollution by nutrients, pathogens, and antibiotics.

Through diversification of farm activities, integration of crop-livestock has been identified to mitigate the effects of price fluctuations on crop or input (Ryschawy *et al*., 2012). Crop-livestock systems have also been found to mitigate the effect of climate variability on farm performance due to the flexibility gained from the production of a wider range of agricultural products (Bell *et al*., 2014). The Borgeby experiment was designed more than 50 years ago to answer questions about farm specialization but without the concern regarding the effect of synthetic inputs on the environment. The design of future cropping system experiments should allow management practices such as inorganic fertilization, weed management and plant protection to vary between systems. That would allow identifying which cropping system might be better at delivering nutrients, or at dealing with weeds and disease (Varvel, 2000).

3.5. Diversification Crop Rotation and Crop Yield

The number of species in the rotation (crop diversity) affected yields in all three crops (Table 2; Figure 2A–C). However, the strongest effects of crop diversity were in corn, where over-yielding (% increase in yield compared to the monoculture) was over 100% in some treatments. Over the 3 years, corn yields in the highest diversity treatment averaged 6.9 Mg ha^{-1}) compared to 3.4 Mg ha^{-1}) in the lowest diversity treatment (Figure 2A). In all 3 years, there was a significant positive linear relationship between the number of crop species in the rotation and corn yield. The slope of this relationship increased each year, suggesting an increasingly strong diversity effect with time (Figure 3). Removal of treatment 1 (the only treatment that did not include a legume) from the analysis resulted in only a slight change in the relationship between crop species richness and corn yield; the relationship was non-significant in 2002, but remained significant (P < 0.05) and positive in both 2003 (r 2 = 0.56, slope = 0.75) and 2004 (r 2 = 0.43, slope = 0.86).

Corn yields generally increased with the number of legume species in the rotation; having one legume (crop or cover crop; treatment 1 vs. 2-4) increased corn yields from 1.0 to 1.8 Mg ha)1 compared to the monoculture. Increasing from one to two legume species in the rotation resulted in an additional increase of 1.8 to 2.6 Mg ha^{-1} (Tukey HSD, P < 0.05; treatments 2-4 vs. 5 and 6) (Figures 2 and 4). Effects were similar whether the diversity increase was due to the inclusion of soybean or Trifolium cover crops. The number of non-legume crops in the rotation did not affect corn yields appreciably (that is, treatment 2 vs. treatments 3 and 4). Interestingly, corn yields in the most diverse treatment (treatment 6) were not significantly different from the Kalamazoo county average for conventionally managed corn each of the 3 years (t-test, df = 3; 2002: t =) 2.9, P = 0.63; 2003: t =) 1.3, P = 0.28; 2004: t =) 1.1, P = 0.35).

In soybean and winter wheat, the effects of the crop diversity treatments on grain yields were significant (Table 2), but were of lower magnitude than those in corn (highest yielding treatments were 32 and 53% higher than the monocultures, respectively). Soybean grain yields in treatments with at least two species in the rotation were equal to or greater than the county average in 2002 (t-test, df = 3, t > 0, P £ 0.05) and comparable in treatments 1–5 in 2004 (t-test, df = 3, t < 0, P > 0.05). The significant crop diversity treatment effect in winter wheat was due to low yields in the monoculture (treatment 1); the other diversity treatments did not differ from one another (Tukey HSD, P > 0.05). With the exception of treatment 6 in 2002, yields each year in winter wheat at all levels of crop diversity were significantly lower than the county average (t-test, df = 3, t < 0, P < 0.05).

Aggregate yields collected over the entire 3-year sequence of each diversity treatment (total grain yields) may provide a more appropriate analog to the common metrics assessed in other plant

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diversity–ecosystem function studies. Total grain yields, yields of all harvestable grains produced over the course of the study, varied with the level of crop diversity ($F_{5,15} = 18.63$, $P < 0.0001$), and were over 60% greater in the highest diversity treatment compared to the lowest diversity treatment (Figure 2D).

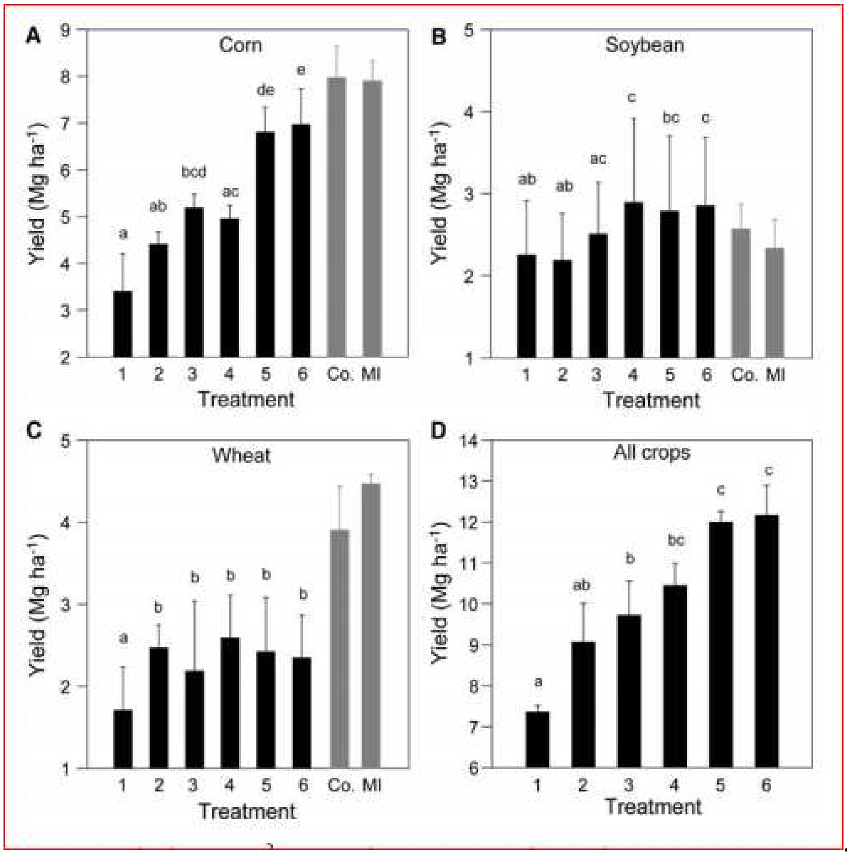

Figure 2. Comparisons of average grain yields for (A) corn, (B) soybean, and (C) winter wheat across crop diversity treatments in the BExP (black bars), Kalamazoo County (Co.), and the State of Michigan (MI). Values are means of treatment averages ± SE, n = 3 years. BExP treatments are listed in order of increasing diversity (number of species in rotation: see Table 1 for details). Panel D is total grain yields of all crops summed over the study period. Among the BExP treatments, bars sharing the same letter are not significantly different from each another at the P = 0.05 level (Tukey HSD) based on analysis of treatment means, n = 12 (panels A–C) and n = 4 (panel D).

Increasing the diversity of crop species in a rotation had significant effects on grain, but effects were often crop-species specific. In corn, yields increased linearly with increasing diversity of the rotation and in the highest diversity treatment were not significantly different from the county average for conventionally managed corn in each of the 3 years. This similarity in yields is remarkable given the absence of synthetic chemical inputs (fertilizer or pesticides) in the BExP, and suggests that diverse cropping systems can provide an ecosystem service that replaces (or reduces) reliance on chemical inputs in some systems. Other agronomic studies have reported corn yields that were similar (Poudel and others 2002; Delate and Cambardella 2004; Pimentel and others 2005; Smith and Gross 2006) or only moderately reduced (< 10% Porter and others 2003; but see Teasdale and others 2007) in diverse organic and low-input cropping systems when compared to those in conventional input systems. Grain yields in soybean and wheat also were lower in the monocultures than in any of the multiple species treatments, but beyond that there was no effect of species diversity on crop yields. The different responses of the three crop species to diversity suggest that species traits will influence how crops respond to increasing diversity and its impacts on ecosystem services in row-

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crop systems (Porter and others 2003). Despite the differences among crops in their response to diversity, total grain yields harvested over the course of the study were greatest in the highest diversity treatments (Figure 2D), suggesting that increases in over-all productivity (in terms of grain yield) may compensate for the decreased corn frequency in the higher diversity rotations.

An important ecosystem service provided by crop diversity that could impact grain yields is the availability of nutrients, particularly soil nitrogen (Drinkwater and others 1998; Ma¨der and others 2002). The diversity treatments in the BExP likely impacted soil nitrogen availability through at least two major mechanisms: (1) changes in the intensity of nitrogen export from soil reservoirs due to differential crop uptake and (2) differences in biological nitrogen fixation related to the inclusion and frequency of legumes. The relative importance of each mechanism to the observed yield responses appeared to be crop dependent. In corn, nitrogen availability was higher early in the growing season in the more diverse treatments and this was strongly correlated with grain yields. Corn is an effective competitor for nitrogen; export by corn of the nitrogen provided by previous soybean and leguminous cover crops may have reduced availability to subsequent crops, particularly in the lower diversity treatments where corn occurred more frequently. In contrast to corn, soybean, because it can fix its own nitrogen, is typically not highly responsive to added nitrogen (Reese and Buss 1992), which may explain its lack of responsiveness to increased diversity in this study. The lack of responsiveness in wheat is more difficult to explain, but may be due to asynchronies in the timing of nitrogen availability relative to crop demand (Boman and others 1995). The fact that weed abundance was not greater in treatments with greater available nitrogen suggests also that weeds were unable to take advantage of the increased nitrogen availability, likely due to the effectiveness of the mechanical control early in the growing season (Mohler and others 1997).

Differences in inorganic nitrogen availability and corn yields among the treatments appeared to be driven primarily by the number of legume species in the cropping sequence, suggesting that cropfunctional traits were important determinants of ecosystem function in this system. These results parallel those from rotation studies in agricultural systems (Drinkwater and others 1998; Gentry and others 2001) and studies in grasslands that have attributed diversity effects to the identity and functional traits of the species (Hooper and Vitousek 1998; Diaz and Cabido 2001; Spehn and others 2002; Lambers and others 2004). In many of these experiments legumes were identified as important drivers of positive diversity–productivity relationships due to their stimulation of overyielding in non-nitrogen fixing species, particularly those with the C4 photosynthetic pathway (Spehn and others 2002; Lambers and others 2004; Hooper and others 2005).

Another potentially important ecosystem service provided by crop diversity that could impact grain yields is weed suppression (Liebman and Dyck 1993). In row-crops, yields are often correlated with variation in weed biomass (Weiner and others 2001). Crop diversity could influence weed biomass or composition by increasing the prevalence of stress and mortality factors that affect weeds or by changing resource use by crops and weeds such that crops preempt resources used by weeds (Liebman and Gallandt 1997; Liebman and Staver 2001). However, we found little evidence that the observed yield differences in relation to crop diversity were due to effects on weed biomass across these treatments. We detected no differences in weed abundance among diversity treatments in corn and soybean despite the fact that weed management practices differed among the three crops (inter-row cultivation in corn and soybean, no cultivation in winter wheat). Treatment differences in weed abundance in winter wheat due to the presence of cover crops were not related to yields.

4. Summary and Conclusion

Crop or cropping system diversification refers to a shift from often a less productive, less resilient and less sustainable cropping system to a more productive, resilient and sustainable one. The shift is usually in response to specific farm goals. These may include new markets, soil fertility improvement, pests and diseases suppression, increasing crop productivity and stabilizing household food, nutrition and income. Cropping system diversification is also used as an insurance against a possible crop failure. Cropping system diversification is thus a key pathway to sustainable intensification of crop production. Several crop diversification options exist within the framework of sustainable intensification (e.g. agro-forestry, green manure intercropping and rotations with cereals). Cereal-grain legume rotation, spatial and temporal intercropping systems appear readily adaptable to the biophysical and socio-economic context of smallholder farming systems are being used.

Reintegration of crop and livestock production, as represented by the forage legumes and manure applications present in the more diverse systems, is not simply another aspect of cropping system diversification. Instead, it embodies an important principle in sustainable agriculture: system boundaries should be drawn to minimize externalities. Substantial improvements in the environmental sustainability of agriculture are achievable now, without sacrificing food production or farmer livelihoods.

Future directions

Cropping system diversification would result in the development of ecosystem services over time that would supplement, or eventually displace, the role of synthetic external inputs in maintaining crop productivity and profitability. A potential limitation to the adoption of diverse crop rotation has been that diverse crop rotation lowers the revenues of diversified operations in a given year compared to the selection of few high-priced crops and reduces the benefits associated with economies of scale. Therefore, integration of economic aspects is key to appreciating the more general benefits of crop diversification. Integration of farm economic performance in farm with contrasting levels of diversification (either in terms of cropping system or crop rotation) would provide a next step in investigating the applicability of diversification.

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