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Editorial

Sustainable Cropping Systems

Jeffrey A. Coulter

Department of Agronomy and Plant Genetics, University of Minnesota, St. Paul, MN 55108, USA; jeffcoulter@umn.edu

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Abstract: Crop production must increase substantially to meet the needs of a rapidly growing human population, but this is constrained by the availability of resources such as nutrients, water, and land. There is also an urgent need to reduce negative environmental impacts from crop production. Collectively, these issues represent one of the greatest challenges of the twenty-first century. Sustainable cropping systems based on ecological principles, appropriate use of inputs, and soil improvement are the core for integrated approaches to solve this grand challenge. This special issue includes several review and original research articles on these topics for an array of cropping systems, which can advise implementation of best management practices and lead to advances in agronomics for sustainable intensification of crop production.

Keywords: cropping systems; sustainable crop production; agroecology; nutrient use efficiency; water use efficiency; environmental quality

1. Introduction

The global human population reached 7.7 billion in 2019 and is predicted to be 8.5 billion in 2030 and 9.7 billion in 2050 [1]. Increases in crop production will be needed to meet the requirements of the growing human population. Worldwide, total demand for all agricultural products is anticipated to increase by 1.1% per year until 2050, while that for cereals is expecded to grow by 0.9% per year until 2050, compared to the demand in 2005 to 2007 [2]. However, many of the resources needed for crop production are limited, including land, water, and nutrients, making it essential that they be used responsibly.

Since the 1960s, increases in global crop production have been associated with expansion of land in crop production, increased cropland under irrigation, and greater use of chemical fertilizers [2], along with reliance on chemical pesticides [3]. However, these factors have been linked to negative impacts on the environment. Expansion of cropland can result in loss of soil organic carbon [4], biodiversity [5,6], and ecosystem services [7], and cultivation of marginal land that is highly susceptible to soil erosion [8]. Large-scale irrigation can result in decreased downstream river flow [9], declining aquifer levels [10], and soil salinization and desertification [11]. High application rates of chemical fertilizers, especially nitrogen (N) and phosphorus fertilizers, promote nutrient losses to the ambient environment, which can lead to contamination of surface and ground waters [12–14], eutrophication of non-saline surface waters and coastal waters [13], and greenhouse gas emissions [15]. Additionally, chemical pesticide use can cause a reduction in beneficial predators and parasites, pesticide resistance in pests, a decline in pollinators, injury to target and non-target crops, reduced biodiversity, and pollution of ground and surface waters [16]. Therefore, it is imperative to increase crop production while decreasing its negative effects on the environment. Sustainable cropping systems rooted in agroecological principles, coupled with judicious use of external inputs and soil enhancement, are key to accomplishing this task.

2. Special Issue Overview

This special issue provides an international base for revealing the underlying mechanisms of sustainable cropping systems to drive agronomic innovations and guide the application of best management practices. It includes two review and 16 original research articles reporting novel scientific findings on the development of cropping systems for improved crop yields with greater resistance to abiotic and biotic stressors, enhanced resource use efficiency and profitability, reduced risk of negative environmental impacts, improved soil conditions, and enriched ecosystem diversity. These papers are broadly focused on farming system design, crop rotation, N management, residue management, cover crops, organic management, and crop management for efficient use of irrigation water, and are introduced below.

2.1. Farming System Design

Adaptation of farming systems for improved sustainability requires an understanding of the multifaceted interactions that they are affected by [17], along with the effects of altered agronomic practices on system performance. The article by Merot and Beohouchette [18] proposes a method for applying ecologically-based hierarchical patch dynamics theory to farming systems analysis, which considers spatiotemporal heterogeneity and variation in crop management and fields. The authors applied this method in a case study of a French vineyard undergoing transition to organic production. The results showed that it was useful for hierarchical characterization of the farming system from the farm to field scale and for understanding interactions between farming practices and biological processes. This revealed new biophysical indicators that should be considered in the development of an organic farming system, along with fields that were good candidates to remove from production prior to organic transition due to their greater management requirements.

To control stemborer damage in maize (*Zea mays* L.), improve soil fertility, and increase maize yield on smallholder farms in Ethiopia, a push–pull cropping system was developed [19], by which the drought-tolerant legume desmodium [*Desmodium intortum* (Mill.) Urb.] is intercropped with maize and used to repel (i.e., push) stemborers to a trap (i.e., pull) crop of Bracharia hybrid grass planted in the field borders [20]. The paper by Kumela et al. [21] evaluated this cropping system with monoculture maize in on-farm trials across two neighborhoods in 2016 and four neighborhoods in 2017. Maize grain yield with the push–pull cropping system was significantly greater than that of monoculture maize in all cases except for in one neighborhood in 2017. In a survey of farmers following the 2016 growing season, the majority of respondents who tested the push–pull cropping system rated it as better than monoculture maize based on its ability to provide livestock feed and control stemborer damage, and 96% reported that they were interested in utilizing the push–pull system in the next growing season.

Intercropping shade-tolerant crops with trees is a viable strategy for increasing the utilization efficiency of arable land to meet the needs of an ever-growing human population. Potato (*Solanum tuberosum* L.) is a shade-tolerant food crop [22] that is commonly intercropped with trees in tropical and sub-tropical regions where there are high levels of solar irradiance. In these regions, shading has been shown to have minimal effect on potato tuber yield [22–25]. However, little is known about the performance of potato under shade at higher latitudes where solar irradiance is less. To provide a basis for the development of potato/tree intercropping at higher latitudes, the article by Schulz et al. [26] reports on the effects of artificial shading on potato in southwestern Germany. Compared to the non-shaded control during the three study years, tuber starch content was not significantly affected by shading, while tuber dry matter yield was reduced in zero, one, and two, years with shade levels of 12%, 26%, and 50%, respectively. Since the yield reduction with 26% shading occurred in the year with low total solar irradiance, the authors concluded that potato is a suitable intercrop for agroforestry systems with shading up to 26% under normal levels of solar irradiance in this region.

The review by Sellami et al. [27] synthesizes data from agronomic research on protein crops in Europe. It shows that sowing date and density, fertilization, and deficit irrigation had the greatest effect on seed yield, that faba bean (*Vicia faba* Roth), pea (*Pisum sativum* L.), and lupin (*Lupinus albus* L.)

produced greater seed yield than quinoa (*Chenopodium quinoa* Willd.), amaranth (*Amaranthus* spp.), chickpea (*Cicer arietinum* L.), and lentil (*Lens culinaris* Medik.), and that highest seed yield occurred in central European growing environments, providing insight for sustainable intensification of protein crop production.

2.2. Crop Rotation

Crop rotation has long been recognized as a key component of sustainable cropping systems. The paper by Pagnani et al. [28] reports on the effects of crop rotation and tillage system (conventional tillage and no-tillage) on durum wheat (*Triticum turgidum* L. subsp. *durum* (Desf.) Husn.) over two growing seasons in a Mediterranean region. Compared to monocropped wheat, a two-year faba bean-wheat rotation increased wheat grain yield by 8%, across years and tillage systems. Crop rotation also promoted remobilization of N to grain, and crop rotation coupled with no-tillage improved multiple indices of grain quality when compared to monocropped wheat under conventional tillage.

The article by Qaswar et al. [29] summarizes a long-term study on green manure rotations on an acidic paddy soil in a double rice (*Oriza sativa* L.) cropping system. Compared to a rice–rice–winter fallow cropping system, replacing winter fallow with a green manure crop improved grain yield and the sustainable yield index of early and late rice, soil organic matter, soil total and available N and phosphorus, and phosphatase and urease activities, and reduced the apparent N and phosphorus balances. The authors also quantified the effect of soil biochemical properties on grain yield, providing understanding into the mechanisms driving the rotation effect.

2.3. Nitrogen Management

Nitrogen is typically the most limiting nutrient for the production of cereal crops [30], but the recovery of applied N in harvested grain is only about 35% of the amount applied worldwide [31], rendering the excess N susceptible to loss, which can lead to environmental degradation [32,33]. To advance N use efficiency in maize production through improved synchrony between N supply and crop N requirements, the review by Asibi et al. [34] summarizes recent research and provides new understanding on N assimilation, utilization, and remobilization in maize.

Compost, or decomposed organic material, can improve soil fertility [35] and serve as a slow-release source of N to crops [36,37]. The paper by Maucieri et al. [38] evaluated different types of compost as a substitute for mineral N fertilizer in a three-year maize-wheat (*Triticum aestivum* L.)-sunflower (*Helianthus annus* L.) sequence in Italy. Treatments included a non-N-fertilized control and N applied as 100% mineral fertilizer or compost, and 50% compost plus 50% mineral fertilizer. Highest maize grain yield occurred with 100% mineral fertilizer or 50% compost plus 50% mineral fertilizer, and was lowest with 100% compost. In the subsequent years, grain yields of wheat and sunflower were not significantly different among treatments, but total aboveground biomass of all crops in the three-year study was greatest with 100% mineral fertilizer or 50% compost plus 50% mineral fertilizer. These findings indicate that compost can be used to offset synthetic N fertilizer application in crop production, and that it can be a key component of sustainable cropping systems.

2.4. Residue Management

Crop residues are an important source of nutrients, and their return to soils is considered fundamental for sustaining crop production and soil quality [39]. The article by Tian et al. [40] reports on soil carbon and N storage as affected by the method of maize residue retention under simulated tillage in northeastern China. Treatments included mixing maize residue with soil (to simulate rotary tillage) to a soil depth of 10, 30, or 50 cm, or burying maize residue (to simulate moldboard plow tillage) at 10, 30, and 50 cm soil depths. When residue was mixed with soil, its decomposition and the release of carbon and N decreased as the depth of mixing increased in both study years, but the results differed between years when residue was buried. Greater soil organic carbon content occurred when residue was buried in soil compared to when it was mixed with soil. There was a positive correlation between residue decomposition and the release of carbon and N in the 0–20 cm soil layers, while a negative correlation was present for the 20–60 cm soil layers. Hence, the authors concluded that burying maize residue at a depth of 30 cm was the most suitable method for residue retention among the treatments that they tested.

2.5. Cover Crops

Integrating cover crops into annual cropping systems can provide many benefits, including protection against soil erosion, improved physical, chemical, and biological properties of soil, uptake of water and N to reduce nitrate-N leaching, pest suppression, and enhanced crop yields [41]. The paper by Halwani et al. [42] assessed the performance of soybean [*Glycine max* (L.) Merr.] in northeastern Germany following a winter rye (*Secale cereal* L.) cover crop among systems where rye was harvested as silage followed by plowing and planting of soybean, or terminated by herbicide or crimping followed by no-tillage planting of soybean. The system with rye crimping did not use herbicides for weed control in soybean, while the other systems did. Additionally, the planting date of soybean in this system averaged 11 days later than that of the other systems. Weed control was effective in all systems. Soybean yield was greatest with herbicide termination of rye and no-tillage in all three study years, but was not significantly greater than that from the plow-based system in two of the years. Averaged across years, crimping of rye and no-tillage produced the lowest soybean yield. Dates for termination of rye and soybean planting varied among systems, and earlier dates of these operations were associated with higher soybean yield. This paper also reports on cover crop biomass, soybean plant density, and net economic return, and provides a basis for future research and development of no-tillage cover crop systems for soybean.

The article by Everett et al. [43] summarizes a study across 19 sites in the upper Midwest USA that evaluated the effects of a winter rye cover crop on soil nitrate-N and maize yield when sown before autumn injection of liquid manure in fields where the previous crop was silage maize or soybean. Across sites, use of a rye cover crop reduced nitrate-N concentration in the 0–60 cm soil layer in the spring by 36% without affecting maize silage or grain yield, demonstrating its utility for reducing the risk of N losses without restricting maize productivity in these cropping systems.

The paper by Andersen et al. [44] evaluated five faba bean cultivars, one forage pea cultivar, and one field pea cultivar for their potential as cover and forage crops when sown after wheat in the USA Northern Great Plains. On average, ground coverage prior to the first killing frost was greatest with forage pea (44%), followed by field pea (27%) and the faba bean cultivars (17%), and was least with no cover crop (6%). Forage yield was not significantly different among cover crops (mean = 450 Mg ha^{-1} of dry matter), but crude protein in forage was higher for faba bean and forage pea compared to field pea. Grain yield of the subsequent unfertilized maize crop was not significantly affected by cover cropping. These results show that faba bean and pea can be suitable options for dual-purpose cover and forage in a wheat–maize rotation.

The effects of a winter cover crop of Chinese milk vetch (*Astragalus sinicus* L.) on subsequent double-cropped rice in southern China is discussed in the article by Nie et al. [45]. Under moderate and high N input, they found that a Chinese milk vetch cover crop increased grain yield of the early and late rice crops compared to no cover crop, largely due to increased tillering. Additionally, annual grain yield was not significantly different between rice following Chinese milk vetch with a moderate N rate and rice following no cover crop with a high N rate, confirming the value of Chinese milk vetch for improving the sustainability of double-crop rice production.

Living mulch systems are an innovative approach to cover cropping, in which a perennial cover crop is intercropped with a cash crop. The paper by Alexander et al. [46] reports on the yield and economic responses to N fertilization for first- and second-year maize grown in kura clover (*Trifolium ambiguum* M. bieb) living mulch in the upper Midwest USA. Nitrogen fertilization did not increase grain or stover yields of first-year maize, and the economically optimum N rate for grain yield of second-year maize was similar to the local recommendation for maize following soybean.

Across the two study years, net economic return from grain and stover of first- and second-year maize grown in kura clover living mulch averaged \$138 ha^{-1} greater than net economic return from grain of conventionally managed maize following soybean. These findings reveal that kura clover living mulch can reduce N fertilizer requirements for maize while enhancing profitability for farmers, and contribute to a growing body of literature indicating that use of kura clover living mulch is a viable tactic for sustainable maize-based cropping systems [47–51].

2.6. Organic Management

Organic crop production uses non-genetically modified crops and relies on ecologically based practices such as diversified crop rotations including forage legumes, cover cropping, use of manure and other organic soil amendments, and mechanical weed control in place of synthetic fertilizers and pesticides. Crops produced using certified organic practices are eligible for price premiums, but there is a three-year transition period following the conversion from conventional to organic production in the USA when crops must be produced organically before organic certification is approved [52]. During this transition period, organically produced crops are not eligible for price premiums, thereby complicating decisions on whether to convert to organic production and what the optimal agronomic practices are during the transition period. To address these issues, the article by Cox et al. [53] assesses the agronomic and economic performance of red clover (*Trifolium pretense* L.)–maize, maize–soybean, and soybean–wheat/red clover rotations under organic and conventional management with recommend or high levels of inputs during the transition period in the northeastern USA. With recommended inputs, organic maize had significantly lower grain yield, higher production cost, and lower net economic return in the maize–soybean rotation, but equivalent grain yield, production cost, and net economic return in the red clover–maize rotation, compared to conventional maize. For soybean with recommended inputs, grain yield, production cost, and net economic return were comparable between organic and conventional production in the soybean-wheat/red clover and maize–soybean rotations. With recommended inputs, organic wheat in the soybean–wheat/clover rotation had equivalent grain yield, significantly higher production cost, and lower net economic return compared to conventional wheat. Across all crops, net economic return was greatest for the conventional maize–soybean rotation with either level of inputs. High levels of inputs did not enhance the agronomic and economic performance of organic compared to conventional management. With recommended inputs, net economic return across all crops was similar among the three rotations. These results provide a basis for best practices during the transition from conventional to organic production and serve a foundation to advance the development of ecologically based cropping systems.

Organic cropping systems can vary widely, with some intensive organic systems lacking an overarching ecological approach to crop production and simply replacing conventional inputs with organic inputs. Although such systems can produce high crop yields while meeting organic certification standards in some countries, they can have negative environmental impacts that are similar to those from their conventional counterparts [54]. The paper by Ciaccia et al. [55] compares organic soil fertility management systems during a two-year vegetable rotation under un-heated tunnel greenhouses in a Mediterranean environment, and provides a comprehensive assessment of crop performance, soil fertility, and the abundance of soil arthropods. The results showed that the input substitution system, where commercial organic fertilizers were substituted for synthetic fertilizers, had slightly higher crop productivity than systems utilizing agroecological service crops (i.e., crops grown for cover and green manure) combined with cattle manure or compost, but no improvement in long-term soil fertility parameters or soil arthropods. Meanwhile, the two systems with agroecological service crops exhibited improvement in long-term soil fertility parameters that were associated with changes in the community structure of soil arthropods. This confirms the importance of concurrently evaluating multiple agronomic, soil fertility, and soil biodiversity indices when assessing agroecosystem performance, and shows that soil arthropods can be used as bioindicators for comprehensive evaluation of cropping systems.

2.7. Crop Management for Efficient Use of Irrigation Water

Declining aquifer levels are a serious threat to crop production in semi-arid and arid areas that rely on them for irrigation. The article by Leghari et al. [56] uses data from the North China Plain and simulation modeling to assess crop productivity and water and N use efficiencies for the predominant winter wheat–summer maize double-crop system under standard and optimized rates of irrigation and N, and for monocropped spring maize and a two-year winter wheat–summer maize–spring maize rotation under optimized irrigation and N rates. Across the two study years, the double-cropped system under optimized irrigation and N rates produced the greatest total grain yield, which was 6% greater than that of the same system when 22% more water and 162% more N were applied. Monocropped spring maize and the two-year rotation produced the lowest total grain yield over the two study years, which was 23% less, on average, than that of the double-cropped system under optimized irrigation and N rates. However, monocropped spring maize received 47% less water and 51% less N than the double-cropped system under optimized irrigation and N rates, and, therefore, exhibited the highest water and N use efficiencies in this study. This article also reveals opportunities to improve water and N use efficiencies in these cropping systems based on simulation modeling for a range of irrigation and N rates, and suggests that tradeoff in crop productivity may be needed for responsible stewardship of water and N resources in some areas.

The paper by Machicek et al. [57] reports on forage yield and quality, and water use efficiency of irrigated brown midrib sorghum–sudangrass (*Sorghum bicolor* (L.) Moench ssp. *Drummondii*) and brown midrib pearl millet (*Pennisetum glaucum* (L.) Leeke)) under three, two, and one harvests on 30-, 45-, and 90-day intervals, respectively. Averaged across harvest intervals, sorghum–sudangrass had 35%–52% greater forage dry matter yield than pearl millet in the two study years, but 26% lower water use efficiency in the one year when it was measured. For both crops, one harvest per year produced greater total forage dry matter yield and water use efficiency, but lower quality forage compared to multiple harvests per year. These results demonstrate the importance of forage crop and harvest schedule on forage production and water use efficiency.

3. Conclusions

Increasing global crop production to keep pace with rising demand on a limited supply of resources, while reducing its negative environmental effects, is one of the greatest challenges facing humanity. Sustainable cropping systems based on agroecology, rational use of inputs, and soil improvement are key to meeting this challenge. This special issue contains several articles that synthesize previous research and present original research on various aspects of these topics from a wide range cropping systems around the world. This information can guide on-farm adoption of best management practices and it serves as a base for the agronomic innovations needed for widescale sustainable intensification of crop production.

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