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RESEARCH INTRODUCTION

# The 4Rs for cover crops and other advances in cover crop management for environmental quality

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Humans have used soil resources for thousands of years. Human use has degraded and eroded soil worldwide in ways that damage food production, biodiversity, and ecosystem services. A direct implication of soil degradation is that soil scarcity will become a critical future problem for global agricultural production. With limited new lands for cultivation worldwide and a projected increase in global population to 10 billion this century, long-term agricultural sustainability is an increasing global concern. To conserve soil, better agricultural methods that sustain the soil are needed (Montgomery 2007). Soil management must focus on regaining a balance in (1) organic carbon (C) inputs and losses, (2) soil erosion and production, and (3) release and loss of nutrients (Amundson et al. 2015). Soil does far more than just support farming and forestry. It stores C, filters water, transforms nutrients, and sustains plant and animal biodiversity by conservation of critical shrinking wildlife habitat. It is unclear how these essential processes will respond to agricultural intensification, or how they might be enhanced in tandem with farming (Banwart 2011).

Fortunately, the recent renewed use of cover crops management practices can help address this problem. Cover crops have enormous potential to improve soil and water conservation and improve the sustainability of corn (*Zea mays* L.) and soybean (*Glycine max* [L.] Merr.) cropping systems.

Cover crops can be used to provide multiple benefits, including increasing soil sustainability (Dabney et al. 2001; Reeves 1994; Woodruff and Siddoway 1965; Frye et al. 1985; Holderbaum et al. 1990; Bilbro 1991; Langdale et al. 1991; Decker et al. 1994; Thorup-Kristensen et al. 2003; Delgado et al. 2007), reducing erosion, and improving soil quality and health in the face of a changing climate (Delgado et al. 2011; Lal et al. 2011). Cover crops can also be used to maintain soil organic matter and increase the potential for C sequestration (Sarrantonio 2007; Clark 2007; Lal 2002; Al-Sheikh et. al. 2005, Sainju et al. 2002), and they have the potential to reduce the use of agrochemicals, helping to improve water quality (Dabney et al. 2001).

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Cover crops can be used as green manures to add nutrients to a cropping system, especially nitrogen (N), and improve nutrient management. Legume cover crops can fix atmospheric N and cycle N to increase the yield of the following cash crop; this is especially important in low input systems of developing countries and can add to organic matter that can help moderate climate change (Kambauwa et al. 2015). Cover crops can be nutrient scavengers to recover N in the soil (even deeper in the soil), which can limit the loss of N to the environment (Delgado 2001, 1998; Delgado et al. 2001a, 2001b). They can even be used to remove nitrate ($NO_3$) from groundwater and contribute to improved underground water quality (Delgado 2001, 1998; Delgado et al. 2001a, 2001b). Cover crops can contribute to increased yields and quality of the crop that follows (Delgado et al 2007; Essah et al. 2012).

They can also help climate change mitigation efforts by reducing emissions of greenhouse gases, especially when cover crops with high C to N ratios (nonlegume cover crops) are used (Delgado et al. 2011; Lal et al. 2011; Basche et al. 2014).

Cover crops can be useful tools to improve nutrient management and protect air, soil, and water quality. However, when using cover crops, producers need to determine the type of cover crop and details about the cover crop management to optimize use for site-specific conditions of soil and climate. There is a need to use the *right* cover crop or cover crop mixture, select the *right* time to plant and harvest (or kill) the cover crop, and apply the *right* cover crop management practices at the *right* location, to increase the benefits of cover crops (the 4Rs for cover crops).

## RECENT ADVANCES IN COVER CROP USE FOR IMPROVED SOIL QUALITY AND SOIL HEALTH

This special issue of the *Journal of Soil and Water Conservation* presents recent advances in and synthesis of cover crops research showing the positive benefits of cover crops across landscapes. Franzluebbers and Stuedemann (2015) reported that for crop-livestock systems, cover crops are useful management tools that can provide high quality forage during short periods between cash crops. They conducted long-term studies (seven years) on the effects of grazed and nongrazed cover crops on the biologically active soil C and N fractions for disked and no-tillage systems. They found that grazing did not have negative effects on the biologically active soil C and N fractions. Franzluebbers and Stuedemann (2015) also found that in the southeastern United States, no-tillage cropping was the most effective way to preserve biologically active soil C and N fractions. However, they also found that a vigorous cover crop in a conventional disk tillage system provided a significant source of C and N to the soil, thus keeping the biologically active fractions of C and N the same as those of no-tillage systems at the 0 to 30 cm (0 to 12 in) depth during many years of a seven-year period. These studies on crop-livestock systems agree with studies of cropping systems that showed that cover crops can contribute to increased C sequestration and improved soil quality and health (Sarrantonio 2007; Clark 2007; Lal 2002; Al-Sheikh et. al. 2005, Sainju et al. 2002).

Sainju et al. (2015) conducted a three-year study to assess the effects of removal of aboveground biomass of sorghum (*Sorghum bicolor* [L.] Moench) grown for bioenergy on levels of soil organic C, total soil N, and inorganic N content in the top

30 cm (12 in) of soil, and the potential of cover crops to maintain C sequestration and environmental quality. They found that a combination of hairy vetch (*Vicia villosa* Roth)/rye (*Secale cereale* L.) contributed to the maintenance of soil organic C levels and increased C sequestration and storage of N in the top 30 cm for bioenergy sorghum systems of the southeastern United States. Their results agree with studies that have reported that cover crops are a tool to sequester C and conserve soil quality (Lal 2002; Sainju et al. 2002).

## RECENT ADVANCES IN COVER CROP NUTRIENT MANAGEMENT FOR WATER QUALITY

Komatsuzaki and Wagger (2015) studied the potential of a cover crop to scavenge residual soil $NO_3$ by assessing the N recovery by cover crops in relation to time of planting and growth termination in a North Carolina Coastal Plain sandy loam soil. They studied N uptake for cover crops planted after corn and for cover crops planted after corn that received an additional surface broadcast application of 80 kg N $ha^{-1}$ (71 lb N $ac^{-1}$) as ammonium nitrate ($NH_4NO_3$) after harvest of the corn to simulate a high residual soil $NO_3$ level. They found that time of planting (October, November, or December) and time of termination (mid-March, early April, or late April/early May) of the cover crop affects the percentage of aboveground N uptake. Early-planted (October) and early-terminated (mid-March) rye and black oat (*Avena strigosa* L.) have higher N content (about 52 kg N $ha^{-1}$ [46 lb N $ac^{-1}$]) than late-planted (November or December) and early-terminated (March) rye and black oat. On average, late termination (early April or late April/early May) increased N uptake, independent of planting date (October, November, or December). The early-planted (October) and late-terminated (late April/early May) wheat (*Triticum aestivum* L.) showed higher N uptake (about 78 kg N $ha^{-1}$ [70 lb N $ac^{-1}$]). Similar effects of early planting and late planting were observed for winter wheat and winter rye in Colorado (Delgado 1998, 2001; Delgado et al. 1999, 2001a, 2001b; Dabney et al. 2001). The early-planted cover crops, wheat or rye, showed significant, large amounts of N uptake; the range was as high as 178 to 300 kg N $ha^{-1}$ (159 to 268 lb N $ac^{-1}$) for winter cover rye following vegetable crop. For the cover crops planted late in October, there was a lower N uptake of about 20 kg N $ha^{-1}$ (18 lb N $ac^{-1}$).

Thorup-Kristensen and Rasmussen (2015) studied 20 different deep-rooted plant species for the potential to recover $NO_3$ from deep in the soil profile. In their five-year studies, they found that root depths with a number of species were as deep as 0.8 to 1.6 m (2.6 to 5.3 ft); the deepest cover crops with root depths of 1.6 to 2.4 m (5.3 to 7.9 ft) were dyer's woad (*Isatis tinctoria* L.) and viper's bugloss (*Echium vulgare* L.). They found that legumes had the higher N content, but their roots were not as deep as the nonlegume cover crops. The legumes with the higher N content were white clover (*Trifolium repens* L.), kidney vetch (*Anthyllis vulneraria* L.), and black medic (*Medicago lupulina* L.) with a range of 170 to 202 kg N $ha^{-1}$ (152 to 180 lb N $ac^{-1}$). The maximum N content of nonlegumes was around 105 kg N $ha^{-1}$ (94 lb N $ac^{-1}$). Other studies found that the N uptake of a cover crop will also depend on how much $NO_3$ is in the soil. If there are large amounts of residual soil $NO_3$ in the soil profile, the nonlegume cover crop has great potential to reduce the $NO_3$ in the soil profile and take up large amounts of N ranging from 178 to 296 kg N $ha^{-1}$ (159 to 264 lb N $ac^{-1}$) (Delgado et al. 1999; Dabney et al. 2001).

Ashworth et al. (2015) studied the effect of adding a legume as an intercrop with switchgrass (*Panicum virgatum* L.) on forage yields and quality. They found that there is potential to increase forage quality with legumes. They concluded that intercropping selected legumes with switchgrass might enhance forage yield and quality and provide additional environmental benefits such as reducing fertilizer input and losses of fertilizer to air and groundwater. Hively et al. (2015) studied the potential to use remote sensing to monitor cover crop adoption in southeastern Pennsylvania. Over the four-year study, their remote sensing analysis found that farmers are increasing adoption of cover crops following corn harvest.

## RECENT ADVANCES IN ADDRESSING CHALLENGES IN COVER CROP ADOPTION

Kaspar and Bakker (2015) studied the effect of seven winter rye cultivars, two winter triticale cultivars, and three winter wheat cultivars on corn yields in a soybean–corn rotation grown at Iowa State University's Agricultural Engineering and Agronomy Research Farms, located in Boone County, Iowa. Although some differences in yield by cultivar were found, they also found lower corn yields in two of the four years due to the use of cover crops because of weather or environmental factors. However, some cultivars did not reduce the yields in the two years that the corn yields were reduced, suggesting that additional research is needed to better understand the effect of cover crop cultivars as well as the effect of corn varieties on lower yields. They suggested that these studies should consider the effects of variability, and be conducted across different regional soil and weather conditions. Other scientists have reported increases in yield following cover crops (Thorup-Kristensen et al. 2003; Delgado et al. 2007; Essah et al. 2012; Clark 2007). However, findings of lower yields by Kaspar and Bakker (2015) using cover crops agree with previous research findings that cover crops, due to various reasons (e.g., allelopathic effect or nutrient and water availability), could also contribute to reduced yields of the following crop (Thorup-Kristensen et al. 2003; Essah et al. 2012; Clark 2007; Unger and Vigil 1998).

Mitchell et al. (2015) studied the trade-offs between winter cover crop production and soil-water depletion in the San Joaquin Valley, California. They conducted a long-term water balance project monitoring water balances over 15 years. These studies showed that although there are some environmental benefits from the use of cover crops, this comes at the cost of soil water depletion in this semiarid, drought-prone region. They concluded that because of low and erratic precipitation, use of cover crops that produce vigorous aboveground biomass may not be possible in all the years. Moreover, use of cover crop, when compared to fallow systems, will use significantly more water in the top 90 cm (35 in). Similar reports on the water balances were reported by Unger and Vigil (1998) for the Great Plains. In the dryland cropping systems of the Northern Plains, cover crops could potentially contribute to reduced yields in the following crop due to water use from the soil profile (Unger and Vigil 1998). This data shows that for irrigated systems in the San Joaquin Valley, California, cover crops could potentially increase irrigation water use by the crop that follows, since there will be a water-depleted soil profile when the next cash crop is planted.

Arbuckle and Roesch-McNally (2015) studied farmer perspectives on adoption of cover crops in Iowa. Arbuckle and Roesch-McNally (2015) found that perceived benefits were a good predictor of farmers' use of cover crops. However, perceived risk of using cover crops was correlated with nonadoption of cover crops. Arbuckle and Roesch-McNally (2015) report that it is important to communicate the potential benefits of cover crops when use of cover crops is being promoted.

Lal (2005) reported that payments for ecosystem services could be an incentive and thus contribute to increased use of cover crops. Lal (2015) stated that although the history of cover crops dates back 3,000 years in China, their use could be a key management practice today. Cover crops can be an important tool for reducing the effects of climate change by increasing soil organic matter (Lal et al. 2011; Lal 2005). However, Wallander (2013) reports that cover crop usage today remains low for US cropland and that only 3% to 7% of farms use cover crops in rotations. Continued research must help identify ways to promote wider adoption of cover crop rotations to optimize crop yield while sequestering organic C, reducing soil erosion, and reducing loss of nutrients.

## SUMMARY

Recent studies show that cover crops can be used to provide many different ecosystem services. They have enormous potential to improve the sustainability of corn and soybean cropping systems, add soil organic matter and reduce its loss, reduce soil erosion, improve soil health, fix N, and reduce loss of nutrients, thus conserving critical shrinking lands for all uses. Cover crops can also be used for climate change adaptation and mitigation (Delgado et al. 2011).

These studies also show some of the challenges when using cover crops. Although cover crops can potentially contribute to higher yields, they may also contribute to reduced yields (Kaspar and Bakker 2015; Thorup-Kristensen et al. 2003; Essah et al. 2012; Clark 2007; Unger and Vigil 1998). Additionally, use of cover crops can be problematic in the drier western United States, where water balances and water availability are significant issues (Mitchell et al. 2015; Unger and Vigil 1998). Perceptions of cover crop use are key in adoption of cover crops. Farmers using cover crops are maximizing conservation and sustainability of these systems. One of the most difficult problems to overcome may be soil-water availability for a given crop management system. Continued work can be used to provide information on the benefits of cover crops while maintaining and/or increasing yields of the subsequent crop. As the papers in this special issue show, there are advantages to using cover crops, and they provide great benefits as far as ecosystem services. However, there are challenges and needs for additional research to reduce the chance of negative impacts, such as reductions in yields. This continued work will help discover, document, and communicate how to use the right cover crop or cover crop mixture with the right time of planting and harvesting (killing), with the right management practices, and at the right location to maximize the benefits of cover crops (the 4Rs for cover crops).

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