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DEVELOPMENT OF CONTINUOUS LIVING COVER BREEDING PROGRAMMES TO ENHANCE AGRICULTURE'S CONTRIBUTION TO ECOSYSTEM SERVICES

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ABSTRACT

Over the last half century, 'Green Revolution' technologies have dramatically enhanced crop yields, but because of the emphasis on annual row cropping systems these increases have often come at the expense of food security and sustainability. Globally, many fear that agriculture is nearing a tipping point, with concerns that population pressure, declining natural capital, and diminished ecosystem service delivery will reduce global food security. As a result, a new Green Revolution is needed – a ‘Forever Green Revolution’ – that embraces continuous living cover on working lands through the development of a new suite of high yielding perennial (intermediate wheatgrass, sunflower, hazelnuts) and winter annual (pennycress, winter rye, winter barley) crops that provide economic return and improve multiple ecosystem services. By adding such crops to agricultural systems we can: enhance agricultural productivity, support rural economic development, and provide major environmental benefits to all citizens. Because these systems have longer growing seasons, they are able to capture more solar energy, water, and nutrients than purely annual systems and may be able raise crop yields, produce new high-value commodities (food, feed, and biomaterials), enhance soil quality, provide wildlife habitat, increase species biodiversity, and improve water resources. Additionally, agricultural systems that include perennial and winter annual crops may show greater resilience to climate change, as well as to weed, disease, and insect pressures. To accomplish a ‘Forever Green’ landscape, we propose three significant shifts in thinking: 1) focus public plant breeding programmes on development of crops that provide continuous living cover and high-value commodities 2) diversify and enhance agricultural stakeholder engagement in sustainable enterprise development, and 3) re-evaluation of concepts of production and efficiency in agricultural systems.

Keywords: agro-ecosystem, economic valuation, ecosystem service, RUSLE, tradeoff analysis yield

INTRODUCTION

Over the past half century, Green Revolution technologies have dramatically enhanced crop yields (Baulcombe *et al.* 2009) while simultaneously reducing other ecosystem service outputs (Tilman *et al.* 2002). Globally, many fear we are nearing a tipping point (Garnett *et al.* 2013), and that given increased population pressure (Foley *et al.* 2011; Runge *et al.* 2003), declining natural capital (Jordan *et al.* 2007), and overall diminished ecosystem service delivery (Tilman *et al.* 2011) a new green revolution is needed – a “Forever Green Revolution” – that embraces continuous living cover on working lands through a new suite of perennial grain and biomass crops, and winter annual crops. Conceptually, this is related to the concept of evergreen agriculture that has been discussed as a way to improve food security across the world (Garrity *et al.* 2010). These crops must not only enhance profit for landowners, commodity groups, and agribusiness, but also ecosystem services for society. We propose that a sustained focus on developing continuous living cover is an essential avenue for sustainable intensification of agriculture (Garnett *et al.* 2013).

The potential benefits of continuous living cover have long been touted (Teasdale *et al.* 2007, Scheinost *et al.* 2001): decreased autumn tillage during the multi-year lifetime of a crop stand, leading to reduced input costs and soil erosion; reduced herbicides from spring weed suppression; increased habitat for beneficial insects (pollinators and predators), providing a biological control that reduces inputs and increases pollination services; decreased surface and subsurface water pollution. However, despite these benefits, relatively little has been done to include these crops in rotations or improve them. Nationally, perennial grains and winter-cover crops constitute less than 7 percent of all cropland (Wallander, 2013) in the United States. This is likely due to the limitations of current plant material to improve environmental quality and simultaneously increase economic viability of agricultural operations. However, it is possible to breed with multiple benefits in mind – benefits not only including high yield, but also increased ecosystem service delivery. The starting and ending point of sustainable intensification is land management, which primarily focuses on the questions, "What plant material is available?" and "Where should plant material be placed on the landscape?" To implement continuous living cover in current temperate-zone agro-ecosystems, there are two major options: winter-hardy annuals, and perennial grain and biomass crops.

Historically, winter-annual crops have provided multiple values to landowners not just as a winter cover, but also as livestock feed. Today, the increased segregation of animal and plant agricultures (Godfray *et al.* 2010) and the shift in animal rations toward maize and soybean derivatives, has meant that winter and cover crops are no longer as relevant to producers. Forage legumes and grasses are still important parts of the landscape, but they are disappearing due to this increased separation between animal and crop agriculture. While current winter annual cover crops such as winter rye (*Secale cereale* L.) can mitigate the off-site nutrient transport, soil erosion, and loss of soil organic matter that occurs under a maize (*Zea mays* L.) and soybean (*Glycine max* L.) rotation without jeopardizing landowners' livelihoods (Creamer *et al.* 1996; Strock *et al.* 2004; Kaspar *et al.* 2012), they offer little other value to farmers. Additionally, farmers commonly find current cover crop options difficult to establish and terminate without increasing risk to the subsequent cash crop (Leavitt *et al.* 2011). These concerns largely explain the small area devoted to cover crops in the United States. In response to cover crops' lack of economic viability, new winter annuals are being evaluated and developed, such as pennycress (*Thlaspi arvense*) and camelina (*Camelina sativa*). Both produce valuable oilseed in addition to their other ecological benefits (Phippen and Phippen, 2012).

The second form of continuous living cover is perennial grains and other herbaceous perennial crops, including high-yielding biomass crops. Perennial grains are less well-developed than other perennial crops; initial attempts to produce a perennial grain have been met with mixed results, with yields ranging from 10-70 percent of annual check cultivars (Scheinost *et al.* 2001; Sacks *et al.* 2003; Sacks *et al.* 2006). These mixed results have led some to question whether it is possible to breed a high-yielding perennial grain. This debate centres on whether it is physiologically possible for a plant to allocate resources to both sexual and asexual production in a way that would allow for yields comparable to sexual grains. Additionally, it has been argued that high yielding perennial grains do not occur in nature, have not already been domesticated, and therefore, are likely impossible to develop.

Counter to this, perennial plants introduced to novel environments where consumers are absent can experience rapid evolutionary change and allocation of resources to increased seed and biomass production (Evolution of Increased Competitive Ability Hypothesis) (Bossdorf *et al.* 2005). Further, Cox *et al.* (2002) and DeHaan *et al.* (2005) developed a framework suggesting that because of a longer growing season, perennial grains could capture more sunlight resources resulting in greater total biomass, which could be allocated to seed production. Indeed, many of the arguments against high-yielding perennial grains have drawn information from what is possible or observed in natural systems. But, in the novel environment of an agricultural system, it may be possible to develop new life strategies by changing the selective constraints the plants experience. For instance, insect herbivory, soil nutrients, water availability, and the degree of group selection all can be varied in an agricultural system. Barnes *et al.* (2013) explored some of these possibilities by developing a physiologic model of plant resource allocation that showed perennial seed production equaled or surpassed that of annuals under certain conditions, implying that high-yielding perennial grains may be bred for in the real world, and may offer a competitive alternative to annuals. Additionally, Bell *et al.* (2008) has shown that, under certain conditions, even if a perennial grain crop produces 30 percent less yield than an annual system, decreased input costs can make up the difference in profit, even as the perennial crop provides additional ecosystem services.

Major questions remain regarding perennial grains such as how they will respond to domestication. Will perennial grains transition similarly as annual crops and undergo "domestication syndrome" (the development of a series of traits related to domestication, which have been altered in a similar way in many species across many taxa) (Harlan, 1992; Vaughn *et al.* 2007; Weeden, 2007)? Even more uncertain is whether the annual domestication syndrome phenotype is the ideal phenotype (ideotype) for a perennial grain domesticate. For example, does the ideotype of the perennial *Helianthus* seed crop have a single inflorescence or multiple inflorescences that flower simultaneously (Kantar *et al.* 2014)? The above findings and questions simultaneously reinforce the need for continued research investment in perennial grains and provide cautious hope surrounding their potential success.

In order to rapidly develop continuous living cover as a strategy for sustainable intensification of temperate-zone agro-ecosystems, we call for interrelated paradigm shifts in two areas – plant breeding and stakeholder engagement. In essence, we argue that breeding must be situated in an integrative and systemic approach to sustainable intensification. Below, we describe a new approach to development of plant germplasm for sustainable intensification of agriculture. We term this approach the '*Reflective Plant Breeding Paradigm*' and we are developing it in the context of an ongoing research and development programme for continuous living cover and sustainable intensification at the University of Minnesota.

THE FOREVER GREEN INITIATIVE

The Forever Green initiative lays out a cohesive vision for how to accomplish "sustainable intensification" of the Upper Midwest agro-ecosystem. The initiative grew out of Minnesota's history with cover crops and perennial grains as well as the obligation of a Land Grant University to engage with multiple stakeholders: farmers and their advisors, agricultural industry, and the general public. Realizing this obligation resulted in the merging of traditional plant breeding focused on farmer needs with a diverse array of disciplines (Table 1). We are approaching this task from the ideological point of view that germplasm must be developed to create both economically and ecologically profitable crops. The initiative involves more than 15 disciplines ranging from ecology and agronomy to plant breeding and food science to economics and sociology, all focused on two interconnected questions: 1) What plant material? and 2) Where is the material best placed on the landscape? These two questions form two continuous, synergistic feedback loops where enterprise development and stakeholder engagement interact with the plant breeding process in the Reflective Plant Breeding Paradigm (Figure 1). The Reflective Plant Breeding Paradigm includes robust engagement of many different disciplines in order to define the agro-ecological performance of germplasm, and define the trade-offs and synergies that are present as part of the germplasm being tested under different enterprise development scenarios (Figure 1). The 'Forever Green' initiative is an attempt to empirically develop crops that when strategically placed on the landscape will fit new ecological niches and provide environmental services while simultaneously providing economic benefits through a commercial product. In essence, it is an empirical attempt to test "sustainable intensification". Specifically, the 'Forever Green' initiative is examining a wide range of crops including winter-annuals, short-rotation woody species, perennial grains, and perennial plants for natural products (individual projects are outlined in Table 1).

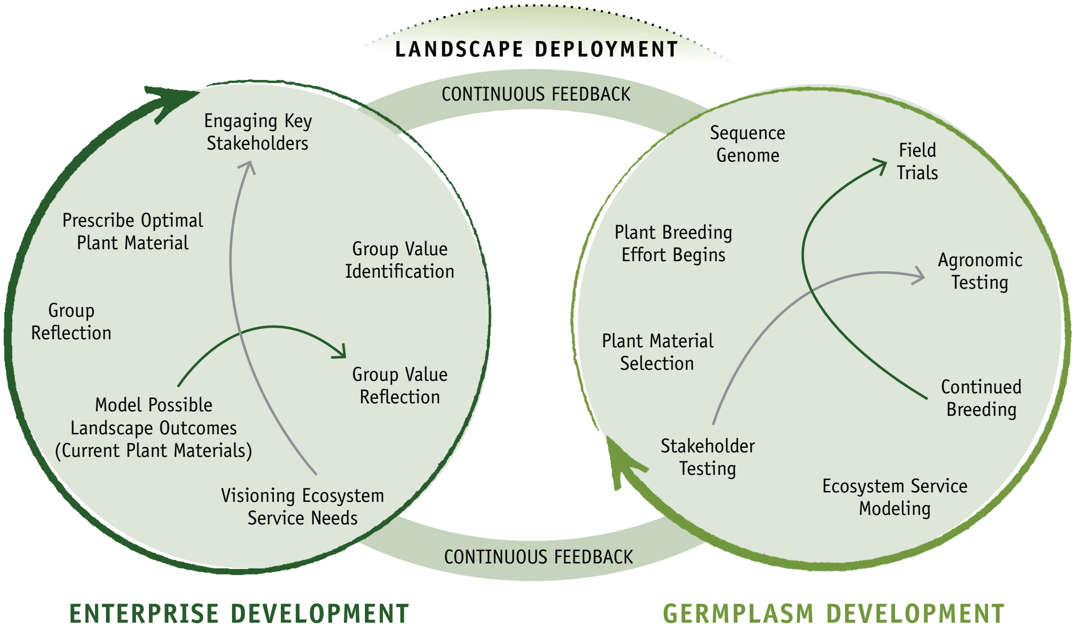
TABLE 1. BRIEF DESCRIPTION OF SOME OF THE CROPS THAT THE UNIVERSITY OF MINNESOTA IS WORKING ON TO INCREASE YEAR-ROUND GROUND COVER

CROP	DESCRIPTION OF PROGRAM	UNIVERSITY OF MINNESOTA DEPARTMENTS INVOLVED
INTERMEDIATE WHEATGRASS	A perennial grass crop that can produce many different high-value products, providing economic opportunities that in turn support the environmental benefits that perennials provide. It produces large yields of seeds that are a high-quality substitute for wheat, while its dense root system and rapid regrowth after harvest build soil carbon, store water for later use, and prevent soil erosion. It can also be harvested for hay or biofuel and is highly tolerant of weather extremes, including droughts and intense storms.	Agronomy and Plant Genetics Applied Economics Soil, Water, and Climate Ecology, Evolution, and Behaviour Food Science and Nutrition Plant Pathology Public Policy

CROP	DESCRIPTION OF PROGRAM	UNIVERSITY OF MINNESOTA DEPARTMENTS INVOLVED
FIELD PENNYCRESS	A new winter-annual cover crop for corn/soybean farmers. It is planted after harvest of maize or soybean and resumes growth in early spring after winter dormancy. It provides crucial protection for soil during autumn, winter and spring, and produces high-value oil and protein meal from unused fertilizer and water that would otherwise be wasted. As well, pennycress suppresses weed growth, reducing herbicide costs, and supports honeybees and other endangered pollinators.	Agronomy and Plant Genetics Applied Economics Soil, Water, and Climate Ecology, Evolution, and Behaviour Plant Biology Plant Pathology Bioproducts and Biosystems Engineering Animal Science
WINTER MALTING BARLEY	A potentially high value cover crop that could be double cropped with soybeans. Current winter barley varieties do not consistently survive winters in northern climates.	Agronomy and Plant Genetics Animal Science Plant Pathology
WINTER CEREAL RYE	A winter-annual cover crop that has been shown to provide many environmental services without impacting the soybean yields in a corn/rye/soybean rotation.	Agronomy and Plant Genetics
PERENNIAL FLAXSEED	An excellent source of omega-3 fatty acids, whose value as a dietary supplement is widely recognized, while offering the soil protection, habitat, and resource-use benefits of perennial crops. An emerging natural products industry is interested in sourcing key ingredients for many products from native and sustainably-grown crops.	Agronomy and Plant Genetics
PERENNIAL SUNFLOWER	An emerging perennial crop that can produce food oils that are highly valuable because they are free of trans fats, while also providing all of the benefits of perennial crops, including use of otherwise-wasted resources, soil protection, reduced costs, and better tolerance of droughts and floods, which are predicted to become more common in coming years.	Agronomy and Plant Genetics Ecology, Evolution, and Behaviour Horticulture Law School Entomology American Indian Studies
HAZELNUTS	A new food and energy crop. Hybrids between native and European hazelnuts combine beneficial qualities of each. As a long-lived shrub, hazelnuts can fit profitably into many niches in the agricultural landscape. For example, farmers could gain significant revenue from hazelnuts grown as windbreaks, shelterbelts, and living snow fences. In addition to valuable nuts, mature hazelnuts can produce large yields of edible, heart-healthy oils or biofuel oils.	Agronomy and Plant Genetics Horticulture Plant Biology Forestry
WILLOWS	A rapidly growing woody perennial crop. As a small tree, this crop can provide many options for improving the habitat value of Minnesota landscapes, while providing all of the advantages of perennial crops and providing new bio-products, including sustainably produced construction materials and bioenergy. Grown and harvested on a three-to-five-year cycle, willows can bring substantial revenue streams to farms that can support the environmental benefits that they provide.	Agronomy and Plant Genetics Horticulture Plant Biology Forestry
ALDERS	Woody trees and shrubs with the capacity to be grown on sites that cannot support traditional row-crop agriculture. Due to the symbiotic relationship alders form with the nitrogen-fixing bacterium Frankiia alni, the trees can be gown on low-nutrient soils without the need for additional nitrogen inputs. The species naturally occur on wet margins and saturated soils, areas that are not typically farmed. As such, alders represent a potential bioenergy crop that will not compete with food crops for growing space on the landscape.	Agronomy and Plant Genetics Horticulture Plant Biology Forestry
KURA CLOVER	A crop with unique application in soil conservation and as a living mulch crop. We propose to promote use of Kura clover as a living but suppressed perennial sod into which maize or other grain crops are planted into strips killed with an herbicide. When the crop is harvested, Kura clover, which has underground- spreading rhizomes, can regrow into the space where the maize was grown. The Kura clover can then be grazed in the late autumn and following year.	Agronomy and Plant Genetics Horticulture Plant Biology Soil, Water, and Climate
NATIVE PERENNIAL SPECIES	Native species across the Upper Mississippi River Basin have been examined for antimicrobial, antifungal, and antioxidant activity. Promising species have been examined and selected for larger-scale production.	Agronomy and Plant Genetics Horticulture Plant Biology Law School American Indian Studies

FIGURE 1. SHOWS SYNERGISTIC RELATIONSHIP AMONG STAKEHOLDER ENGAGEMENT, BREEDING, AGRONOMICS, AND MODELING THAT ARE A PART OF THE FOREVER GREEN INITIATIVE'S ATTEMPT TO DEVELOP A REFLECTIVE PLANT-BREEDING PARADIGM

The illustration shows Enterprise Development focusing on stakeholder engagement on the left, and research goals focusing on Germplasm Development on the right, with a permeable membrane connecting the programmes. Lines within each programme indicate an example of feedback relationships among the various parts; in theory all nodes are interconnected. The Reflective Plant-Breeding Paradigm is built upon the traditional plant-breeding paradigm, which is primarily focused on enhancing crop yield and disease resistance. The new paradigm attempts to bring the traditional strengths of plant breeding into contact with other disciplines such as ecology and public policy in order to effectively identify and select plant material and characteristics that will maintain yield and simultaneously provide the greatest number of other environmental services that are required for a truly sustainable system. The University of Minnesota's programme incorporates perspectives from 15 different disciplines to more effectively address the challenges of new crop and enterprise development, while acknowledging that plant material will only be adopted across the landscape if it is economically profitable. The integrative approach helps identify the appropriate plant material, landscape position, and end use for a plethora of plant material.



The Forever Green initiative is engaging with enterprise development and stakeholders as part of the plant breeding process to answer the "what" and "where" from communities' perspectives. Research in social learning shows that often people react in unexpected ways to newly developed scenarios depending on their perspective (Johnson *et al.* 2012). By including the public in discussions through social learning processes, there is a greater sense of ownership where potential social and scientific solutions can be more easily understood and imagined

(Johnson *et al.* 2012). Recent calls for more system-based approaches (Power, 2010) require that the public perception of new technologies be included in any assessment of their potential use. Specifically, landowners need to be shown the direct benefits of new plant materials for any changes in management practices to occur. Ultimately, short of heavy-handed legislation, landowners will be the ones to implement land cover change, so it is critical to include their input and values in the design of new plant material. In addition, it is essential that the process be transparent, equitable, and inclusive of all stakeholders in land management.

Many landowners perceive that one or more high-yielding crops mean the most profits. Our goal is to change that perception to one that is more holistic, so that landowners are concerned with net economic output (including ecosystem services) per hectare over time. This could incentivize double cropping and justify the potential yield reduction of one crop in favour of new practices that could increase the overall profitability of and reduce the risk to the agricultural system. This would require a dramatic culture shift among farm communities. As Warner (2007) stated, “the greatest obstacle to ecologically informed alternative practices has not been a shortage of ideas; it has been the dearth of practical educational initiatives.” The process would need to be conducted iteratively over a long period of time to allow social learning to take place (Dana and Nelson, 2012).

Accordingly, a pivotal feature of the Reflective Plant Breeding Paradigm is the developing concept of ‘*Landlabs*’ (Jordan *et al.* 2013). These are place-based, coordinated efforts to design and implement new agricultural enterprises that meet high performance standards in economic, environmental and social terms. Landlabs engage a wide range of local and regional stakeholders and innovators. The goal is to engage these actors to develop and coordinate novel land-use configurations, supply chains, and policies necessary for the emergence of new sustainable enterprises. In essence, Landlabs serve as active “incubators” for coordinating technological, economic and policy innovations in enterprise development, and thereby reduce the economic and environmental risks and uncertainties faced by farmers, entrepreneurs, and public and private investors. Thus, Landlabs provide a social and institutional context for the coupling of germplasm and enterprise development (Figure 1) that is essential to the Reflective Plant-breeding Paradigm.

Simultaneously, multiple academic disciplines are working together to respond to the findings in the Landlabs to further refine the genetic resources required by the public. This is being done through an iterative process of breeding and then modelling landscape scale performance. These findings are being provided on an ongoing basis in Landlabs to inform the innovation needed for sustainable enterprise development (Jordan *et al.* 2013). Ideally, the Reflective Plant Breeding Paradigm will engage stakeholders by identifying new plant material that fits changing values and production needs. Farmers will then play an integral role in testing new material and providing feedback to make sure that the shifting target of “sustainable intensification” is met without compromising the values of people or the researchers. The process involves iterative stages allowing for simultaneous enterprise and germplasm development (Figure 1). Incorporating a process of value identification and testing into germplasm development may facilitate adoption once the material is developed (Jordan *et al.* 2011).

New production systems that combine summer annual crops, winter annual crops, and perennials can optimize use of limited land, water, and nutrient resources more efficiently than current systems do. For this reason, we call these systems high-efficiency agriculture. These systems are arguably the most promising vehicle by which we can rapidly and sustainably intensify agriculture and enhance its ability to withstand climate variability. In a spirit similar to that of the Reflective Plant-Breeding Paradigm, two areas need further research and development to realize the great potential of these high-efficiency systems: 1) genetic improvement of plant materials, and 2) development of new strategies to integrate perennial crops into the landscape in ways that provide environmental benefits and economic opportunities. Current work at the University of Minnesota on high-efficiency agriculture systems—as part of the Forever Green initiative—focuses on a portfolio of highly promising options for improving Minnesota agriculture's productivity, efficiency, and adaptability to variable climates (Table 1). Although each individual programme has its own unique challenges, all are being evaluated based on the Reflective Plant-Breeding Paradigm (Figure 1). The Forever Green initiative represents an empirical attempt to put into practice the theory of sustainable intensification whereby systems are created that can successfully increase ecosystem service delivery and economic profitability.

ANALYSIS OF TRADEOFFS AND SYNERGIES AS THE LENS OF SUSTAINABLE INTENSIFICATION

While the Reflective Plant-Breeding Paradigm encompasses both enterprise and germplasm development, germplasm development and landscape deployment are both explicitly and implicitly involved in economic and ecological tradeoffs and synergies. Analysis of tradeoffs at the plant and landscape scale frames the process of enquiry in terms of what is biophysically and politically possible. At the plant scale, we are actively working to explain and model the tradeoffs between length of life and annual seed production. Theoretically, it is possible for a perennial to be high yielding (Barnes *et al.* 2013), however several potential constraints merit further consideration. In *Helianthus*, for example, the advancement of yield is being weighed against with other essential agronomic characteristics such as synchronous flowering time and shattering. In intermediate wheatgrass, the interaction between nutrient treatments and baking quality and post-harvest processing is being examined. In pennycress, the interaction between yield of the cover and yield of the subsequent soybean crop is being investigated. Emerging results suggest that old and new breeding techniques can either entirely overcome the initial tradeoffs or significantly mitigate their severity in many cases.

Implementation of perennial crops at the landscape scale suggests several areas where synergies or tradeoffs occur among ecosystem services. Four major ecosystem services – sediment retention, carbon sequestration, pollinator services, and biological control – are examined qualitatively below. First, it has long been observed that an increased reliance on the corn-soybean rotation has led to increased sediment and nutrient loss with small critical landscape positions contributing disproportionally more sediment and phosphorous to waterways (Galzki *et al.* 2011). However, implementing current best management practices, which do not target landscape positions for conservation practices, would lead to only incremental reductions in nutrient export (Vache *et al.* 2002). Identifying fine scale differences in terrain could allow for better temporal and landscape position of management practices to ensure maximum conservation benefits (Galzki *et al.* 2011). Further, nutrient and sediment loadings in waterways can have significant adverse effects on humans and ecosystems (Jones *et al.* 2001). Strategic development and landscape placement of new perennial plant material could lead to disproportionately large reductions in sedimentation at the watershed scale (Parish *et al.* 2012) while producing economically competitive yields, an example of synergism among ecosystem services and agricultural productivity.

Second, increasing soil carbon is an important ecosystem service to mitigate climate change and can be accomplished by land use changes (Powlson *et al.* 2011). Recently it has been shown that reductions in carbon emissions from reduced tillage are not as large as previously thought (Luo *et al.* 2010; Mishra *et al.* 2010), however the reductions from changing annual vegetation to perennial vegetation still have the potential to decrease atmospheric CO_2 (Collins *et al.* 2010). Therefore, perennial crops can potentially increase the amount of carbon that is sequestered in stable forms in agricultural soils.

Third, another significant benefit of continuous living cover cropping systems is their potential to attract and support beneficial insects for pollination and biological control. For example, there is widespread evidence showing that diversification of cropping systems enhances biological control of insect pests (Letourneau *et al.* 2011). Provisioning resources, such as floral nectar and pollen, in a diversified planting can attract and enhance predator populations leading to greater biological control (Hogg *et al.* 2011). Particular perennial plants and plant breeding programmes have the potential to contribute germplasm that enhances biological control. For example, *Helianthus* species are known for producing extra-floral nectaries, a nectar source excreted primarily from the petioles. Such nectar can provide an early pre-flowering, alternative resource for such beneficial predators as coccinellid beetles, which are shown to perform equally on sugar versus prey-only diets (Lundgren, 2009). Further, sunflowers have been shown to increase the density of these beetles in adjacent annual crops (Jones and Gillett, 2005). Given the importance of coccinellids as a beneficial predator (Gardiner *et al.* 2009), there is potential for strategic integration of perennial sunflowers to enhance biological control. This further illustrates the value of breeding for multiple benefits including nectar production for biological control while producing seed for oil production.

There are many and varied perspectives on what is considered highly productive. Productivity is intertwined with cultural values and, in practice, incorporation of values is accomplished through stakeholder engagement. Tradeoffs and synergies between ecosystem service phenotypes and traditional phenotypes for breeding programmes provide new targets for plant breeders; these phenotypes are inherently based on a different scale than traditional measures of productivity. These considerations are necessary to define the set of ecosystem goods and services that are valued by stakeholders in any given situation, and to define goals for breeding in the context of developing new sustainable agricultural enterprises.

A CASE STUDY: WATONWAN COUNTY, MINNESOTA

To demonstrate how new plant material could potentially function in a highly productive region of the United States, we conducted a case study involving the fertile landscape of southern Minnesota. Specifically, our analysis of Watonwan County, Minnesota, illustrates the *Germplasm D*evelopment side of the Reflective Plant-Breeding Paradigm, where breeding, agronomic testing, and continued breeding feed into ecosystem service modelling (Figure 1).

Minnesota has 10.93 million hectares of farmland, occupying nearly half the 22.5 million hectares in the state. Two highly productive and profitable crops, maize (3.52 million hectares planted in Minnesota in 2012) and soybean (2.87 million hectares) are the foundation of the state's agriculture, together with other important production systems such as animal agriculture, small grains, and horticultural crops. Most of Minnesota's current cropping systems consist of summer annuals. Considering Minnesota's strong cropping system base and the in-development plant materials of pennycress and intermediate wheatgrass, we began to ask: How do current Minnesota agro-ecosystems compare with the native prairie ecosystem in terms of ecosystem service delivery? How will these new crops potentially alter the delivery of ecosystem services when compared with current cropping systems and the native prairie?

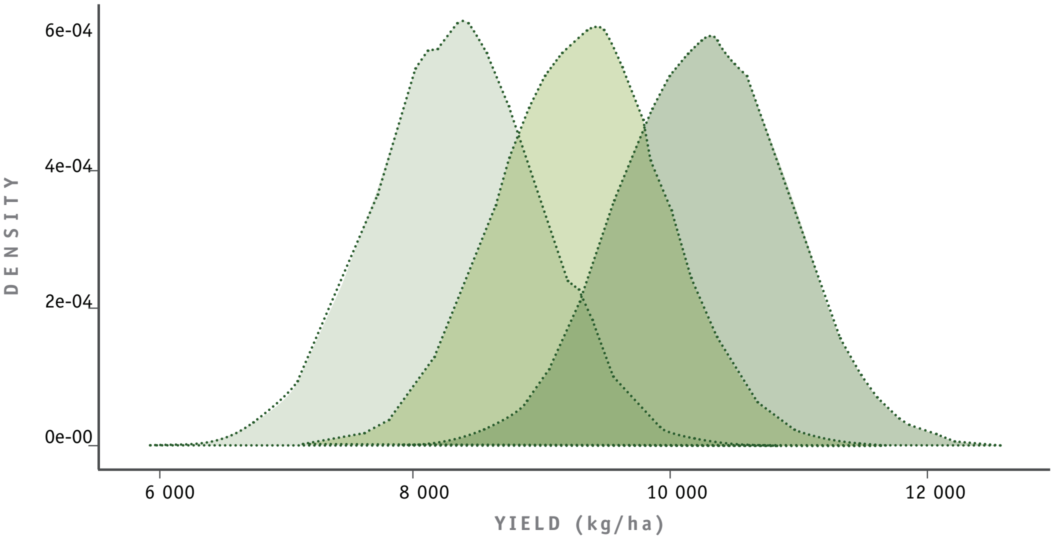
We performed a preliminary analysis that examined the tradeoff between the ecosystem services of sediment retention and total net return in the county given seven crop rotations – continuous maize (C), continuous soy (S), maize/soybean (CS), maize/rye/soybean (CRS), maize/pennycress/soybean (CPS), soybean/spring wheat (SW), and continuous intermediate wheatgrass (IWG). *We hypothesized that the new crops would enhance sediment retention and net economic output of Watonwan County, when compared with currently existing cropping practices.*

EXPERIMENTAL PROCEDURE FOR WATONWAN COUNTY, MINNESOTA CASE STUDY

For a full description of methods see Appendix 1. To summarize, we modelled sediment retention with the Revised Universal Soil Loss Equation (RUSLE) altered slightly to be applied in a geographic information system (GIS). We downloaded the baseline digital elevation model of Watonwan County from the Minnesota Department of Natural Resource's data warehouse. The 2006 National Land Cover Dataset (NLCD) for Watonwan County was downloaded from the Multi-Resolution Land Characteristic Consortium website (Fry *et al.* 2011) in order to differentiate between cropped and non-cropped land. To calculate the net economic return for each cropping system over the period of 2001-2010, we utilized crop production economic data containing average yield, production costs, gross return per acre (converted to gross return per hectare), net return per acre (converted to gross return per hectare, and price per bushel from the USDA-Economic Research Service (ERS) (retrieved July 2013).

Yield for each crop within each grid cell (100 m^2) was determined by creating three random normal distributions – a high, average, and low (Figure 2). Crop yield for each grid cell was then multiplied by the average value of the crop over a ten year period, and then adjusted to represent the respective value in rotation with other crops. To explore the comparative delivery of ecosystem services offered from the different cropping systems compared with the native prairie, we developed a series of landscape change scenarios. The scenarios consisted of transitioning the cropped area of Watonwan County from 100 percent native prairie to 100 percent agro-ecosystem for each crop rotation listed above. Land was placed into a rotation in 10 percent increments by soil erosion decile. Soil erosion and net return were summed across the landscape for each cropping system scenario. Graphs were all created using ggplot2 (Wickham, 2009) in R version 3.0.1 (R Core Development Team, 2013).

FIGURE 2. CORN-YIELD DISTRIBUTIONS CREATED AT RANDOM FROM EMPIRICAL DATA, USED TO MODEL YIELD ACROSS THE LANDSCAPE

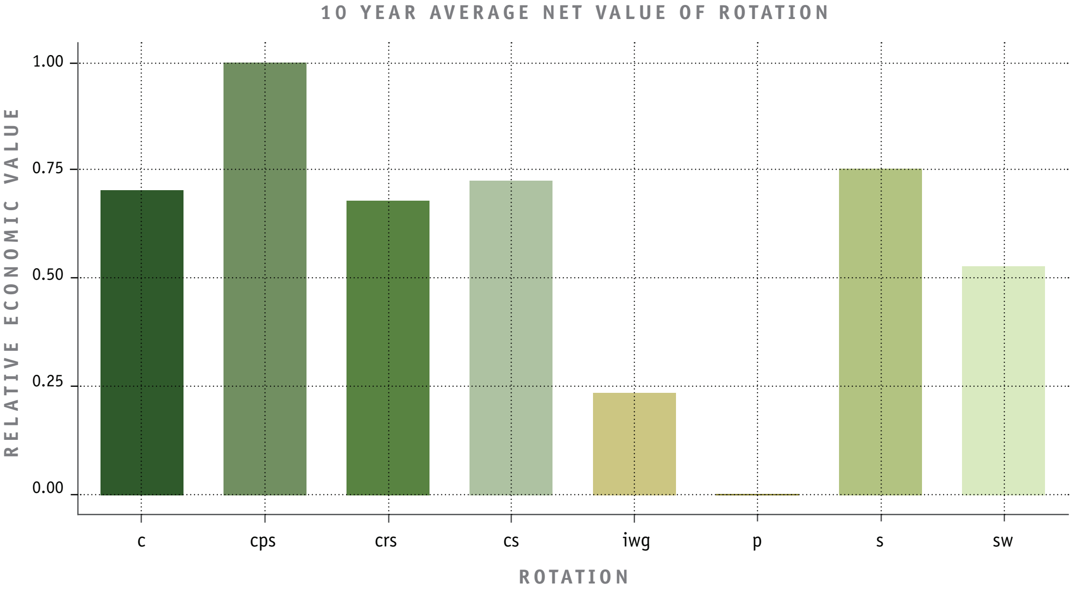


CASE STUDY RESULTS AND DISCUSSION

By modelling the effect of rotations on the potential for soil loss in Watonwan County; with RUSLE, we observed several trends. The seven rotations examined over a ten year time frame resulted in the following projections for soil-loss risk per crop rotation, ordered from greatest to least: SW, C, CS, S, CPS, CRS, IWG, and P (native prairie) (Figure 3). Comparatively, the C, S, and CS rotations, and the CRS and CPS rotations were similar. Intermediate wheatgrass had the least soil erosion potential compared with the other cropping systems analysed. SW had the greatest erosive potential likely due to the short amount of time spring wheat covers the landscape. P had essentially no erosion, which is verified in the literature (Kort *et al.* 1998). In Watonwan County ~15 percent of the land is at risk for sediment loss (greater than 5.5 Mg/ha/yr potential soil loss), so while the county in general is not at risk certain landscapes are, and different rotations could be used on these landscapes. For example, an intermediate wheatgrass planting reduced the risk of soil loss by approximately threefold compared with a corn/soybean rotation (Figure 3). Our data suggest that there is a great benefit from going to continuous cover on any landscape position; however, the greatest benefit will be seen on marginal lands.

FIGURE 3. RELATIVE SEDIMENT LOSS RISK DERIVED FROM THE REVISED UNIVERSAL SOIL LOSS EQUATION (RUSLE) OVER A 10-YEAR CROPPING SYSTEM OF EIGHT DIFFERENT CROPPING ROTATIONS

C = continuous corn, CPS = corn/pennycress/soybean, CRS = corn/rye/soybean, CS = corn/soybean, P = prairie, IWG = intermediate wheatgrass, S = continuous soybean, SW = soybean/wheat.



The modelled economic return from greatest to least was CPS, S, CS, C, CRS, SW, IWG, and P (Figure 4). Native prairie (P) was valued at zero because our interest was in comparing an unmanaged ecosystem to an agro-ecosystem, though we acknowledge that prairie mixtures could potentially be harvested and sold for biomass. Over the ten-year period, C, S, CS, and CRS produced similar net economic returns. If we had done the analysis over a shorter time period – say from 2008 to 2012 – we would have likely seen different economic outcomes because of the high value of maize and soy starting in 2008 caused partially by the United States' ethanol mandate (Zilberman *et al.* 2013) and an increased demand for soybean as animal feed in China (Godfray *et al.* 2010). The IWG rotation performed at approximately a third of the value of the CS rotation. The CPS rotation produced the greatest net return economically. This likely resulted from the ability of the CPS rotation to capture the high productivity and value of the CS rotation while simultaneously adding an additional cash crop half of the years, whereas rye does not offer the same economic benefits. Our analysis corresponded with USDA-ERS national average data for the general economic trends where data was available (Figure 5).

FIGURE 4. RELATIVE TOTAL NET ECONOMIC RETURN FOR A 10-YEAR CROPPING SYSTEM OF SEVEN DIFFERENT CROP ROTATIONS

C = continuous corn, CPS = corn/pennycress/soybean, CRS = corn/rye/soybean, CS = corn/soybean, P = prairie, IWG = intermediate wheatgrass, S = continuous soybean, SW = soybean/wheat.

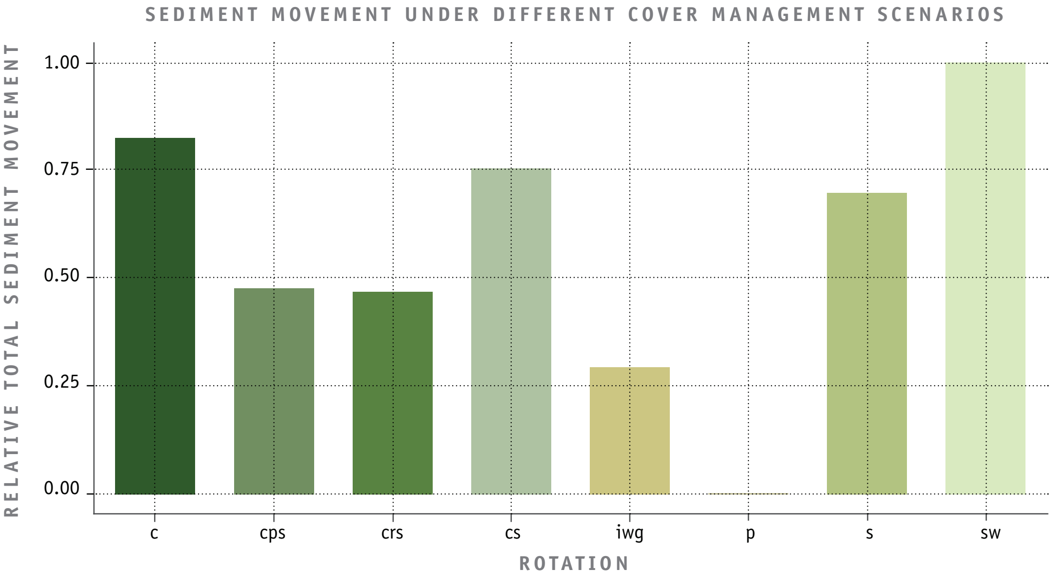


FIGURE 5. TEN-YEAR MEAN FOR NET RETURN PER HECTARE FROM USDA-ERS, 2001-2010

Intermediate wheatgrass return was calculated by discounting the value to 85 percent of wheat and modifying the input costs to account for decreased seed and field pass cost. Pennycress value was calculated as 50 percent of the value of soybean with the input costs being discounted, as it is only in the rotation for half of the years. Rye was not given an off-farm value, but additional costs were added for growing the cover crop after corn.

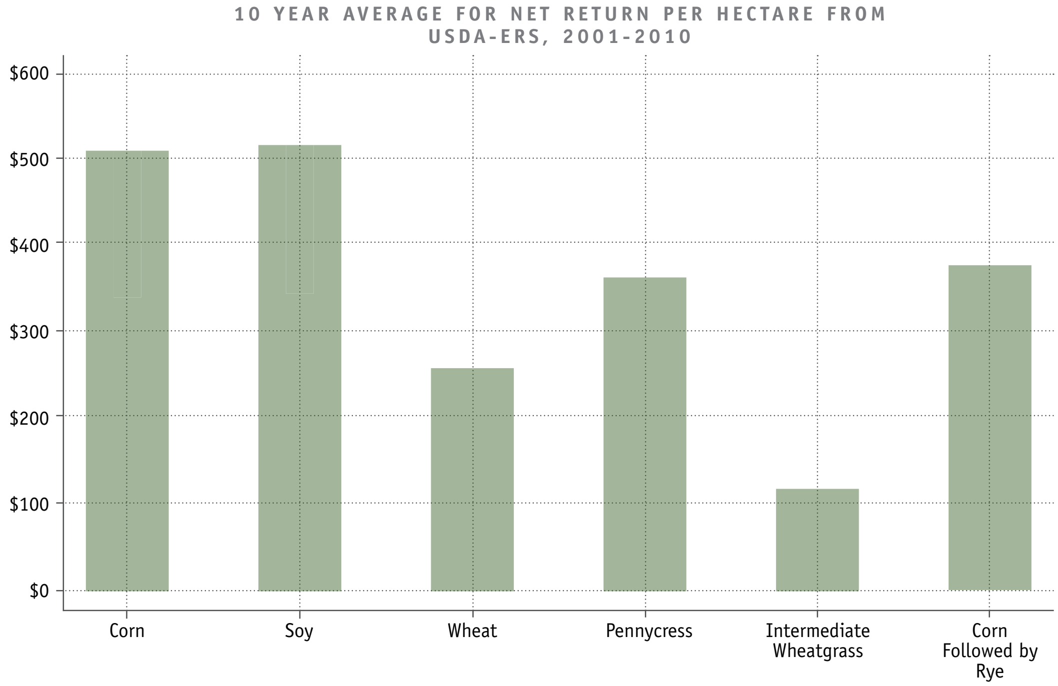
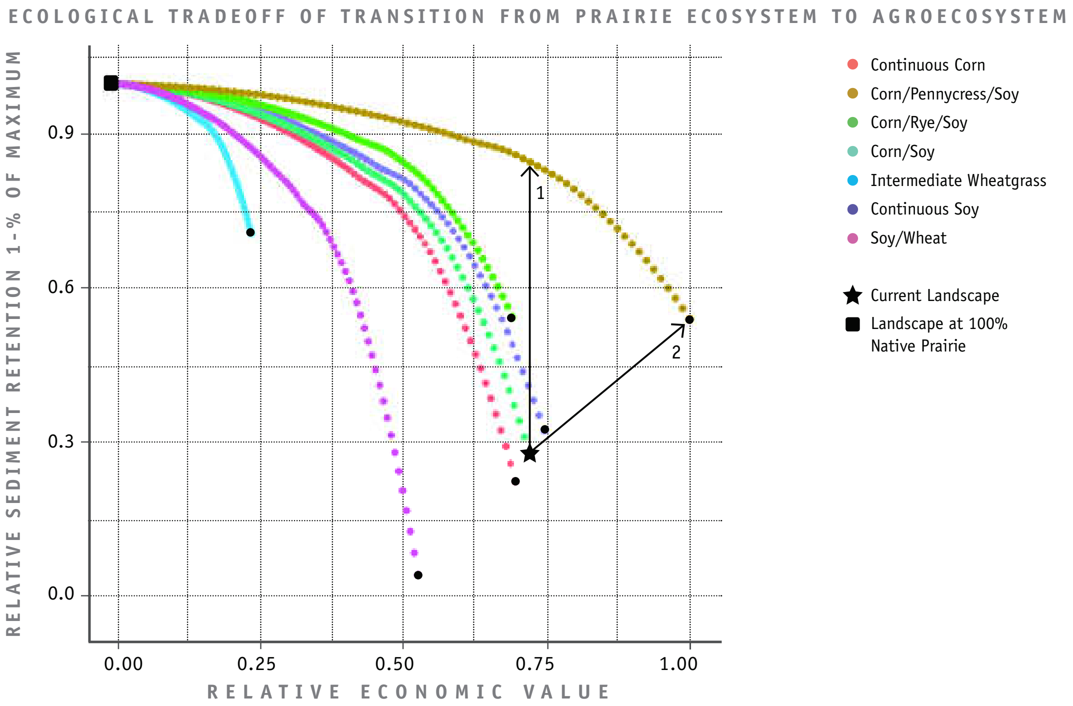


Figure 6 illustrates modelled changes in ecosystem delivery in Watonwan County from 100 percent native prairie to 100 percent managed agro-ecosystem. The relative loss of the ecosystem service of sediment retention was significantly reduced under certain rotations, even though economic output was greatly increased. For example, in the CPS rotation, there is a substantial increase in the delivery of ecosystem services when compared with CS, C, and S. Additionally, while the CRS rotation offered a similar level of sediment retention, the economic output from the CRS system was substantially less than with the CPS rotation. Both SW and IWG underperformed economically compared with corn- and soybean-based rotations; however, the ecological productivity of the IWG was much closer to prairie than any other rotation.

In Figure 6, the star represents an approximation of Watonwan County's current ecosystem service delivery. Black Arrow one shows the sediment retention service gain that could be made without losing any economic output at the county level by switching to a CPS rotation with approximately 15 percent of the landscape remaining in native prairie. Black Arrow two shows the potential economic and ecosystem service gains that would be possible by shifting 100 percent of cropped land from the existing rotation to 100 percent CPS rotation. This situation illustrates one of the major goals of the Forever Green initiative: to develop new material that positively alters both the economic and environmental output of a landscape. Our examination of perennial wheatgrass showed an increase in sediment retention and a reduction in profit compared with other crops. Nevertheless, the difference between intermediate wheatgrass and its closest relative, wheat (Figure 5), is relatively small. Economically, neither performs well against maize or soybean, however.

FIGURE 6. ECOLOGICAL TRADEOFF FOR SEVEN DIFFERENT CROP ROTATIONS AS CROPPED LAND IN WATONWAN COUNTY, MINNESOTA, IS CHANGED FROM 100 PERCENT PRAIRIE TO 100 PERCENT OF EACH OF THE DIFFERENT CROP ROTATIONS

Curves indicate the tradeoff between relative sediment loss and relative economic value of each rotation. The black dot at the end of a curve represents the maximum potential loss, and the star represents the position of the current landscape. The square represents a landscape that is entirely native prairie. Black arrow one shows the sediment retention service gain that could be made without losing any economic output at the county level by switching to a CPS rotation. Black arrow two shows the potential economic and ecosystem service gains that would be possible by shifting 100 percent of cropped land from the existing rotation to 100 percent CPS rotation.



The Forever Green crops that we modelled fit both ends of the spectrum. Intermediate wheatgrass provided excellent environmental benefits, but in its current form did not produce the required profitability. The corn/pennycress/soybean rotation provided an increase in ecosystem services (though not as great as with intermediate wheatgrass) and an increase in profit compared with the current system. This shows that we have existing technologies that can be applied to the landscape, as well as technologies that are on their way to being developed that may have greater environmental benefits.

IMPLICATIONS FOR THE FUTURE

The continued development of new plant material through integrated approaches such as the Forever Green initiative's Reflective Plant-Breeding Paradigm could provide win-win scenarios that deliver the profitability and the ecosystem services that stakeholders desire. In the current plant-breeding paradigm, now largely driven by markets for crops that support profitability, the breadth of ecosystem services desired by society are often overlooked because they lack sufficient profitability. Fortunately, universities and other non-profit organizations can take long-term views and greater risks, and produce outcomes from cropping systems once thought unimaginable. Perennial grains show promise, but at current levels of yield, their adoption by farmers is highly unlikely. While intermediate wheatgrass remains under development, other continuous cover crops such as pennycress appear to be nearly ready for landscape deployment. In the short term, increasing continuous landscape cover though the use of winter annual covers offers a promising avenue to deliver ecological and economic services. Eventually, as these cropping systems and associated supply and value chains (Jordan *et al.* 2013) are made less risky, growers and supply-chain firms may see these "alternative" crops as reasonable for investment. Given the preliminary results of the Watonwan County case study and other research being done at the University of Minnesota, the time of "reasonable for investment" may be close at hand.

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APPENDIX 1. **METHODOLOGY FOR WATONWON COUNTY, MINNESOTA, CASE STUDY.**

We chose Watonwan County in southern Minnesota to explore our cropping system scenarios because it represents highly productive land similar to that across much of the United States Corn Belt. The data for RUSLE was easily accessed from public sources of information. RUSLE is an empirically derived model that estimates rill and inter-rill erosion in tonnes/ha*yr (A) as a function of flow length in metres (L), slope in dimensionless units (S), rainfall and runoff erosivity index in MJ*mm/ha*yr (R), inherent soil erodibility in dimensionless units (K), cover type in dimensionless units (C), and supporting conservation practices in dimensionless units (S) (Renard *et al.* 1991; Desmet and Grovers, 1996) so that:

$$A = L*S*R*K*C*S.$$

We downloaded the baseline digital elevation model of Watonwan County from the Minnesota Department of Natural Resource's data warehouse in order to calculate the slope length and steepness (LS factor). The DEM was derived from Light Detection and Ranging (LiDAR) data captured in the spring of 2010 and downloaded orthorectified at a 1 metre spatial resolution in Nicotinamide adenine dinucleotide (NAD) 83 Universal Transverse Mercator (UTM) 15 coordinate system (retrieved July 2013). For further details on the creation of the DEM, refer to the online metadata (Minnesota DNR, 2010). The K factor was taken from the gridded Soil Survey Geographic (gSSURGO) database downloaded from the Natural Resources Conservation Services (NRCS) Data Gateway *(***Soil Survey Staff, 2013***)*. Data to calculate the R factor was found in the Agricultural Handbook (AH) 537 for Watonwan County (Wischmeier and Smith, 1978). The C factor was derived using the method found in AH 537 (Wischmeier and Smith, 1978), and because no supporting practices are being assessed for this study, the S factor was determined to be 1. All data was cropped to the area of interest and reprojected in the NAD 83, UTM zone 15 coordinate system in the Esri Geographic Information System software (ArcGIS) 10.0 (ESRI, 2011). The digital elevation model was resampled by interpolation to a 10 m^2 spatial resolution to correspond to the gSSURGO database. The LS factor was calculated entirely in ArcGIS 10.0 (ESRI, 2011) by first calculating the slope from the DEM using the slope tool. Flow direction was calculated from the DEM using the flow direction tool, and from the flow direction raster, flow accumulation was calculated. Following the recommendations established in Desmet and Grovers (1996) and Mitasova *et al.* (1996), flow length was replaced with flow accumulation, and then the LS factor was calculated using the equation:

$$LS = \left(\frac{A}{a_o}\right)^m \left(\frac{S}{s_o}\right)^n$$

where A is flow accumulation, a_0 is 22.13 metres based on the length of original test plots, S is slope, s_0 is 0.09 based on the slope of the original tests plots, and m and n are 1.4 and 0.5 – constants determined by empirical testing or the literature (Rabia, 2012). The equation was calculated using the raster calculator tool resulting in an LS raster. The K factor was then isolated from the gSSURGO database, and multiplied by the LS raster resulting in an LSK raster.

The C factor for each of the seven rotations and native prairie was calculated by the method established in AH 537 (Wischmeier and Smith, 1978) for a ten-year period. Utilizing the data table (Dowle *et al.* 2013), plyr (Wickham, 2011), and stats (R Development Core Team, 2012) packages in R version 3.0.1 (R Development Core Team, 2013), the C factors were each multiplied by the LSKR factors and then divided by 1 000 to give sediment movement (A) under the different cropping systems for each 100 m^2 grid cell. A was then put on a relative to maximum scale across all rotations.

In order to isolate the cropped land, the NLCD data layer was reclassified using the raster reclassification tool where classes 81 (Hay/Pasture) and 82 (Row Crops) were one and all else was 0. Using the raster algebra tool, the reclassified NLCD layer was multiplied by the LSK raster and the R factor from AH 537 to result in a cropland LSKR raster. This raster was then resampled to a 100 m spatial resolution and exported as a CSV file with a key field, the LSKR calculation, and the Crop Productivity Index (CPI) for each grid cell derived from the gSSURGO database.

To calculate the net economic return for each cropping system from 2001 to 2010, we utilized crop production economic data containing average yield, production costs, gross return per acre (converted to gross return per hectare), net return per acre (converted to gross return per hectare), and price per bushel from the USDA-ERS (retrieved July 2013). We calculated the net profit per kilogram of yield. The value of pennycress was calculated as 50 percent of the value of soybean, and intermediate wheatgrass as 85 percent the value of wheat. Input costs were modified to represent pennycress being in the rotation five of ten years, and intermediate wheatgrass having seeding costs only twice in the ten year period. We assumed intermediate wheatgrass would develop with the first year for establishment resulting in full input costs without any grain produced. Subsequent years were assumed to have reduced input costs and full yield until year six when it would need to be reseeded. Rye was not given an off farm value, but additional costs were added for growing the cover crop after corn.

Yield for each crop within each grid cell was determined by creating three random normal distributions – a high, average, and low (Figure 2) - built from the USDA-ERS 2001 to 2010 data and empirical data collected from 2006 to 2012 in Minnesota for pennycress and intermediate wheatgrass as a part of the Forever Green program, additional data for biomass value was gathered from Barnhart *et al.* (2012). The average distribution for each crop was based off of the mean and standard deviation of yield for the respective crop. The high and low distribution means were determined as the mean of the average plus or minus 1.5 times the standard deviation. The standard deviation from the average distribution was used in the high and low. Using the CPI for each grid cell in Watonwan County, yield was chosen at random from the appropriate distribution for each crop. This process resulted in a spatially informed yield for each grid cell.

Crop yield for each grid cell was then multiplied by the average value of the crop over a ten year period, and then adjusted to represent the respective value in rotation with other crops. The valuation resulted in a net rotation return per grid cell. Net value of a rotation was chosen because it captures what landowners would gain for themselves after the costs of production were met, and gives a sense of what type of livelihood can be made from the landscape under a given cropping system.