Hydrologic impacts of an alternative agricultural land use: a woody perennial polyculture

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Problem and Research Objective

Conversion of the Midwestern U.S. from native vegetation to intensive row crop agriculture dominated by the corn-soybean rotation has severely altered the region's hydrologic cycle. The physiological and physical properties of the vegetation, along with soil moisture properties, affect the weather and climate by altering the transfer of energy and water from the land surface to the atmosphere. The once-dominant matrix of oak savanna contained a diverse mix of perennial plants, which had very different physiological and physical properties than the now-dominant monocultures of annual crops. This conversion has reduced leaf and stem area, increased stomatal conductance, shortened the growing season, decreased rooting depth, and reduced surface roughness.

Restoring the hydrologic cycle of the region, along with other valuable ecosystem services, has important implications for climate change adaptation and mitigation, water quality, and agricultural production. While complete reversion to native ecosystems would likely eventually restore the Midwest's natural hydrologic cycle and other ecosystem services, this option is clearly not viable given the growing population's ever-increasing need for calories (of both food and fuel). Here, we propose an alternative land-use option for the U.S. Midwest that maintains current economic and agricultural capacity while substantially altering hydrologic and ecological processes. This system is a woody, perennial polyculture (WPP) that has the macrostructure and function of a Midwestern oak savanna, the once-dominant ecosystem of the region, but has the composition and management of a modern agricultural system.

The woody and perennial growth habit, extended growing season, low-chemical requirements, heterogeneous structure, and diverse composition give the WPP the potential to ameliorate the hydrologic and environmental impacts described above. While profitable, large-scale examples of this type are already in place on once-degraded farmland across the Midwestern U.S., there has been no direct comparison of the hydrologic impacts of a WPP to the corn-soybean rotation. Our project studies the potential of a WPP to alter the hydrologic cycle in a side-by-side comparison to a corn-soybean rotation (CSR).

Methodology

This project utilizes a research site established in the spring of 2012 at the University of Illinois at Urbana-Champaign. The site consists of four replicates each of WPP and CSR arranged in a randomized complete block design. Site land 2use history has been conventional Illinois agriculture for over 100 years, allowing an ideal comparison for modeling conversions statewide. The site's 3,200 woody plants include 6 species: chestnut, hazelnut, apple, grape, raspberry, and currant.

A robust combination of technologically advanced field measurements and state-of-the-art modeling techniques are being used to test this project's hypotheses by comparing the hydrologic cycle of a WPP to CSR. High-frequency soil moisture measurements (every three days), continuous precipitation monitoring, and measurements of plant stomatal responses combine to provide a complete picture of the major water fluxes and pools. The surface water runoff and infiltration measurements described in the original proposal were abandoned due to the relatively flat slope of the research site and negligible preexisting overland flow. Focus, instead, has been on capturing heterogeneity with the soil moisture measurements and discerning species-specific influences on evapotranspiration (ET).

Data coming in from the field is used to parameterize and validate temporal and spatial modeling of hydrologic processes using the DayCENT biogeochemical model. Integration of modeling was delayed due to delayed receipt of funds, but ongoing work continues to refine the modeling work.

Principal Findings and Significance

Our principal findings around the hydrology of WPP systems can be grouped into three general categories: magnitude, seasonality, and heterogeneity.

Magnitude

- During the second and third years after establishment, the WPP system generated approximately the same soil moisture and daily ET as the CSR system during the growing season (Figure 1, top and middle panels). At first glance, therefore, there seems to be very little difference between these two systems. When scaling evapotranspiration by yield, however, a metric known as water-use-efficiency (WUE), the corn/soy system really emerges as the winner. With practically no yield in the first few years, since the crops are not yet at maturity, the WUE of the WPP system is an order of magnitude lower than the CSR. Yield-weighting key environmental metrics in this way is crucial to understanding the trajectory of long-lived systems through time.
- Despite similar growing season ET magnitudes so far, extrapolation of these early results using growth data from the tree species at the site suggest that the WPP system will quickly cross the tipping point and surpass mean CSR ET in the next few years. Once the student point is reached, the WPP growing season ET will continue to increase until plant maturity is reached around 30 years after planting. While this growth in both biomass and annual ET is exponential right now, the overall curve is sigmoidal, as growth will begin to slow as maturity is reached. Eventually, daily ET may drop once again as species begin to decline or until management and mortality replacement by the farmer ceases.

Seasonality

- The most dramatic difference in hydrology between the WPP and CSR systems is the seasonality of both soil moisture and ET. The growing seasons of both corn and soybean are several months shorter than the average growing season of species in the WPP system. Therefore, ET is significantly higher and soil moisture is consequently significantly lower in the WPP system during the spring and fall months (Figure 1, bottom panel). The cumulative result for net annual ET was then much greater for the WPP system in both years. Even though growing season daily ET was about the same between both systems (as described above) the dramatic seasonal differences in the spring and fall really cause the systems to diverge.
- Even within the WPP system itself, seasonality plays a large role. They alleys of hay between rows of woody plants in the WPP system contribute much more to the system's water use in the early spring and fall, with the woody plants dominating at

mid-summer. Understanding the temporal contribution of the different WPP system components to evapotranspiration can provide insight into designing optimal systems with broader seasons of activity and higher productivity.

Heterogeneity

- Even in just the first few years of growth, the two different row-types that make up the WPP system at this research site had dramatically different rates of ET, with rows containing the fast-growing bramble species transpiring much more than rows containing currants and long-lived nut trees. Analyses of different row compositions like this can provide insight into designing optimal systems with specific hydrological goals. The brambles may grow quickly and have a large impact on ET now, but the long-lived tree species dominate in models of the long run.
- Part way through this study, the first ever round of pruning was performed in the WPP system. This pruning round completely coppiced the brambles (raspberries) to the ground and significantly reduced stem biomass in both currants and the apples. While it was clear that pruning has a very significant affect on the balance of ET sources within the WPP system, the overall affect was quite small. Since pruning goals, methods, and timing can vary dramatically among farmers implementing these systems, it will be important to further analyze the effect that pruning and coppicing can have on intra- and inter-annual hydrologic variability.

Students on the Project

Kevin Wolz, the main student working on the project, is a PhD student under Professor Evan DeLucia in the Program for Ecology, Evolution, and Conservation Biology at the University of Illinois at Urbana-Champaign. Kevin's work focuses on the environmental and ecological impacts of transitioning conventional annual cropland into diverse agroforestry systems in the Midwest. Kevin has spearheaded both the field measurement and modeling portions of the project. The work completed as part of this project will be a key component of his PhD dissertation, which he intends to complete in 2017.

Adam Kranz, an M.S. student under Professor Jim Miller in Department of Natural Resources Environmental Sciences, also helped during the summer months to aid in field data collection. Prior to this project, Adam was not sure of his true research interests, and working on this project helped focus his interests on the large-scale environmental impacts of diverse agroforestry systems.

Publications and Broader Impacts

Kevin Wolz presented a poster that primarily focused on results from this study at the 99th Annual Conference of the Ecological Society of America in August 2014 in Sacramento, California. The poster was well received and stimulated much discussion among the agroforestry section of the conference. Kevin intends to complete modeling portion of the study and submit a combined field measurement-modeling publication in the fall of 2015. This publication will also be incorporated as a chapter in his PhD dissertation.

One of the most important outcomes of this study is that it has been essential in directing experimental design and hypothesis creation for a new research site being developed at the University of Illinois. The Woody Perennial Polyculture Research Site, at which of this study was carried out, was the first site of its kind. The results from this study, as well as others, at that site helped the research group secure funding for a new research site that is over 10 times the size and will be able to answer much deeper questions on hydrology, water quality, and other key environmental metrics of diverse agroforestry systems in the Midwest. Without the results and key methodological insights from this study, the design and hypotheses of the new research site would not be well guided. Furthermore, the methodologies utilized and honed during this project will likely be adopted and expanded by the new research site. The data collected at the Woody Perennial Polyculture Research Site will serve as an indispensible reference and source of validation data as the new site moves forward.

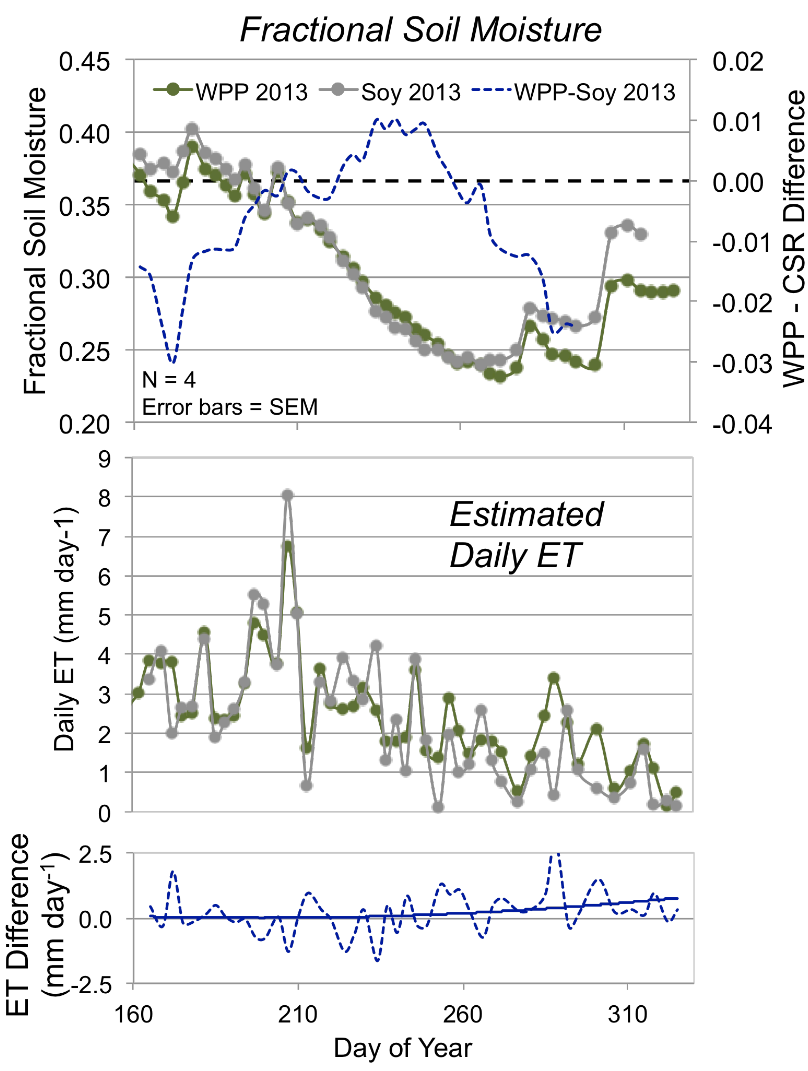

Figure 1. Treatment averages of fractional soil moisture (top panel), estimated daily evapotranspiration (middle panel), and daily evapotranspiration difference (bottom panel) at the Woody Perennial Polyculture Research Site. Only 2013 data are shown for simplicity.