

# Coupling landscape water storage and supplemental irrigation to increase productivity and improve environmental stewardship in the U.S. Midwest

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[1] Agriculture must increase production for a growing population while simultaneously reducing its environmental impacts. These goals need not be in tension with one another. Here we outline a vision for improving both the productivity and environmental performance of agriculture in the U.S. Midwest, also known as the Corn Belt. Mean annual precipitation has increased throughout the region over the past 50 years, consistent with climate models that attribute the increase to a warming troposphere. Stream gauge data indicate that higher precipitation has been matched or exceeded by higher stream flows, contributing to flooding, soil loss, and excessive nutrient flux to the Gulf of Mexico. We propose increasing landscape hydrologic storage through construction of ponds and restoration of wetlands to retain water for supplemental irrigation while also reducing flood risks. Primary productivity is proportional to transpiration, and analysis shows that in the U.S. Midwest both can be sustainably increased with supplemental irrigation. The proposed strategy should reduce interannual yield variability by limiting losses due to transient drought, while facilitating adoption of cropping systems that “perennialize” the landscape to take advantage of the full potential growing season. When implemented in concert, these practices should reduce the riverine nitrogen export that is a primary cause of hypoxia in the Gulf of Mexico. Erosive sediment losses should also be reduced through the combination of enhanced hydrologic storage and increased vegetative cover. Successful implementation would require watershed-scale coordination among producers and landowners. An obvious mechanism to encourage this is governmental farm policy.

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## 1. Introduction

[2] One of the great challenges facing the current generation is to sustainably increase the net photosynthetic productivity of managed landscapes. Global population has doubled in the past 40 years, and while the rate of increase is slowing, the population is expected to reach 9.2 billion in 2050 [Bongaarts, 2009]. Per capita meat consumption has also doubled over the past 40 years, and substantially more grain is required to sustain a person if the grain is first fed to an animal [Bouma *et al.*, 1998; Gerbens-Leenes *et al.*, 2002]. To compound matters, there is now an expectation that agricultural lands will also make a meaningful contribution to society’s need for energy [Perlack *et al.*, 2005].

[3] Crop yields have risen dramatically in recent decades, primarily due to the interaction between genetic improvements and management changes, including increased use of fertilizers and pesticides, better equipment, and better agronomic knowledge [Duvick, 2005]. However, the likelihood of continuing the current yield trajectory is uncertain [Long and Ort, 2010]. Tollenaar and Lee [2002] note that the maximum U.S. corn contest yields have leveled off at approximately 20 Mg ha<sup>-1</sup>. Tollenaar [1983] had previously used a physiological model to calculate a theoretical maximum yield of 25 Mg ha<sup>-1</sup>. They thus concluded that attempting to improve yield potential is probably not the best strategy for genetic improvement. Lobell *et al.* [2009] extended this conclusion globally, noting that maximum yields of the major grain crops, i.e., most productive farming practices on the best soils, with irrigation, have leveled off in recent years at about 80% of their theoretical yield potential, which may be a practical limit. Actual mean yields are much lower, typically less than 50% of record yields, due to a variety of stressors, most notably water.

[4] In addition to uncertainty about the potential for further yield increases, there is concern that the very techniques that have driven agricultural production to its current

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level are environmentally unsustainable, due to degradation of soil and water resources [Tilman, 1999]. Erosive losses of sediment and phosphorus have degraded local and regional water bodies [Engstrom *et al.*, 2009], and fertilizer nitrate export has been implicated as the principal cause of an expanding zone of annual hypoxia in the Gulf of Mexico [Turner and Rabalais, 2003] and other coastal areas around the world. To this point, the primary policy tool for addressing these problems in the U.S. has been to reduce production through programs that pay landowners not to farm. As rising demand continues to put upward pressure on grain supplies, it will become increasingly difficult to sustain this approach [Secchi *et al.*, 2009]. However, our contention is that wiser environmental stewardship and further increases in productivity need not be mutually exclusive, and in fact may be tightly coupled. In the discussion that follows, we consider this thesis in the context of the Midwestern region of the U.S. known colloquially as the Corn Belt.

## 2. Changing Hydroclimatology of the U.S. Midwest

[5] Mean annual precipitation has increased substantially across the Midwestern U.S. [Qian *et al.*, 2007; Changnon and Hollinger, 2003]. In Figure 1a we have mapped linear regression estimates (Matlab, Natick MA) of the rate of change in mean annual precipitation for each eight-digit hydrologic unit code (HUC) watershed across the region over the past 50 years. The analysis was restricted to watersheds currently composed of at least 25% corn and soybean to avoid the complicating effects of urban areas. These data were produced with the PRISM system (<http://www.wcc.nrcs.usda.gov/climate/prism.html>), which provides estimates of areal totals of precipitation from a gridded data product that is based on interpolation and orographic adjustment of data from the cooperative observer network of precipitation gauges. Figure 1a shows that mean annual precipitation increased  $>1 \text{ mm yr}^{-1}$  over the majority of the region during the period from 1960–2009 and  $>4 \text{ mm yr}^{-1}$  in portions of Indiana and Ohio.

[6] This increase in precipitation is likely attributable to the warming atmosphere [Trenberth, 2011]. The saturation mixing ratio increases by 7% for each  $1^\circ\text{C}$  rise in temperature, and ocean evaporation rates rise with temperature as well, increasing the mean atmospheric total column water vapor. This impacts atmospheric circulation and energy transfer in the following ways: more intense drought in dry subtropical zones and a poleward shift of the storm track, with more total precipitation, but also more episodic heavy rainfall in the mid to high latitudes. As Trenberth points out, climate models reproduce these trends and project that they will continue.

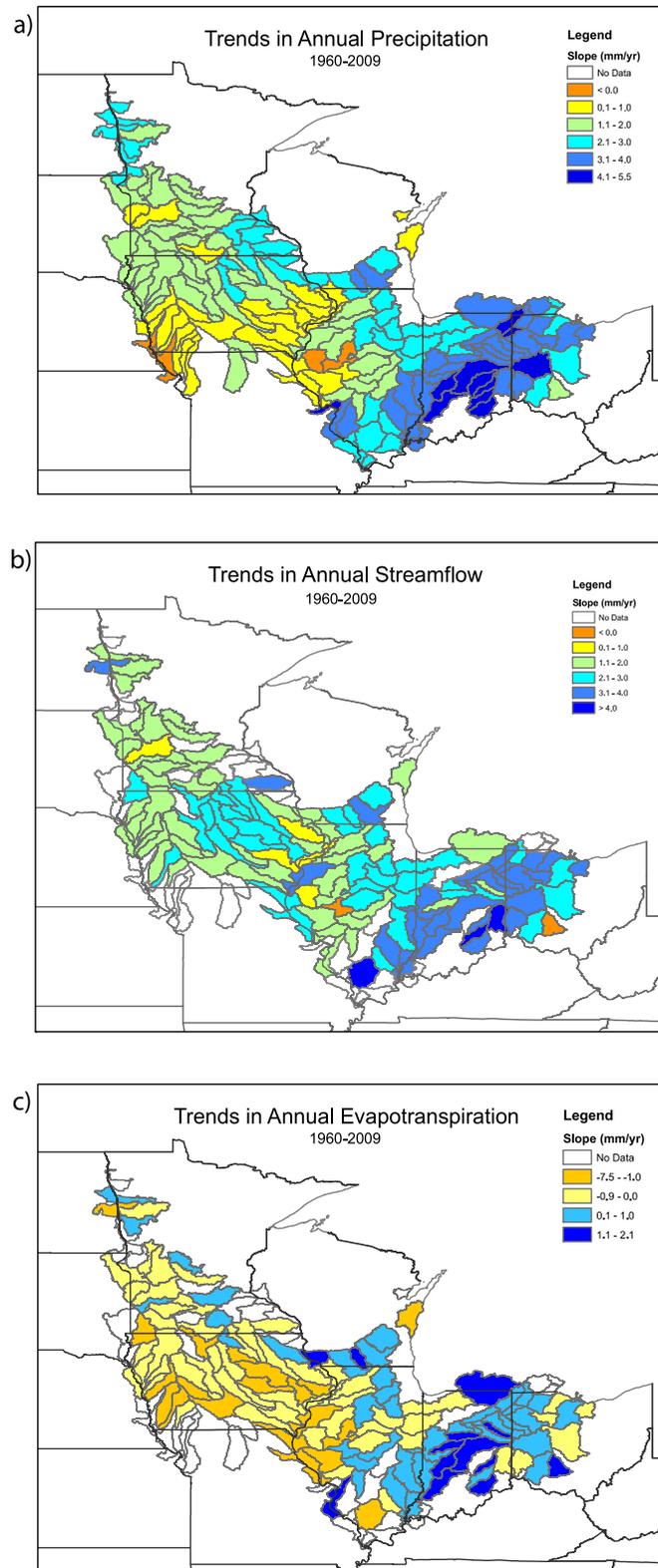
[7] Precipitation increases in the Midwest have generally been matched or exceeded by changes in streamflow, with more frequent incidence of surplus water throughout the central USA [Mauget, 2004]. Figure 1b is a map of the changes in mean annual area-weighted streamflow for the same eight-digit HUC watersheds, computed from USGS gauge data (<http://waterdata.usgs.gov/nwis>). Streamflow increases for the period from 1960–2009 were  $>1 \text{ mm yr}^{-1}$  for most of the region, similar to the precipitation trends in Figure 1a, and  $>4 \text{ mm yr}^{-1}$  in some watersheds. Neglecting annual

changes in water storage, we calculated watershed evapotranspiration (ET) by subtracting annual streamflow from annual precipitation for each watershed. Regression analysis was then used to estimate changes in basin-average ET (Figure 1c). Trend estimates for a majority of the region were generally  $\pm 1 \text{ mm yr}^{-1}$  or smaller. These temporal trend data in precipitation and streamflow imply that basin-scale annual ET has been stable, and even decreasing slightly, particularly in the central part of the region.

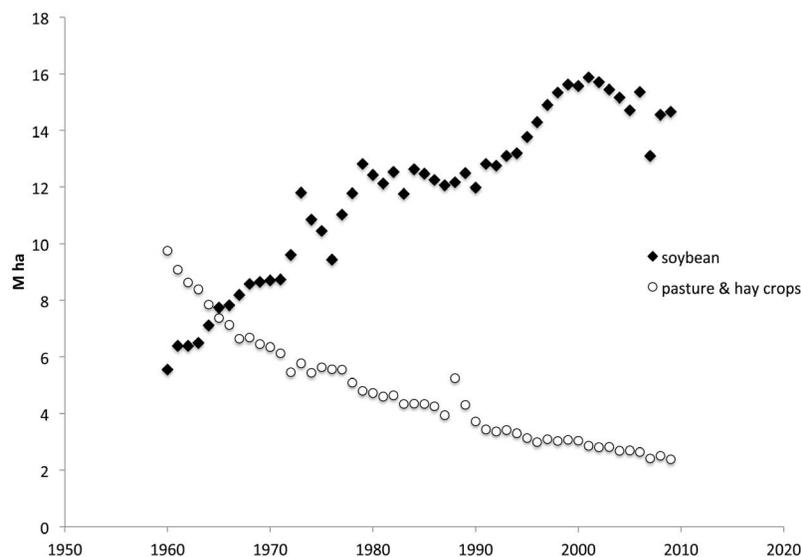
[8] By contrast, Qian *et al.* [2007] contend that ET has been increasing in recent decades over the Mississippi basin in concert with increasing precipitation, based on computer simulations with the Community Land Model. However, they did not factor in shifts in vegetation and land cover over the length of their simulation, 1948–2004, when in fact there were significant changes in the upper Midwest over this period, most notably a tremendous increase in soybean acreage that has been primarily at the expense of perennial pasture and hay crops (Figure 2). Pasture and hay crops in the upper Midwest transpire for 6 months or more, while soybean has a much shorter growing season; it is planted in late spring, canopy closure does not occur until midsummer, and most varieties lose their leaves in early September. Five years of gas exchange data in eastern Nebraska [Suyker and Verma, 2009] showed that growing season ET for soybean was lower than that of maize by 10%–15%, which itself has a short growing season relative to perennial vegetation. Schilling and Zhang [2004] have documented the hydrologic impact of increased row crop cultivation in Iowa, and Tomer and Schilling [2009] used a novel approach to separate the impacts of increased cropping intensity (particularly the substantial increase in soybean production) from the impacts of changing climate. They found that both were contributing to an increase in streamflow in the four agricultural watersheds they examined. Others have also noted that drainage, base flow, and groundwater recharge for the region have all increased [Baldwin and Lall, 1999; Donner *et al.*, 2002].

[9] Water that leaves a watershed by streamflow or recharge is often referred to as “blue water,” in contrast to “green water” ET [Falkenmark and Lannerstad, 2005]. It is intuitive that the increase in blue water fraction that occurs when perennial vegetation is converted to annual row crops is due to the shorter photosynthetic season, but there are still more reasons why basin scale blue water fractions in the U.S. Midwest have increased. The most obvious is a long-term, ongoing program of land drainage. There is no credible, comprehensive census of drained land, but one source guessed that more than 16 million ha of land in the five states of MN, IA, IL, IN, and OH had been artificially drained by 1987, either to convert wetlands to agriculture or to facilitate removal of excess water from existing fields [USDA, 1987]. This represents between 25% and 50% of the cropland in each of these states. In a separate analysis that omitted IN but included MI and WI, Dahl [1990] estimated that more than 14.5 million ha of wetlands were drained between 1780 and 1980. And though legislation has since made it more difficult to alter permanent wetlands, new installation of subsurface drains in seasonally wet fields continues across the region.

[10] Urbanization and development have increased the blue water fraction as well. Based on analysis of Landsat



**Figure 1.** (a) Regression-estimated change in mean annual precipitation from 1960 through 2009 for all eight-digit HUC watersheds in MN, WI, IA, IL, IN, and OH with >25% of their area in corn and soybeans. Data obtained from the NRCS PRISM database. (b) Regression-estimated changes in mean annual streamflow for the same watersheds, taken from USGS gauge records and converted to an equivalent depth by dividing by the catchment area. Watersheds for which streamflow data were incomplete have been eliminated from the analysis. (c) Changes in mean annual ET for the same watersheds, estimated as the difference between annual precipitation and annual streamflow.



**Figure 2.** Land area planted in soybeans (◆) and pasture and hay crops (○) in MN, IA, IL, IN, and OH from 1960 through 2009. Data were obtained from the USDA National Agricultural Statistics Service ([www.nass.usda.gov](http://www.nass.usda.gov)). Pasture and hay crops include three NASS categories: alfalfa, nonalfalfa hay crops, and oats. In the upper Midwest U.S., oats have historically been included in rotations as a spring companion crop for first year alfalfa [Martin *et al.*, 1976].

images, Bauer *et al.* [2008] estimate that the amount of impervious surface in the state of Minnesota increased by 44% between 1990 and 2000, with the total now approaching 400,000 ha. Thus, an area equal to 5% of the cropland in the state (and twice the current irrigated area) now has negligible ET. Assuming similar increases in other Midwestern states, this represents a significant further addition to runoff in the region. The observed increase in blue water fraction has had decidedly negative consequences, including more frequent and more extensive flooding [Olsen *et al.*, 1999], an increasing rate of sediment transport [Engstrom *et al.*, 2009], and stubbornly high nitrogen delivery to the Gulf of Mexico [Mitsch *et al.*, 2001]. From both environmental and productivity standpoints, strategies are needed to transform blue water into green by increasing net primary productivity (NPP).

### 3. Rationale for Supplemental Irrigation

[11] The U.S. Midwest is already one of the most productive agricultural regions in the world, with large expanses of deep, fertile soils, a growing season long enough for corn and soybeans to reach maturity, and ample precipitation, *on an annual basis*, to supply the water needed for transpiration. Agronomically, this area is as technologically advanced as any on Earth, and yet it may still be far from its potential productivity. Net primary productivity in the U.S. Midwest is often constrained by water. In some situations there is too much of it, in others too little, and the irony is that an individual producer is often bedeviled by both problems within the same year. Federal crop insurance records for the five state area show that indemnities for yield losses due to the contrasting causes of excess water and drought have been roughly equivalent over the past 10 years—between 2.5 and 3 billion \$USD

each (<http://www.rma.usda.gov>). Paradoxically, although climate models predict that the observed regional increase in annual precipitation in recent decades will continue, the frequency of drought is also expected to increase since more rain is forecast to occur in intense storm events [Trenberth, 2011]. Thus, yield reductions due to transient drought, already a relatively common occurrence, may happen with more frequency and intensity. We propose exploration of a strategy to simultaneously address environmental problems and limitations on agricultural production by increasing both landscape water storage capacity and supplemental irrigation capacity.

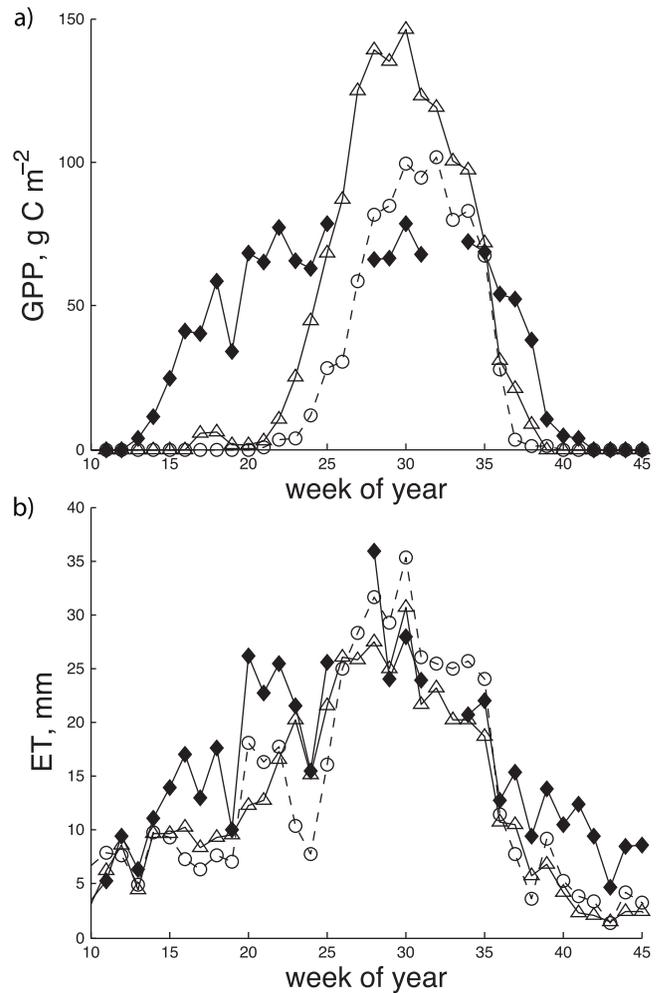
[12] Recent global analyses of the potential yield benefits associated with local capture, storage, and use of water for supplemental irrigation indicate possible gains in food production of 19% to 35% [Rost *et al.*, 2009; Wisser *et al.*, 2010]. It is well established that biomass production  $B$  is proportional to transpiration  $T$  when  $T$  is normalized by the mean vapor pressure deficit (vpd) [Tanner and Sinclair, 1983]. The coefficient of proportionality, or transpirational water use efficiency, differs substantially between C4 species and C3 species, but interspecific differences within those broad functional groups are much smaller. Consequently, an increase in  $T$  implies an increase in  $B$ , so long as it is not occasioned by a large-scale displacement of C4 plants with C3 vegetation or by an increase in mean vpd. Two avenues by which  $T$  and  $B$  can both be increased in managed ecosystems are by alleviating transient drought and expanding the growing season. These are not independent of one another since expansion of the growing season can induce or exacerbate drought stress, so both strategies can be facilitated with increased landscape storage and supplemental irrigation. Widespread adoption of these practices in the Midwest could provide multiple benefits: higher and more stable agricultural productivity, less erosion, more

wetland habitat, decreased likelihood of damaging floods, and improved water quality. The ultimate goal is a more resilient landscape in which the impacts of fluctuating precipitation on net primary productivity and streamflow are damped.

[13] Both experimental data and models show that the achievable yields in rain fed systems are much below those of irrigated systems. In fact, *Lobell et al.* [2009] draw a crucial distinction in referring to “maximum possible yields under rain-fed conditions as ‘water-limited yield potential’ because most rainfed crops suffer at least short-term water deficits at some point during the growing season.” Their estimate is that mean annual productivity for unirrigated land in the Midwest is typically less than 50% of potential yield, far from the 80% that is achievable under optimum conditions. Corn is particularly sensitive to water stress during the reproductive phase, which induces responses that lead to kernel abortion [*Boyer and Westgate*, 2004]. In a field test *Otegui et al.* [1995] found that each millimeter of reduced ET during tasseling and silking lowered kernel counts by 4.7 kernels  $m^{-2}$  and final yield by 17.7  $kg ha^{-1}$ . Conventional wisdom dictates that investment in irrigation is not warranted in the region. And yet rainfed crops in the region frequently experience yield-limiting drought at some time during the year, a fact that has not escaped the attention of plant breeders and geneticists [*Campos et al.*, 2004], who have devoted considerable effort to improving the drought tolerance of corn, with limited success thus far.

[14] Short term water deficits are, of course, not the only factors limiting NPP for the annual row crop systems of the Midwest. Another important factor is often overlooked. These ecosystems only photosynthesize for 90–100 days, while the potential photosynthetic season, evident from perennial vegetation in the region, exceeds 200 days. For example, corn exhibits remarkably high midsummer photosynthesis rates, but because it has a base temperature for metabolic activity of approximately  $10^{\circ}C$  and little frost tolerance, its effective growing season is only about 95–110 days long, despite a potential growing season of more than 200 days throughout the region. Even in the most northern reaches, more than 1/3 of the photosynthetically active radiation (PAR) during the potential growing season is received either before corn emerges or after it has senesced. This is why the regional NPP is much lower than the potential NPP of climax vegetation for the region [*Haberl et al.*, 2007], consistent with a meta analysis of gas exchange data by *Baldocchi* [2008], which showed that net primary productivity of natural ecosystems correlated better with growing season length than with peak photosynthetic rates.

[15] We have hypothesized [*Baker and Griffis*, 2009] that NPP in the region could be increased by combining highly productive annual crops like corn and soybeans with winter cover crops like rye [*Ruffo et al.*, 2004; *Kaspar et al.*, 2007] or with perennial, N-fixing companion crops like alfalfa or kura clover [*Affeldt et al.*, 2004] that can take advantage of otherwise unused PAR, primarily in the spring (Figure 3a). Cropping systems that include cover crops or living mulches also provide a means to take advantage of documented increases in the length of the growing season [*Linderholm*, 2006] to a greater extent than determinate monocrops. A primary impediment to the adoption of such practices has been the increased risk of



**Figure 3.** (a) Weekly gross primary productivity and (b) weekly ET for three adjacent fields with the same soil type at Rosemount, MN in 2010, determined from eddy covariance measurements. Maize ( $\Delta$ - $\Delta$ ), soybean ( $\circ$ - $\circ$ ), and kura clover ( $\blacklozenge$ - $\blacklozenge$ ). Gaps in kura clover data are due to cutting and harvesting of hay.

drought-induced yield reductions for the high value annual crop due to the concomitant additional ET (Figure 3b) in spring and early summer [*Krueger et al.*, 2011; *Ochsner et al.*, 2010]. If this risk can be mitigated with supplemental irrigation, these cropping systems should enjoy a distinct advantage in net primary productivity relative to a conventional unirrigated corn or soybean field. The form in which this added productivity is harvested could be forage for livestock or biofuel feedstock. In the latter case, the winter cover crop or living mulch could either be harvested directly or, more likely, assume the environmental roles of corn stover (erosion protection, maintenance of soil organic matter) so that both corn grain and stover could be sustainably harvested.

#### 4. Landscape Water Storage and ET

[16] *Milly* [1994] developed an analytical model based on the hypothesis that the long-term water balance of an area is determined solely by the local interaction of

precipitation and evaporative demand, as mediated by soil water storage, a physical variable defined in physiological terms as the difference in volumetric water content between field capacity and wilting point, integrated over the plant rooting depth. All three components are inexact, but field capacity and wilting point were considered to be the water contents corresponding to water potentials of  $-10$  and  $-1500 \text{ J kg}^{-1}$ , and the effective rooting depth was taken to be 1 m. Milly's model employed seven dimensionless numbers to partition average annual precipitation between ET and runoff, and produced reasonable estimates of both values for the United States east of the Rocky Mountains, without prior calibration. Sensitivity analyses indicated that both the mean value of storage capacity  $\bar{S}$  and its variability across the landscape  $\sigma_s$  exert control over the ratio of mean annual ET to mean annual precipitation. The impact of  $\sigma_s$  is due to the nonlinear dependence of ET on storage, i.e., negative spatial deviations in  $S$  have a larger effect on areal mean annual ET than positive deviations.

[17] As defined,  $\bar{S}$  would not seem amenable to much modification, but notably the impact of temporal variation in rooting depth was not explicitly considered. This is a more serious consideration for lands planted in annual crops than it is for perennial vegetation. In corn and soybean systems rooting depth is zero for more than 8 months of the year, and extends only gradually during the growing season. Dwyer *et al.* [1996] found that corn roots in two different soil textural types were primarily confined to the top 20 cm up to the 12 leaf stage, and did not proliferate to 1 m until anthesis. Kirkham *et al.* [1998] studied rooting depths and densities as well as soil moisture depletion under both corn and soybeans. They found that both eventually developed roots to 1 m or more, but that maize root water uptake was primarily confined to the upper 0.9 m, while soybean uptake was primarily confined to the upper 0.5 m. They also noted that soybean roots did not reach the lower portion of the root zone until late in the growing season. Thus the effective storage capacity of a given soil or landscape depends on the vegetation that is present, in particular the temporal and spatial dimensions of its root system, and in an average sense would be lower if planted with an annual crop, particularly soybean, than it would be if it were in perennial vegetation. Consequently, management changes that perennialize the landscape, e.g., winter cover crops or living mulches, will increase the effective storage capacity by increasing the mean effective rooting volume. These practices are also thought to increase soil organic matter [Sainju *et al.*, 2002], which is positively correlated with water-holding capacity [Hudson, 1994]. At a broader spatial scale, the effective storage capacity of a catchment can be increased with the construction of ponds or the restoration of wetlands, which, when combined with supplemental irrigation, can also effectively reduce the impact of  $\sigma_s$ .

[18] The presettlement landscape of the upper Midwest certainly had substantially greater hydrologic capacitance than it currently possesses. Not only has perennial vegetation been largely displaced by annual crops, but vast areas that were permanently or seasonally wet have been artificially drained [Dahl and Allord, 2004]. Minnesota has lost more than half of an estimated 7.5 million ha of wetlands that were present prior to cultivation, and in Iowa less than

10% of an estimated 2 million ha remains. Illinois, Indiana, and Ohio have also experienced extensive loss of wetlands. Partial renewal of water storage capacity could be accomplished through a combination of wetland restoration, constructed farm ponds, and storm water retention basins, guided by appropriate models. Arnold and Stockle [1991] provided an example in which they coupled simulations of the economic costs and crop yield benefits of farm ponds to a simple optimization scheme, in order to estimate the viability of supplemental irrigation and determine the optimum pond size for a specific location.

## 5. Advanced Cropping Systems Facilitated by Supplemental Irrigation

[19] Increased water storage and irrigation capability afford the opportunity for cropping system modifications that, in return for a modest amount of water, can improve the environmental footprint of row crop systems, e.g., winter cover crops and living mulches. Perhaps no subject has elicited more enthusiasm among researchers and less among farmers than winter cover crops. Documented impacts [Dabney *et al.*, 2001; Hartwig and Ammon, 2002; Brandi-Dohrn *et al.*, 1997] include reduced erosion, scavenging of excess N, and additional biomass production, which can be used for grazing, hay, or as a green manure. Despite these selling points, cover crop adoption in the Midwest remains low [Singer, 2008], and unconvinced farmers cite a variety of concerns, including cost, timing, and a fear of negative impacts on yield of the subsequent crop. In the spring there is reluctance to allow too much cover crop growth since experiments have shown that later kill dates correlate with lower corn yields [Raimbault *et al.*, 1991], so agronomists recommend that cover crops be killed well before corn planting, which unfortunately eliminates photosynthesis at a time when solar radiation is near its annual peak. Observed negative impacts of rye cover crops on subsequent corn yield are generally attributed to either soil water depletion or N immobilization [Krueger *et al.*, 2011], so it is noteworthy that in a field test in Wisconsin where irrigation was used, yields were actually higher and optimal N rates were lower for corn following a rye cover crop than for corn alone [Andraski and Bundy, 2005]. Apparently, irrigation not only eliminated any moisture stress effects but also favored more rapid decomposition of the rye residue, releasing N that had been immobilized.

[20] The high N requirement of corn has inspired many efforts to grow it in combination with legume intercrops and living mulches. Descriptions of Native American agriculture in North America by the first European visitors mention that corn and legumes were frequently planted together—in fact, evidence indicates that this has been the dominant cropping system in Mesoamerica since the dawn of agriculture in the western hemisphere [Mt. Pleasant, 2006]. Corn/legume intercropping is still frequently practiced in many areas of the tropics, but has not found a place in the mechanized agriculture of the Midwestern United States. There has been limited experimentation with the use of alfalfa as a living mulch for corn, with research in Minnesota showing that it reduced corn yield in rain fed systems, but not in irrigated systems [Eberlein *et al.*, 1992]. Alfalfa has also been used as a living mulch for soybean

[Schmidt *et al.*, 2007], where it was found to reduce the intensity of soybean aphid infestation. *Ilnicki and Enash* [1992] successfully used subterranean clover as a living mulch for corn and found that it effectively suppressed weeds while providing N.

[21] Another promising legume for living mulches with corn is kura clover. Like alfalfa, it is a nutritious forage [Sheaffer *et al.*, 1992], but it does not lose vigor after a few years as alfalfa does, and it spreads by rhizomes, allowing it to recover following suppression with tillage or chemicals. This is an important characteristic since it permits the establishment of cleared strips into which corn can be planted. As the corn crop develops and matures, the clover recovers from the suppression and slowly spreads back across the row, reestablishing full cover by the close of the growing season. It has been shown in Wisconsin at the plot scale [Zemenchik *et al.*, 2000; Affeldt *et al.*, 2004] that corn and kura can be grown together with the corn harvested as silage and the kura maintained as a permanent living mulch. The corn in this system required substantially less fertilizer N than a conventional corn crop [Berkevich, 2008]. Initial data indicate that there is less nitrate leaching from a corn/clover system than from conventional corn [Ochsner *et al.*, 2010], but also greater soil moisture depletion in the spring, and results from this work and from trials in Minnesota (unpublished data) show that some reduction in corn yield will often occur due to water stress. Two years of trials under rainfed conditions in Iowa were also less successful than those in Wisconsin [Sawyer *et al.*, 2010]—in the first year excessive competition with the kura resulted in decreased corn yields; in the second year, when there was more vigorous suppression of the kura, yields were similar to conventional corn plots but with little N benefit from the suppressed clover. Thus, while the potential environmental benefits of such a system are enticing, the economic risks of competition with the corn are a substantial impediment to adoption, so supplemental irrigation may be a necessary risk management practice.

## 6. Sustainability Concerns

[22] Globally it is estimated that depletion of aquifers, primarily for agricultural use, exceeds 1000 km<sup>3</sup> per year [Konikow, 2011], and there is a general perception that irrigated agriculture inevitably leads to water scarcity [e.g., Postel *et al.*, 1996]. However, the quantity of water needed per unit land area for irrigation in the humid Midwest is substantially less than in the arid regions where irrigation is prevalent, because evaporative demand is lower and precipitation is greater, so that irrigation in the Midwest is a supplement, not the principal source of crop water through the whole season. The mean annual application rate on currently irrigated lands in the central and eastern parts of the Midwest is approximately 168 mm ([www.nass.usda.gov](http://www.nass.usda.gov)). By contrast, the mean annual application rate for the more arid plains states (NE, KS, OK, TX), where aquifer depletion is a serious concern [Konikow and Kendy, 2005], is 313 mm, nearly double.

[23] Nonetheless, expansion of irrigation can create local water supply problems in humid regions as well, particularly if irrigation is practiced on coarse-textured soils that require more frequent irrigation, and with excessive reli-

ance on groundwater sources. However, much of the cropland in the Midwest is situated on finer-textured soils, with moderate to high water-holding capacities. If supplemental irrigation is focused on these lands, the demand per unit area will be modest. More importantly, aquifer depletion can be avoided through policy measures that couple supplemental irrigation systems to newly developed surface water sources rather than wells. In fact, this linkage is the key to adding ecosystem benefits and reducing the environmental impact of farming.

[24] Connecting surface water storage to supplemental irrigation has already been practiced in some areas with subirrigation systems [Skaggs, 1999], in which water is pumped back in to subsurface drainage systems so that it can rise by capillarity to replenish the root zone. Cooper *et al.* [1991, 1999] showed that this significantly increased mean annual yields of both soybeans and corn in Ohio. However, this option is limited to level fields with relatively dense drainage networks, a small fraction of total farmland in the region. In fields with less systematic drainage systems, aboveground delivery systems such as center pivots, linear move systems, or portable traveling units will be more appropriate. Digitized soil maps and GPS guidance allow such systems to target water application for maximum benefit [Sadler *et al.*, 2005].

## 7. Ancillary Impacts of Increased Landscape Water Storage

### 7.1. Wildlife Habitat

[25] The upper Midwest underlies the principal migratory bird pathway in the western hemisphere, but the massive land drainage that has occurred over the past 150 years has significantly diminished the habitat required by many migratory species, and their populations have correspondingly declined [Fletcher and Koford, 2003]. Efforts to increase bird populations through habitat restoration have had mixed results, but evidence indicates that the most effective approach involves a landscape mix that contains both larger wetlands and small ponds [Naugle *et al.*, 2001]. This suggests that the wildlife benefits associated with increased landscape water storage will be best realized with coordinated watershed-level plans, rather than a patchwork of individual efforts.

### 7.2. Water Quality

[26] Nitrogen export from the farm fields of the Midwest to the Gulf of Mexico has been one of the most stubborn environmental problems of the past 50 years, leading some to conclude that it is an unavoidable consequence of large-scale corn and soybean production. This is partly due to logistical constraints that induce farmers to apply nitrogen long before the corn crop needs it, leaving it subject to leaching during snowmelt and early season rains. The expectation of these losses also compels farmers to apply more N than the crop actually needs. It is generally accepted that total fertilizer use can be reduced, with concomitant decreases in leaching loss, if fall application is avoided [Mitsch *et al.*, 2001], or if preplant applications are reduced and supplemented with later side-dressings at a rate determined by plant or soil sampling [Guillard *et al.*, 1999]. However, the window for such activity is narrow because the corn plant grows rapidly during the vegetative

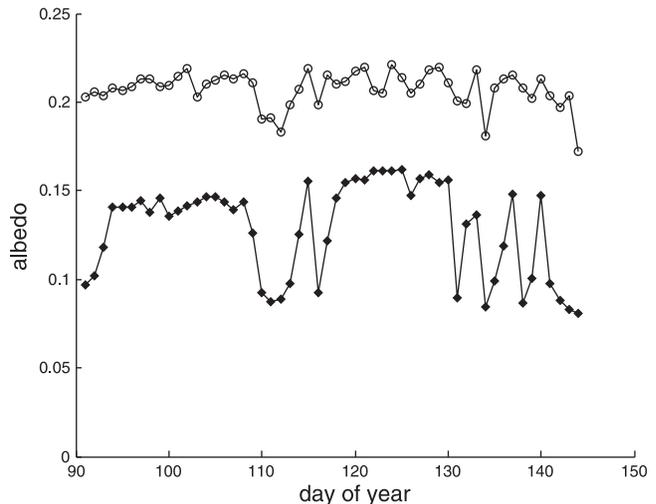
stage, soon making it difficult or impossible to apply fertilizer by conventional means, and it is crucial to avoid early season N stress in corn. A supplemental irrigation system can deliver N at virtually any point during the growing season, offering the potential to better match N availability to crop demand, a practice which has been shown to reduce N leaching [Schepers *et al.*, 1995].

[27] A second important point is that farmers do not usually factor in the expectation of yield-limiting drought in their nutrient plans—economics generally dictate an optimistic fertilization strategy to ensure that N is not the limiting factor. This means that if short-term drought limits crop growth at some point during the season, there will be diminished N uptake and more remaining in the profile at the end of the growing season, subject to leaching during the subsequent year [Morecroft, 2000; Justic *et al.*, 2003]. Randall and Vetsch [2005] observed that N losses in sub-surface drainage from the corn-soybean system were lower during a 6 year period with consistently high rainfall than during a previous period with alternately wet and dry years. Supplemental irrigation should substantially reduce inter-annual variability in both yield and N uptake, and this may reduce N leaching.

[28] Finally, there is evidence that N leaching is lower in living mulch systems [Ochsner *et al.*, 2010] because N fixation by the clover throughout the growing season allows lower pre-season application rates. Winter cover cropping can also reduce N leaching by taking up excess profile N during the fall and spring and releasing it gradually during the summer as the crop residue decays [Dabney *et al.*, 2001; Strock *et al.*, 2004]. Increased landscape water storage should also provide reductions in sediment loading by reducing peak flows, which are a primary source of sediment and phosphorus in the upper Mississippi basin via stream bank erosion [Thoma *et al.*, 2005]. Maintenance of surface vegetation with cover crops and companion crops has also been shown to lower sediment and P loading by reducing within-field sheet and rill erosion [Mutchler and McDowell, 1990; Kleinman *et al.*, 2005].

### 7.3. Albedo and Climate

[29] Albedo changes can have important climatic impacts. The most obvious are those associated with changes in snow or ice cover, but vegetation changes are important too; for instance, Betts [2000] estimated that the albedo effect of forest revegetation might be large enough to entirely negate its carbon sequestration benefits. Bare soils in the upper Midwestern U.S. generally have a lower reflectivity than cropped surfaces, the extent depending on soil organic matter, water content, and the presence of crop residue on the soil surface. A closed crop canopy typically has an albedo in the range of 0.24–0.27, while albedos of bare fields may range from 0.15–0.2 when dry to 0.07–0.1 when wet. Figure 4 shows albedo data from an experiment described by Baker and Griffis [2005] on two adjoining fields in MN with the same soil type, both with a summer soybean crop, where one is preceded by a winter rye cover crop. The cumulative difference in absorbed solar radiation in the two fields between 1 March and 1 June was  $127 \text{ MJ m}^{-2}$ , nearly 9% of the incoming irradiance during the period. The higher absorbed radiation in the bare field elevated the surface temperature, resulting in much higher sensible heating of passing air



**Figure 4.** Spring (April–May) albedo for two adjacent fields of the same soil type in southern MN, one with a winter rye cover crop (open circles), and the other a conventional (bare) field. Both had been in corn the previous year, and the conventional field had been tilled after harvest.

masses—a net difference of  $109 \text{ MJ m}^{-2}$  during the period, indicating that widespread adoption of cover cropping and companion cropping could actually have a mitigating influence in a warming climate. These measurements are supported by a recent modeling study which found that converting agricultural areas in the central U.S. to perennial crops would impart a significant local to regional cooling due to increased transpiration and higher albedo [Georgescu *et al.*, 2011].

### 7.4. Unanticipated Consequences

[30] As with any ecosystem modification, unanticipated consequences are likely. Perennialized cropping systems and increased hydrologic capacitance should, in principle, result in a more resilient landscape that is better equipped to respond to surprises, but there are no guarantees. It is possible that cover crops and companion crops may serve as alternative hosts for insect pests of corn and soybean; or perhaps the increased use of supplemental irrigation will promote new plant diseases, or remove a constraint that currently limits the expansion of some weed or insect pest; maybe wetland restoration will lead to a higher prevalence of mosquito-borne disease. There could also be unforeseen economic consequences. Currently, the primary use of cover crops or companion crops is in livestock production, so their biomass will only have direct monetary value if there are livestock producers in close proximity. Animal production has become concentrated in fewer, larger operations with increasing reliance on grain for feed in recent years, so there are areas where the local market for forage crops is limited. However, increased forage availability, coupled with the price volatility of corn grain and increased consumer demand for grass-fed beef, might induce a return to more broadly distributed animal production, which might bring environmental benefits of its own. Also, emerging technologies for cellulosic biofuel production may provide an alternative end use, in which cover and companion crops could either serve directly as an energy source or provide

the surface cover and soil C replenishment that would allow sustainable harvest of corn stover as a fuel [Baker and Griffis, 2009].

## 8. Implementation

### 8.1. Water Storage Siting

[31] Identification of optimal locations for ponds and constructed wetlands can be facilitated with high resolution elevation data from statewide LIDAR surveys [Liu and Wang, 2008] that have already been collected in several states within the region. In Minnesota a statewide inventory of restorable wetlands has recently been completed. An example of the output at the county level is shown in Figure 5, overlaid with a cropland database. The beige areas that cover virtually the entire map indicate corn and soybean fields, while the green areas denote potentially restorable wetlands, and the blue areas are existing water bodies. Maps of this sort could serve as a starting point for ground-based determinations of optimal locations, sizes, and types of new or renewed surface water bodies, and appropriate rerouting of ditches and subsurface drains. In areas such as these where artificial drainage is extensive, efforts to increase landscape storage must be designed so that they do not cause losses in productivity of nearby lands due to excessive water in the root zone—the goal is well-drained farm lands hydrologically connected by surface and subsurface flow to local wetlands and ponds that can be used when needed for supplemental irrigation.

[32] Storm water retention basins are another potential resource. They are already required in many areas when new development results in additional impervious surface, and their usage is likely to increase. At first glance this seems like an urban issue with little relevance to farming, but most development is occurring at the urban-rural interface, and it is not confined to major metropolitan areas. Bauer et al. [2008] reported decadal increases of impervious surface ranging from 28% to 78% in farming regions surrounding eight smaller Minnesota municipalities. The

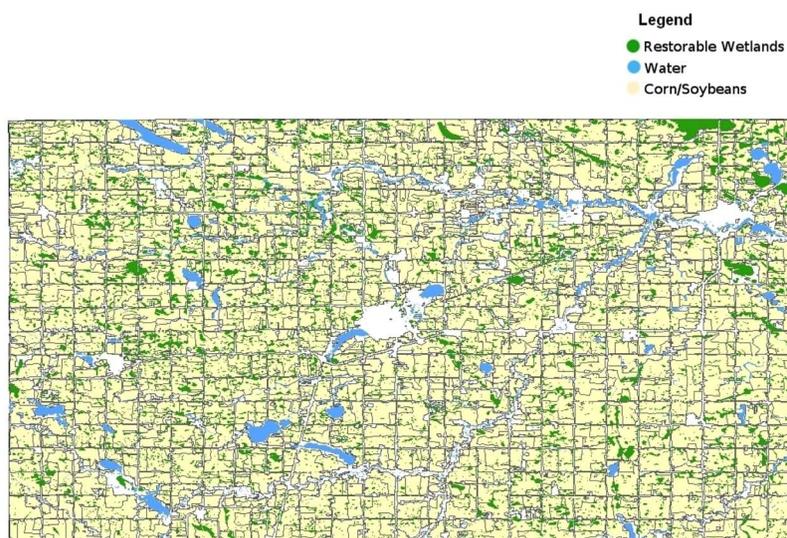
use of storm water basins for irrigation of agricultural crops has been explored with a model by Jaber and Shukla [2004], and is already being practiced by large dairies that are required to capture and store all rain water falling on their barns and surrounding paved areas.

[33] While initial analyses of regional precipitation and streamflow data indicate that there is plenty of water potentially available for supplemental irrigation, how much storage capacity would be needed to support it? Milly and Dunne [1994] found that a storage capacity of 400 mm would be nearly sufficient to damp fluctuations in energy and water supply, thus maximizing ET/P. The Mollisols and Alfisols that predominate in the Midwest U.S. have storage capacities in the range of 150–250 mm. This is consistent with the 168 mm cited above as the average irrigation amount in the region. If ponds and restored wetlands were on average 2 m deep and were viewed simply as reservoirs that are filled during times of excess and drained during times of need, then roughly 1 ha of ponds and wetlands would be needed for every 10 ha of cropland, a landscape modification that may prove impractically large. But it is important to think more broadly about storage capacity.

[34] If ponds and restored wetlands increase recharge to surficial aquifers to support sustainable pumping, their effective storage capacity may greatly exceed their volume. Recall as well that *effective* storage capacity, as it affects the ratio of annual transpiration to streamflow, can be boosted by cropping systems with deeper active root zones. Ultimately, the true potential of these proposed hydrologic and agronomic modifications must be further explored with numerical models that explicitly account for the local soils, topography, and hydrology of representative watersheds across the region.

### 8.2. Financial Considerations

[35] Supplemental irrigation capability can be viewed as a risk management tool [Dalton et al., 2004]. If practiced more widely it could exert a stabilizing influence on grain



**Figure 5.** Inventory of potentially restorable wetlands for a sample county in southern MN of 1140 km<sup>2</sup>, overlaid on a map of corn and soybean lands within the county. Beige indicates land planted in corn or soybeans in 2009, blue indicates water bodies, and green denotes potentially restorable wetlands. Blank areas are cities and towns.

prices while boosting mean annual yield. *Apland et al.* [1980] conducted a numerical analysis of supplemental irrigation in the Corn Belt that considered a broad range of potential economic scenarios and concluded that “even at high irrigation costs and low corn prices, irrigation technologies may be employed by the rational farm manager who is averse to risk.” However, they also pointed out that adoption as a risk aversion tool would be inhibited by price supports and other income-stabilizing policies, of which an obvious example is crop insurance. Crop insurance in the U.S. is heavily subsidized by taxpayers [Babcock, 2009], and when program costs are classified by commodity group, corn and soybean producers have ranked first and third in receipt of payments over the past 15 years. Since payouts scale according to negative deviations from long-term average yields, practices that reduce interannual yield variability should lower program costs. This suggests an avenue for implementation—cost-sharing on pond and wetland reconstruction and irrigation infrastructure as an alternative to subsidized crop insurance. Full exploration of financial considerations will require an integration of models for crop growth, hydrology, economics, and risk analysis. Some initial, site-specific efforts have been conducted that could provide templates for a broader spatial and temporal analysis, informed by accurate information about changes in climate [Apland et al., 1980; Arnold and Stockle, 1991; Ziari et al., 1995].

[36] There is already an alphabet soup of government programs designed to encourage land management practices that provide environmental benefits. These include CRP, CSP, WHIP, EQIP, and WRP (Conservation Reserve Program, Conservation Stewardship Program, Wildlife Habitat Incentive Program, Environmental Quality Incentives Program, and Wetlands Reserve Program). Unfortunately, in some cases program guidelines may restrict their applicability. For instance, wetland restoration projects often qualify for cost-sharing assistance, but use of the water for supplemental irrigation is prohibited. A change in those regulations to permit water withdrawals for environmentally beneficial cropping practices would likely encourage further restoration.

## 9. Conclusions

[37] Nearly 30 years ago, *Tanner and Sinclair* [1983, p. 24] wrote the following:

[38] “*Water resources in the subhumid and arid regions are limited. In humid regions, water resources are available and irrigation often produces yield increases. If we are to increase national food production, the greatest increase per investment is likely to derive where productivity is already high but limited by management rather than resource. It seems reasonable to suggest that should national policy really be concerned with increasing food production, instead of devoting major federal monies to support agricultural water management in arid regions where water resources are limited, we might best make expenditures to learn how to manage water well in the humid regions where there is water.*”

[39] This point is no less valid today than when it was written. In echoing it we make the additional point that if it is done right, supplemental irrigation can not only increase

and stabilize food production, but also improve environmental stewardship in the U.S. Midwest, if it is coupled with practices that perennialize the landscape and restore its ability to retain water during times of excess precipitation. The potential growing season is long enough to support the addition of cover crops and permanent living mulches, and mean annual precipitation is sufficient to provide the necessary supplemental water. The ecosystem services associated with permanent or nearly permanent cover are well known; the benefits of revived landscape water storage capacity may be equally or more important.

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