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Improving water resilience with more perennially based agriculture

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ABSTRACT
Land conversion from natural to managed ecosystems, while necessary for food production, continues to occur at high rates with significant water impacts. Further, increased rainfall variability exposes agricultural systems to impacts from flood and drought events. In many regions, water limitations are overcome through technological approaches such as irrigation and tile drainage, which may not be sustainable in the long term. A more sustainable approach to combat episodes of floods and droughts is to increase soil water storage and the overall green water efficiency of agroecosystems. Agricultural practices that promote "continuous living cover," such as perennial grasses, agroforestry and cover crops, can improve water management relative to annual crop systems. Such practices ensure living roots in agricultural systems throughout the year and offer an approach to agroecosystem design that mimics ecological dynamics of native perennial vegetation. We review how these practices have been shown to improve elements of the water balance in a range of environments, with an emphasis on increased soil hydrologic function. A specific focus on the agriculturally intensive state of Iowa provides insight into how land use centered on agroecological principles affords greater water resilience, for individual farms as well as for broader community and ecosystem health.

KEYWORDS
Agroforestry; climate variability; continuous living cover; cover crops; perennial crops

Introduction

Environmental characteristics, particularly temperature, rainfall and sunlight, are the predominant factors that determine photosynthetic rate and plant growth, which ultimately comprise the foundation of agricultural science (Gliessman 2015). The field of agronomy, for example, evaluates how cultivation can occur in regions most optimal for growth and development of specific crops, given the climate and soil characteristics of different environments (Hay and Porter 2006). However, increased rainfall variability from a warming atmosphere is measured in the recent record and is projected to

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intensify into the future, and this threatens the productivity and resilience of agroecosystems (IPCC 2013; Pryor et al. 2014).

Further, centuries of agricultural development have led to highly mechanized and specialized farming operations, including two practices that dramatically alter the water cycle—irrigation and tile drainage. Water added to agricultural systems through irrigation systems can occur from either surface waters or groundwater. In the United States, irrigated agriculture is concentrated in the West (USDA 2013) and globally, it is estimated to comprise approximately 21% of cultivated lands (FAO 2014). Subsurface tile drainage allows for the rapid removal of water during periods of excess precipitation that could lead to saturated soil conditions unsuitable for crop cultivation (Strock et al. 2010). In the United States, subsurface tile drainage is predominantly located in the northern tier of the Midwestern states, as subsurface drains are installed on approximately 40–50% of agriculture land in Iowa, Indiana, Illinois, and Ohio (USDA-NASS 2014a).

Unfortunately, these alterations of the water balance to optimize agricultural production have come at the cost of sustainable water management in many regions. The irrigation of agricultural crops is depleting groundwater in arid and semi-arid areas (Scanlon et al. 2012). In more humid regions, technologies have enabled cropland expansion into grasslands and wetlands, reducing the ecological flood mitigation capacity of these agroecosystems (Lark, Salmon, and Gibbs 2015; Wright and Wemberly 2013). Although the addition of drainage systems in wetter and/or poorly-drained environments benefits crop productivity, such systems can increase water and pollutant flows (David, Drinkwater, and McIsaac 2010).

More recently, agricultural water management approaches have been developed to evaluate how these technological investments in boosting crop productivity can be balanced with soil and water sustainability. A promising and widely researched effort is the advancement of precision irrigation techniques, which utilize spatial (i.e., GIS, GPS) technologies to maximize irrigation efficiency through site-specific analysis and application (Sadler et al. 2005). Additional research efforts have focused on how best to use controlled drainage structures that allow current drainage systems to adjust the water table in a way that limits excess water flow during high precipitation periods (Strock et al. 2010). Controlled drainage benefits are beginning to be quantified and are demonstrating capacity to buffer water and pollutant flow (Williams, King, and Fausey 2015).

While advances such as precision irrigation and controlled drainage offer improvements in agricultural water management, the previously mentioned concerns—groundwater depletion from irrigation as well as increased water and pollutant flow from tile drainage—indicate that the efficacy of technological approaches is limited. Consequently, there is developing interest in applying water dynamics observed in natural ecosystems to improve managed agricultural landscapes. More complex agroecological systems that mimic natural environments may be one approach to reduce consumptive water use, while also mitigating the impacts of increased rainfall variability due to climate change on agricultural production (DeLonge and Basche 2017; Morris and Bucini 2016; Pryor et al. 2014; Vandermeer 1995). This review will address several aspects of the water cycle—with a focus on soil water storage through improved soil hydrology—that might be maximized for agriculture using lessons from ecological and agricultural research. A closer look at an intensively managed agricultural region, the state of Iowa in the Midwestern United States' "Corn Belt," demonstrates how land conversion from a perennially-based ecosystem to an annually-based agroecosystem created negative hydrological impacts, particularly flooding, and how a greater focus on agroecological processes offers an insight into improving water resilience in the region.

Regional water impacts of agricultural land conversion

The major native biomes of the contiguous United States (Figure 1) include temperate and tropical grasslands and savannahs, Mediterranean and temperate forests and woodlands, as well as deserts and dry shrublands. Because water is a major limiting factor of plant growth (Hay and Porter 2006), the predominant biomes in various regions reflect regional rainfall and climate

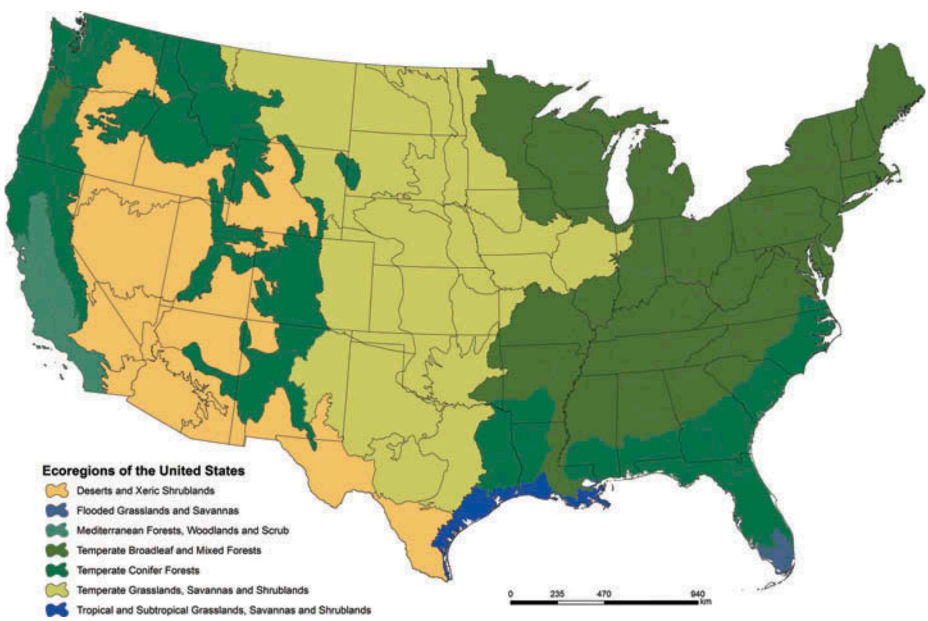

Figure 1. Major ecoregions of the contiguous United States include forest, grassland, desert and shrubland environments. Source: The Nature Conservancy (http://maps.tnc.org). Data from Olson and Dinerstein (2002); Bailey, R. (1995); Wilken (1986).

regimes (Stephenson 1990). More humid regions support grasslands and forests, while arid regions feature shrublands (Figure 2). These biomes consist of perennially-based vegetation ranging from deciduous and coniferous trees, to tall and short prairie grasses, and finally to bush-type shrubland plants as annual rainfall diminishes. Annual evapotranspiration varies in these different environments and can range from greater than 1200 mm in tropical and swamp environments, 400–700 mm in forest environments, 400–650 mm in grasslands, and less than 300 mm in shrublands (Rockstrom et al. 1999). It follows that a crop such as maize, which demands from 500–800 mm per growing season, is cultivated in regions previously occupied by forest and grasslands. It also follows that tropically-adapted crops, such as bananas and sugarcane, are cultivated in warmer and more humid biomes, given that their average water requirements range from 1200 to 2200 mm annually. Wheat and other small grain crops having water requirements in the 450–650 mm range are frequently cultivated in semi-arid regions (FAO 1986).

While land conversion of natural to agricultural ecosystems is necessary for food production, it continues to occur at high rates, both globally and in the United States, and this land conversion often leads to profound impacts on water. The Millennium Ecosystem Assessment calculated that 0.8% of forests and other native environments were converted to agricultural use

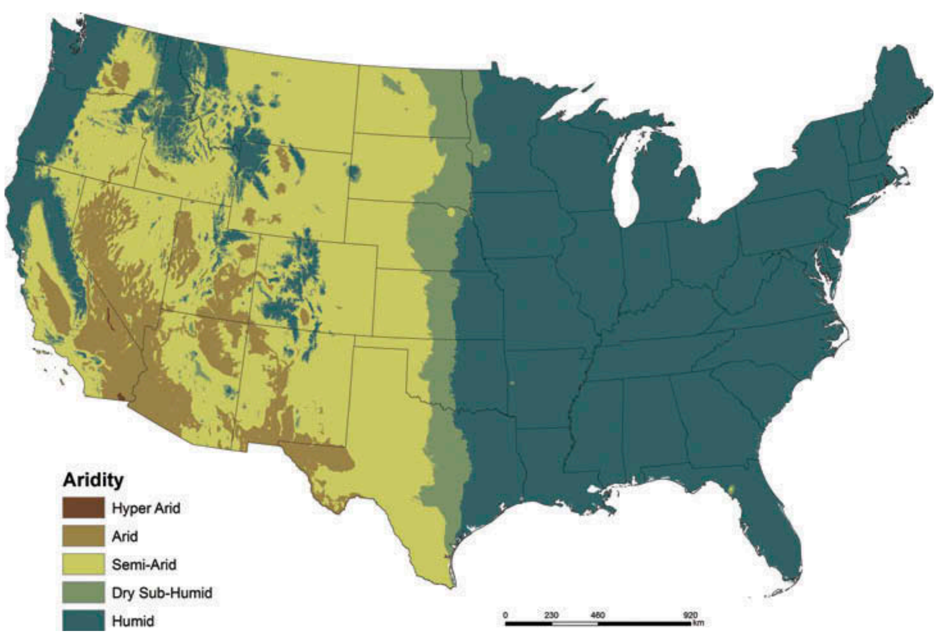

Figure 2. Aridity index (calculated from temperature and rainfall values) for the contiguous United States. Data from the CGIAR-CSI Global-Aridity and Global-PET Database (Zomer et al. 2008).

annually for the last several decades (Vorosmarty, Leveque, and Revenga 2005). More recent estimates of land conversion, particularly in the Midwestern and Plains regions of the United States, suggest that policies supporting grain-based biofuel have led to dramatic land conversion, including up to 5% annual conversion to cropland from grasslands and wetlands, with highest rates in locations proximal to ethanol refineries (Lark, Salmon, and Gibbs 2015; Wright et al. 2017; Wright and Wemberly 2013). Rost et al. (2008) estimate that croplands consume between 85 and 92% of global green water (water that is stored temporally in the soil) when averaged in rainfed and irrigated systems, with the remaining portion consumed by natural, unmanaged ecosystems. Additionally, given the combined effect of land cover on water use through transpiration and of plant communities on preventing runoff, it is estimated that land conversion for general agricultural purposes reduced global evapotranspiration by 2.8% and increased discharge by 5%, from 1970 to 2000 (Rost et al. 2008).

Further underscoring the impact of land conversion and water impacts, an increasing body of research highlights how declining soil structure from agricultural practices has contributed to the reduction of water infiltration and soil water storage capacity (O'Connell et al. 2007; Wheater and Evans 2009). Raymond et al. (2008) analyzed water discharge data from 106 United States Geological Survey (USGS) locations with long-term data (dating back to at least 1966) across the Mississippi River Basin, finding that the amount of land used for general agricultural production in a watershed basin greatly affected the amount of water discharge. In fact, they noted an inflection point where watersheds that had greater than approximately 60% of land in agriculture resulted in exponential increases in discharge that were not accounted for after normalizing data for precipitation trends (Raymond et al. 2008). Therefore, they concluded that modifications in water storage capacity from land use have profoundly changed the relationship between precipitation and discharge (Raymond et al. 2008). To maintain the integrity of ecosystem services in a variety of environments, ecologists now suggest that there is a need to limit land conversion for agricultural uses, as sustainable boundaries for water use are already being approached (Rockstrom et al. 2009).

Benefits of continuous living cover for water cycle management

"Continuous living cover" (Anderson 2005; Jordan and Warner 2008; Asborjsen et al. 2014) is an approach to match the function of perennial vegetation in agroecosystems. While managed agricultural systems cannot directly mimic undisturbed systems, practices that offer continuous living cover, notably maintaining canopy cover and roots in the soil throughout the year, present an opportunity to reproduce and/or apply ecological principles in an agronomic setting. There are numerous practices that could be categorized as continuous living cover, including cover crops, perennial grasses (for bioenergy, grain, or forage), and agroforestry.

Agricultural systems with primarily annual crops are more susceptible to direct water losses through increased soil evaporation, surface runoff, and leaching, than perennially-based agriculture. However, due to longer canopy duration, perennial systems may also increase transpiration which, depending upon location and practices utilized, may offset some of the water savings from reduced soil evaporation and runoff or drainage. It is important to recognize that the increased water use of perennially-based systems may create crop water availability challenges, particularly in more arid regions and during periods of limited rainfall, such as extended drought or even flash drought-type conditions. Research demonstrates, though, that the principles of continuous living cover can increase soil water storage, through increased carbon sequestration and improved soil hydrologic function (e.g., enhanced aggregation, increased infiltration rate or hydraulic conductivity, greater porosity), where a variety of inter-related soil water properties contribute to enhanced soil structure (Table 1). Given these soil benefits and the associated water risks in more arid regions, there is a need for additional research to select perennial crops and/or cover crops that take into account a cropping systems water use approach. This could include breeding efforts that emphasize drought escape or resistance techniques, such as increased rooting depth or rapid phenological development, to optimize both vegetative and reproductive plant growth so that yield components are not sacrificed (Connor, Loomis, and Cassman 2011). Overall, most studies indicate net positive water balance outcomes when the agroecological systems are compared to annual cropping systems, with many researchers recognizing the climate resilience opportunities afforded by such approaches.

Cover crops

There is growing interest in protecting and regenerating soil during periods when it would otherwise be bare—practices that achieve this objective, such as cover crop or green manure incorporation, can also improve agricultural resilience to climate change (Kaye and Quemada 2017). Cover crops can contribute to system resilience to rainfall variability through several mechanisms, including improved soil hydrologic function through aggregation (which increases soil stability and ultimately water storage capacity), greater infiltration rates, and reduced runoff (Blanco-Canqui et al. 2015). Further, cover crops can offer reductions in soil evaporation and increases to water storage, resulting in additional water available for cash crops, even during drought conditions (Basche et al. 2016a) (Figure 3).

Across different climatic conditions and soil types in the United States, there is a great deal of evidence demonstrating how cover crops can improve

Table 1. Overview of water balance impacts from continuous living cover practices.

		Water balance component					
	Location	Soil water storage or content	Soil hydrologic function[b]	ET	Drainage or runoff	WUE	Reference
Perennial grass	Wisconsin	⇑		⇑	⇓		Brye et al. (2000)
	Iowa	⇓		⇑	⇓		Daigh et al. (2014b)
	Iowa				⇓		Hernandez-Santana et al. (2013)
	Upper Midwest					⇑	VanLoocke et al. (2012)[a]
	Southern Great Plains	⇑			⇓	⇑	Chen et al. (2016)[a]
	Northern India		⇑				Verma and Sharma (2007)
	Northeast India	⇑	⇑				Ghosh et al. (2009)
	Iowa		⇑				Rachman et al. (2004)
Cover crop	Iowa	⇑	⇑	⇑			Basche et al. (2016a)[a], (2016b)
	Kansas		⇑				Blanco-Canqui et al. (2011), (2013)
	California		⇑				Gulick et al. (1994)
	California		⇑				Folorunso et al. (1992)
	Illinois		⇑				Villamil et al. (2006)
	Iowa, Indiana	⇑					Daigh et al. (2014a)
	Maryland		⇑				Steele, Coale, and Hill (2012)
	Northwest India	⇑	⇑				Sharma et al. (2010)
	Northern India	⇑	⇑				Walia, Walia, and Dhaliwal (2010)
	Northwest India		⇑				Singh, Jalota, and Singh (2007)
	Southwest Nigeria		⇑				Lal, Wilson, and Okigbo (1978)
Agroforestry	Ethiopia	⇑	⇑				Ketema and Yimer (2014)
	Loess Plateau China		⇑				Wang et al. (2015)
	Kenya		⇑				Kiepe (1995)
	Iowa		⇑				Bharati et al. (2002)
	Missouri	⇓	⇑	⇑	⇓		Anderson et al. (2009), Seobi et al. (2005), Udawaata and Anderson (2008)

Table 1. A selection of published studies analyzing continuous living cover practices and the direction of change for various components of the water balance (ET = evapotranspiration, WUE = water use efficiency), relative to annual cropping systems. Most studies reporting evapotranspiration values did not separate transpiration from soil evaporation but indicated that increases were likely a result of greater plant transpiration.

[a]Modeling studies.

[b]Includes several different hydrologic properties including the following (definitions from Hillel 1998; Nimmo 2004):

Aggregation: Assemblages of organic matter that are bound to mineral particles in the soil matrix.

Aggregate stability: measure of vulnerability to externally imposed destructive forces.

Bulk density: A ratio of the mass of solids to the mass of total soil volume (solids and pores together).

Hydraulic conductivity: Ability of a conducting medium to transmit water.

Infiltration rate: The rate of downward flow of water into the soil, determining how much water will runoff and how much will enter the root zone.

Porosity: index of the relative pore space of the soil, which can be broken down further specific to aggregate porosity or pore size (macroporosity or microporosity).

Soil strength: The capacity of a soil body to withstand forces without experiencing rupture, fragmentation or flow.

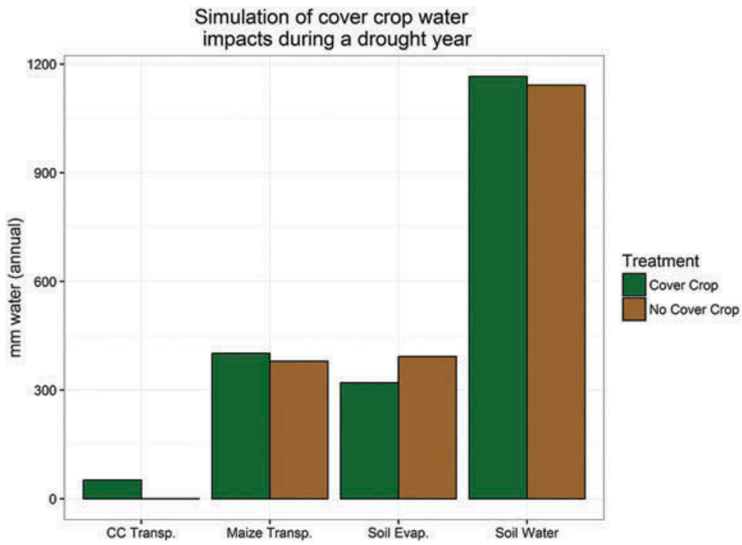

Figure 3. Simulated data based on the modeling experiment of Basche et al. (2016a) for the drought year of 2012 in Iowa, United States. This represents how in an idealized simulation, the various components of the water balance change and by what magnitude with the inclusion of a winter rye cover crop in a corn-soybean crop rotation. Even with cover crop transpiration of approximately 50 mm in the spring, water savings from reduced soil evaporation translates to greater soil water and approximately 22 mm more water available for cash crop transpiration. In this year of the simulation, there was no calculated water lost via drainage or runoff from either system due to low rainfall. Total soil water represents the annual sum of daily values of moisture content multiplied by the depth of the soil profile simulated (1.8 m).

the overall water balance of agroecosystems. In the semi-arid Great Plains, for example, a multi-year experiment found that wheat cover crop systems (including vetch, pea, clover and triticale cover crop species) significantly improved water-stable aggregates compared with wheat fallow or continuous wheat systems (Blanco-Canqui et al. 2013) in a silt loam soil. At another location in Blanco-Canqui et al. 2011 also found that wheat-sorghum rotations including cover crops increased the mean weight diameters of soil aggregates by 80% in the surface soil and improved water infiltration rates up to three times more than in fields that did not include cover crops. There is also evidence of cover crops improving water dynamics in California vineyard environments. Folorunso et al. (1992) found improved soil strength and water intake (by up to 100%) after 5 years of mixed cover crop use in orchard and tomato system environments. Gulick et al. (1994) similarly found that just one to two years of cover crop use in sandy loam environments of California increased infiltration rates by more than 140%.

Cover crops produce similar effects in more humid environments. Experiments in Illinois and Iowa measured increases in plant available water when cover crops were included in maize-soybean crop rotations (Basche et al. 2016b; Villamil et al. 2006). During the drought of 2012, Daigh et al.

(2014a) found that rotations involving winter rye cover and maize-soybean led to greater available water in Iowa and no negative impacts in Indiana, relative to a control with no cover crop. At multiple experimental locations in Maryland with continuous maize systems, incorporating cover crops improved several soil physical properties, including water infiltration and aggregate stability (Steele, Coale, and Hill 2012).

Similar results are documented outside the United States, particularly in regions where water management is critical due to monsoon climatic conditions. In the north-western region of India where maize–wheat systems are susceptible to water stress after the rainy season concludes, Sharma et al. (2010) found that green manure crops, such as sunn hemp, increased both soil moisture and water infiltration, and ultimately led to greater crop productivity compared to the no cover crop control. Similarly, for intensive rice–wheat cropping in the same region of India, Singh, Jalota, and Singh (2007) found that green manure crops increased soil aggregation and infiltration while decreasing bulk density on a loamy sand soil. Relatedly, after 23 years of repeated legume green manure use in a loamy sand in a rice–wheat system, Walia, Walia, and Dhaliwal (2010) reported higher moisture contents and faster infiltration rates compared to fertilizer only treatments of the same nutrient content. Further, in the tropical climate and degraded, sloping soils of southwestern Nigeria, Lal, Wilson, and Okigbo (1978) found significant improvements (up to a 300% increase) in infiltration rates when grass and legume species were grown ahead of annual crops, such as maize, cowpea, pigeon pea, soybean, and cassava.

Agroforestry

Agroforestry systems are also proposed as a climate adaptation and water resilience strategy, because they can also directly influence water balance by reducing runoff and do so indirectly by improving soil hydrology through increased porosity and infiltration (Altieri and Nicholls 2017; Schoenberger et al. 2012). In general, the water balance of these tree and crop systems is more complex than crop only systems, necessitating management of the ideal mix of inter-species water demands. While tree species may have greater water use through transpiration relative to grasslands (Huber, Iroumé, and Bathurst 2008), agroforestry and intercropped systems are known to promote hydraulic lift of water from deeper layers of the soil profile (Asbjornsen et al. 2011; Bayala and Wallace 2015). Therefore, a mix of more deeply rooted trees interspersed with crops offers diverse resource allocation of soil water during periods of variable rainfall (Bayala and Wallace 2015). Further, tree belts have been found to capture significant amounts of rainfall runoff from sloped landscapes (Ellis et al. 2006).

Research on the water relations of agroforestry systems compared with annual crop systems supports the overall benefits of these more diverse agroecosystems. Ketema and Yimer (2014) compared a no-till maize only system to an agroforestry-based mixed crop system with livestock in Ethiopia and found several positive water indicators, including increased soil porosity, reduced bulk density, increased infiltration and greater soil moisture content. Notably, in the agroforestry system there was an improvement in infiltration rates over time, with infiltration rates greater after 15 years than at 5 years (Ketema and Yimer 2014). Wang et al. (2015) similarly reported a consistent improvement in infiltration rate when comparing an alley cropping wheat–walnut system to a wheat monoculture over 11 years in the Loess Plateau of China. An experiment in Kenya found infiltration rates four times greater in hedgerows of *Cassia siamea* compared to the maize-cowpea sections of the field (Kiepe 1995). Agroforestry riparian buffers at an experiment in the Midwestern United States (Iowa) increased infiltration rates by up to 500% relative to a maize-soybean only treatment (Bharati et al. 2002).

Extensive research has been conducted at a long-term agroforestry research site in northeast Missouri in the Midwestern United States. The annual crop treatment at this site is a maize-soybean rotation (established in 1991), and the agroforestry treatment is a mixed grass-legume species hedgerows and mixed oak species agroforestry buffers (established in 1997). Udawatta and Anderson (2008) measured 2–2.6 times more macropores in the grass and agroforestry buffer regions than in the maize-soybean treatment. Seobi et al. (2005) reported significant increases in total porosity, hydraulic conductivity and water storage in the grass and agroforestry buffers compared to the maize-soybean treatment. While larger (but not statistically significant) infiltration rates were recorded in the agroforestry and grass buffer regions, Anderson et al. (2009) also measured lower soil water content in the agroforestry buffer during the cash crop growing season, which they attributed to higher transpiration levels. However, they also found that after rainfall events later in the summer, soil water recharge was greater in the agroforestry buffers than the maize-soybean treatment. Overall, soil measurements from this long-term research site demonstrate the complexity of water dynamics in agroforestry systems, but that overall, soil hydrologic function is improved relative to annual crop systems.

Perennial grasses

Research also notes the opportunity for perennial grasses, with their deep roots and high water use efficiency, to improve climate resilience (Asbjornsen et al. 2014). As is the case with cover crops and agroforestry, there is a need to balance water use among cash crops in mixed annual-perennial systems. Yet numerous experiments in a variety of environments have repeatedly demonstrated the ability of perennial grasses to improve hydrology in a way that might negate any transpiration losses. Verma and Sharma (2007) reported an approximately 10% increase in aggregate porosity after several years when perennial grass management was compared to a rice–wheat system in northern India. In northeast India, perennial forage grass regenerated a topographic landscape, compared to continuous annual crop cultivation, resulting in 20% more soil water, 63% faster infiltration rates, and 40% greater hydraulic conductivity (Ghosh et al. 2009). In one experiment in Iowa, switchgrass hedgerows were found to have six times larger hydraulic conductivity, a greater number of macropores, and higher soil water retention compared to a conventionally tilled continuous maize treatment (Rachman et al. 2004).

Further experimental research from the Midwestern United States comparing perennial grasses to annual cropping systems underscores the ability of perennial grasses to reduce water losses from runoff and drainage. Brye et al. (2000) monitored multiple aspects of the water balance over three crop growing seasons and found that the prairie ecosystem had on average 65–75% less water lost to drainage as compared to a maize-only crop system. The researchers also noted that the prairie ecosystem had higher soil water content and water storage relative to the maize system (Brye et al. 2000). Daigh et al. (2014b) similarly found that a mixed prairie and winter rye cover crop system reduced cumulative drainage by 37–46% compared to maize and soybean systems, due to greater evapotranspiration and lower stored soil water. Intercropping perennial grass strips in maize-soybean crop rotations reduced runoff by 37% in Iowa (Hernandez-Santana et al. 2013).

Modeling studies from the Midwestern United States provide additional insight into the overall water use efficiency of perennially-based systems. VanLoocke et al. (2012) found greater net biome productivity (carbon dioxide converted to dry matter by evapotranspiration) in miscanthus and switchgrass over maize in an experiment with the Agro-IBIS land surface ecosystem and ecosystem process model. This is a unique metric that assesses the tradeoff between carbon and water and provides an overall indicator of productivity per water use. Chen et al. (2016) compared annual cotton production in the Southern High Plains to several different species of perennial grass bioenergy crops using the Soil and Water Assessment Tool (SWAT). They found that, in general, the perennial grasses decreased runoff, increased soil water content during many months of the year, and improved water use efficiency overall. Agroecosystem models are helpful tools in considering tradeoffs associated with water use and productivity, and as these experiments demonstrate, there is added benefit of continuous living cover from a productivity and water perspective.

While we have identified perennial grass opportunities predominantly around forage and bioenergy crops, there is ongoing research with perennial grain crops that might offer significant opportunity to replace land currently under annual crop production (Baker 2017; Glover et al. 2010). Crop breeding efforts are complex because of the many numbers of genes that control the perennial habit, yet they hold tremendous promise as many staple grain crops have perennial relatives (Curwen-McAdams and Jones 2017). A shift toward more perennial grains, given the current predominance of annual grain crops, will require significant financial investments in research and development, and such efforts have recently received a boost on the industry front to support such an expansion (General Mills 2017). Further, research suggests that farmers are cognizant of the multiple opportunities that perennial grains offer for diverse markets, soil regeneration and water quality, particularly on marginal lands, indicating willingness to utilize such new crop technologies (Adebiyi et al. 2016; Mattia, Lovell, and Davis 2016).

Conservation agriculture and agroecological practices that promote continuous living cover

There is much emphasis in the scientific literature around "conservation agriculture," and as generally defined, it includes three principles:

1. Reduced tillage and/or zero tillage agriculture
2. Permanent soil cover through practices that retain crop residues
3. Crop rotations

Many researchers suggest that the principles, which may be achieved through this variety of practices, offer climate resilience and the ability to improve water outcomes in agroecosystems (Delgado et al. 2011; Palm et al. 2014) in a similar manner as has been described for the practices associated with continuous living cover. However, the primary emphasis of this review was to highlight opportunities around more complex agricultural practices that maintain living roots in the soil and describe how ecological principles in agroecosystems can benefit water outcomes, ultimately creating more resilience to climate change.

Greenwater efficiency through altered management adds up globally

Although approximately 70% of all freshwater (blue water) use goes to irrigated agriculture (Vorosmarty, Leveque, and Revenga 2005), it is further estimated that 90% of rainfed and 48% of irrigated agricultural water use comes from water stored temporarily in the soil (green water) (Mekonnen and Hoekstra 2011). Thus, many researchers contend that managing green water deserves greater research attention as an approach for reducing agriculture's water and land use conversion footprint (Raza et al. 2012; Sposito 2013; Stewart and Peterson 2015). Two global modeling studies underscore the importance of these greenwater management approaches. Rost et al.

(2009) estimated how on-farm management changes that recover 25% of current evaporative and runoff water losses could result in up to 19% yield improvements, while current irrigation practices only lead to an approximately 17% yield improvement (Rost et al. 2009). More recently, Jägermeyr et al. (2016) used a similar approach but combined multiple water use efficiency approaches, including rainwater harvesting and soil moisture conservation, and estimated that these strategies had the potential to reduce water-related yield gaps by 62%. As the numerous studies outlined in Table 1 indicate, improved greenwater efficiency is possible through a variety of continuous living cover practices. If scaled up on a global level, as the water and land use estimates in Rost et al. (2009) and Jägermeyr et al. (2016) studies conclude, they could offer significant environmental and water sustainability gains. Biophysically-based models that represent biogeochemical processes on a global scale, as well as agroecosystem models utilized on a more detailed regional scale, are important tools in assessing how complex agricultural management influences multiple aspects of sustainability and are necessary to move forward agronomic and ecological research on green water use efficiency.

Landscape level impacts of perennially based or annually based land use: insights from Iowa

Land use change and climate change in the Midwestern United States

The temperate climate of the Midwestern United States, as well as its fertile soils derived from native prairie grasses, makes the region ideally suited for agricultural production (Aldrich, Scott, and Leng 1975) (Figure 4a). Since the mid-twentieth century, Iowa's agricultural landscape has undergone a profound intensification. First, the overall acreage in crop production increased by 22%, from approximately 20 million acres in 1940 to 24.5 million in 2012 (USDA-NASS 2014b). Further, in 1940, perennial crops and crops that grow over winter (such as alfalfa, hay, barley and oats) comprised approximately 45% of harvested acres. After World War II, though, commodity-based monocultures began to dominate this landscape, as the agricultural sector emphasized increasing output while minimizing both on-farm expenditures and food prices (Gliessman 2015). As a result, by 2012, the same perennial and winter-growing crops represented approximately 7% of harvested acres, while maize and soybean production represented approximately 56% and 38% of harvested acres, respectively (USDA-NASS 2014a, Figures 4b and 5). This landscape simplification is occurring simultaneously to shifts in climate. Scientists observe changes in seasonal rainfall and temperature that are increasing the frequency of flood events in the Midwestern U.S. (Mallakpour and Villarini 2015). Researchers also note that the additional basin wetness resulting from increased precipitation, and anthropogenic

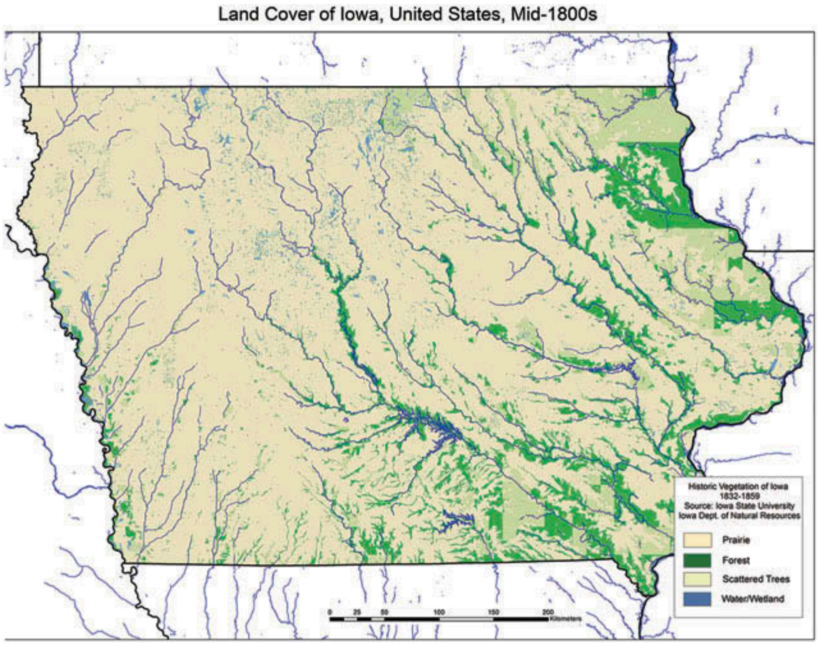

Figure 4a. Historic vegetation for the state of Iowa demonstrating that the predominant land cover was prairie grass and forest in the mid-1800s. Vegetation map created by Anderson (1996) using original public land survey data from 1832 to 1859 and digitized to create a vegetation layer for GIS analysis. Water attributes from the USGS National Hydrography Dataset.

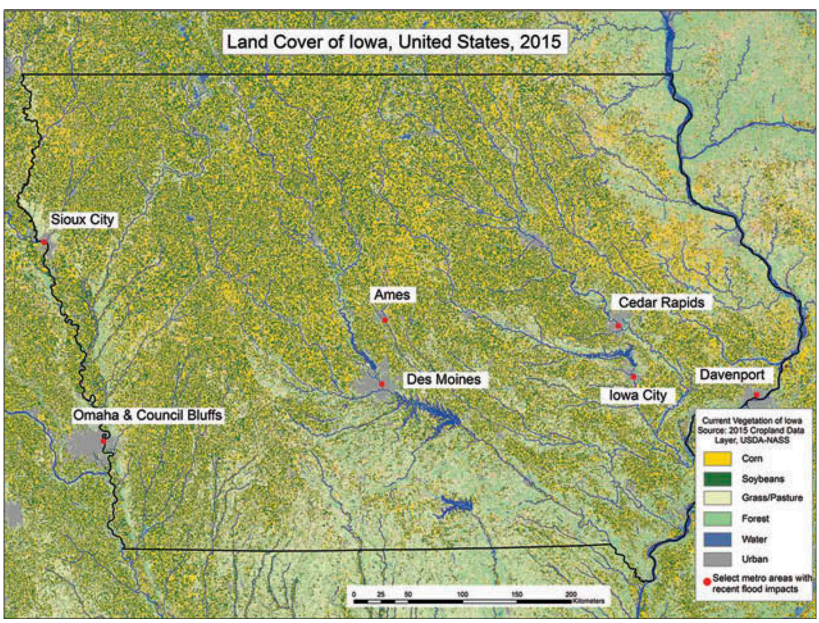

Figure 4b. More recent vegetation for the state of Iowa, demonstrating the predominance of corn and soybean crops across the landscape, which currently represent approximately 94% of harvested acres in the state. Red circles represent select major urban areas that have been affected by flood events over the last several decades. Data from the USDA-NASS 2015 Cropland Data Layer (USDA-NASS 2016) and water attributes from the USGS National Hydrography Dataset.

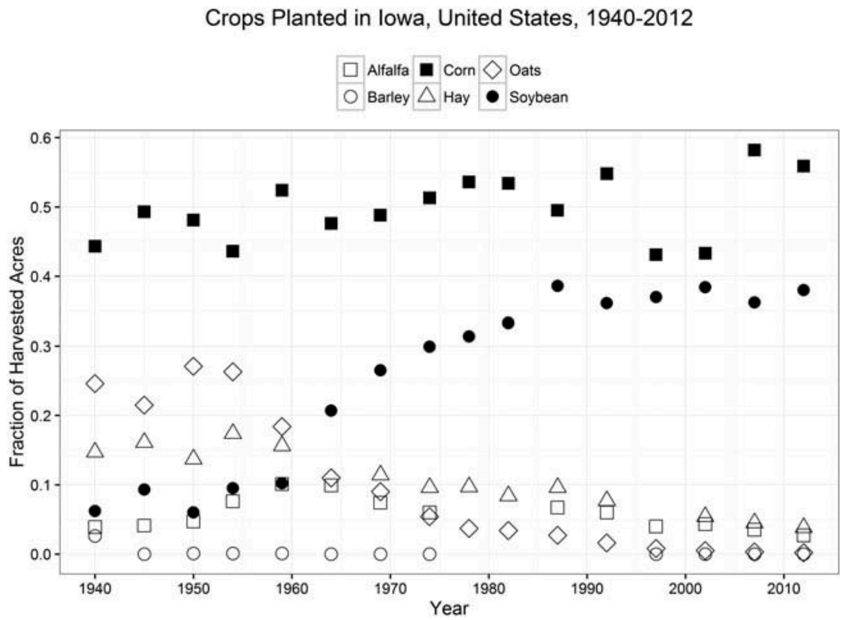

Figure 5. The change in crops planted across the state of Iowa from 1940–2012. Closed symbols represent summer annual crops, while open symbols represent perennial crops or crops that grow over winter. Alfalfa, barley, hay, and oats represented 45% of harvested acreage in 1940 and 7% in 2012. Source: (USDA-NASS 2014b).

impacts (i.e., urbanization and agriculture) become a precondition for increased flood potential (Slater and Villarini 2016).

Sixty-eight percent of Iowa's land area is harvested for agriculture (ISU Extension 2017), so the large shifts in the state's cropping patterns over the last seventy years have resulted in additional impacts to the landscape's hydrology. From a water cycle perspective, the loss of crops growing over winter creates the likelihood that plant transpiration could decrease and water losses from agricultural lands could increase due to greater runoff. In fact, strong evidence from Iowa watersheds demonstrates precisely how these projected water changes have come to fruition. Zhang and Schilling (2006) analyzed streamflow rates at river stations in the Mississippi River basin, including several in Iowa, over the period from 1940 to 2000 and concluded that the conversion of perennial vegetation to annual row crops and related agricultural activities, such as tillage, has affected the basin-scale hydrology of the Mississippi River, leading to increased baseflow and streamflow (Zhang and Schilling 2006).

A simple analysis of two stream gauge locations near urban centers in Iowa demonstrates a statistically significant upward trend in stream flow with time (Figures 6a and 6b). Further, in the past 30 years, the monthly stream flow was 2.6–3.7 times more likely to be two standard deviations above the long-term mean than during the earlier recorded period, even as the region experienced two severe

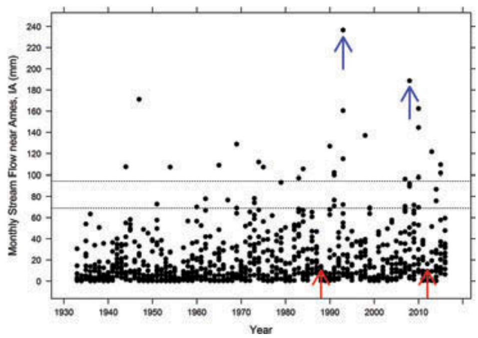

Figure 6a. The monthly stream flow (monthly rates divided by drainage area) near Ames, Iowa since the early 1930s. The red arrows note the droughts of 1988 and 2012, while the blue arrows note the flood events of 1993 and 2008. There was a statistically significant increase in stream flow over time, with a slope of 0.21 mm $month^{-1}$. Dashed lines represent +2 and +3 standard deviations above the mean monthly stream flow. Source: USGS National Water Information Systems (2017).

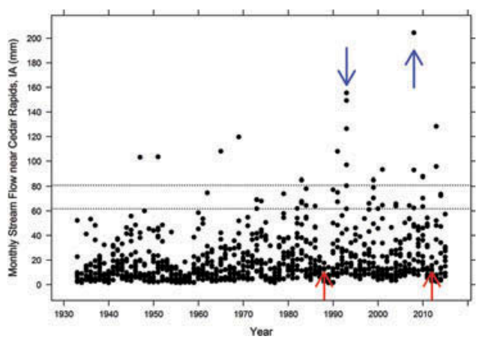

Figure 6b. The monthly stream flow (monthly rates divided by drainage area) near Cedar Rapids, Iowa since the early 1930s. The red arrows note the droughts of 1988 and 2012, while the blue arrows note the flood events of 1993 and 2008. There was a statistically significant increase in stream flow over time, with a slope of 0.21 mm $month^{-1}$. Dashed lines represent +2 and +3 standard deviations above the mean monthly stream flow. Source: USGS National Water Information Systems (2017).

droughts. The more extensive analyses of Zhang and Schilling (2006) arrived at similar conclusions. The relationship of land use and hydrology in agricultural regions suggests that more rainfall variability with climate change may only intensify stream flow and subsequent impacts, assuming continuation of the same annual crop-based land use patterns. While limited research directly links soil function to drought effects in the same way that the research on flood events does, the similar mechanisms that promote water storage for heavier rainfall offer resilience for lesser periods of rainfall. To this point, experts in Iowa identified that the 2012 drought led to a decline in soil structure, which made it more difficult for water retention to occur, exacerbating negative impacts (Al-Kaisi et al. 2013). It has also been demonstrated that drought effects during the Dust Bowl of the 1930s were in large part driven by land use change, including soil degradation and the loss of vegetative plant cover on the landscape (Cook, Miller, and Seager 2009), further demonstrating the feedbacks between climate, agricultural management and negative outcomes in extreme events.

Perennially based agriculture and conservation practices improve water resilience

Research already demonstrates that a more perennially-based agricultural system can reduce the negative consequences of flooding events. Schilling et al. (2014) used the SWAT model for a large Iowa watershed to analyze shifts in downstream flood risks. Their analysis assumed a baseline scenario of current land use where 76% of the watershed was planted with maize and soybean, as well as four hypothetical land use changes, including a 100% shift to perennial crops (Schilling et al. 2014). While their predictions demonstrated that shifting all cropland to perennials offered the greatest reduction in flooding frequency (by 50–100%), implementing extended crop rotations (that included alfalfa), and/or increasing perennial crop plantings in the more vulnerable regions of the watershed also reduced the frequency of downstream flood events by 25–35% (Schilling et al. 2014).

The potential for farmlands to reduce the intensity of flood and drought events through increased water storage capacity is an important point substantiated by disaster reports. For example, the Iowa Flood Disaster Report (IFDR), written by a recovery team after the 1993 severe floods, cited the success of conservation measures, including reduced tillage, in preventing an additional six million acres from flooding (IFDR 1994). It was noted that conservation measures also played a role in reducing urban flood impact and damages to the state's infrastructure (IFDR 1994). A report prepared by the Rebuild Iowa Office, a temporary state agency created by the government following 2008 flooding, concluded that industrial agricultural practices caused a dramatic reduction in the ability of Iowa's land to absorb and hold back water due to a decrease in soil organic material (AETF 2008). This report notes how public policy and expenditures should internalize flood mitigation priorities to encourage practices that foster greater hydrological resilience (AETF 2008).

Flood and drought impacts beyond the farm

Increased precipitation variability not only adversely affects farmers who must cope with flood and droughts on a more frequent basis but also downstream urban citizens who experience negative impacts related to infrastructure and public health. For example, as Iowa endured a major drought in 1988, many municipal water supplies were reduced to dangerously low levels (Kunkel and

Angel 1989), while low water levels on the Mississippi River led to a 50% reduction in barge traffic (Changnon, Kunkel, and Changnon 2007). During the 1993 floods, a failed levee flooded the water treatment plant in Des Moines, causing the city to go without drinking water for 19 days (Parrett, Melcher, and James 1993). In 2008, severe flooding caused multi-billion dollar damages to downtown Cedar Rapids (Morelli 2016).

Another side effect of increased rainfall variability is nutrient runoff and water quality issues, which is a critical issue in the state of Iowa and as far downstream as the Gulf of Mexico (Diaz and Rosenberg 2008; Potter 2011; Raymond et al. 2008; Schilling 2005). Over 700 of Iowa's waterways are impaired because their water quality does not meet the waterway's intended use (i.e., consumption or recreation) (IDNR 2015). Pollution from non-point sources, especially agricultural lands, is estimated to contribute approximately 92% of the total nitrogen and 80% of the total phosphorus that enter Iowa's streams annually (Iowa NRS 2012).

Further, the well-researched social phenomenon known as environmental racism documents the disproportionate impacts of water-related events on communities of color and those with lower socioeconomic coping capacity (Umokoro, 2015). With declining water quality resulting from pollution and increased extreme weather events, water costs rise. A report found that water bill increases grew at a rate much faster than inflation, due to climate events and increased vulnerability (Feinstein et al. 2017). These price increases disproportionately affect resource–scarce populations, as they are forced to spend a greater portion of their disposable income on a basic need. More generally, a recent review found that low-income communities are more vulnerable to flood risks because of their limited housing opportunities and lack of information about, and access to, disaster mitigation and recovery assistance programs (Rufat et al. 2015).

Conclusion

Modern agricultural systems have overcome productivity limitations due to excessive or insufficient water through approaches such as tile drainage and irrigation infrastructure, respectively. While such approaches have been successful and many efforts are working toward improving their sustainability, there are limits to these approaches. There is much to learn from the ecology of natural systems adapted to climatic and environmental limits. One way to mimic the function of perennial and native vegetation patterns in agroecosystems is through practices featuring continuous living cover. Unlike exclusively annual systems, there are practices—such as cover crops, agroforestry, and various perennial forage, grain or bioenergy crops—that ensure canopy cover and living roots in agricultural systems throughout the year. These practices have been shown repeatedly, and in a range of environments, to enhance multiple elements of agricultural water balance, including improved soil hydrology. Amid projections for a changing climate with increased rainfall variability, reducing agricultural water risks is more critical than ever, and the increasing recurrence of water-related extreme events underscores the susceptibility of the current system. The historical shift in Iowa's agricultural landscape highlights how cropping patterns have played a role in increased flood and drought frequency and severity, which adversely impact on-farm water resilience as well as public health and infrastructure downstream. Increased use of perennials or continuous living cover practices that mimic the function of perennial plant communities could significantly improve the ability of agricultural land to enhance resilience and buffer negative impacts of climate change and increased rainfall variability.

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