Meandering water in the prairie pothole region of South Dakota and its economic impact

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Abstract

This study estimates the economic impact of surface water changes in the prairie pothole region (PPR) of South Dakota. Flooding of wetlands and the formation of larger lakes has been documented in this region after 1993. To analyze the land cover change related to climate, or drainage, we examine Landsat 5 satellite data, 30 meter digital elevation model (DEM), the National Hydrology Dataset (NHD), the National Land Cover Database (NLCD), and the NRCS soil survey (SSURGO) using linear discriminant analysis. The changes in surface water, cropland, and grassland acres for 5 counties will be measured in northeast South Dakota between 1990 and 2010. These measurements will identify the area lost and gained for potential agriculture revenue given soil types, historical weather, topography, management characteristics, etc. The agriculture production potential will be estimated by simulation given the location and characteristics of the lost or gained acres utilizing the APEX model. Findings include the net acres lost/gained from cropland and grassland production, and the estimated average revenue potential of grassland and cropland acres inundated, or drained, during the period. These findings will determine direct agriculture economic impact to surface water changes. The findings of this study will aid stakeholders in determining the overall economic impact to surface water changes in PPR regions. The purpose is to improve resource allocation through water management institutions that mitigate economic losses and obtain maximum land resource benefits.

Introduction

The prairie pothole region (PPR) of Northern Great Plains covers approximately 900,000 square kilometers (km^2), extending from north central United States, including parts of Iowa, Minnesota, North Dakota, South Dakota, and Montana, to the south central parts of Canada

(Gascoigne et al. 2011). According to Natural Resources Conservation Service (2000), 90% of the private land in PPR is occupied by agricultural land, which is highly productive for small grains, legumes and livestock (Johnson et al., 2004). Another key element of the PPR landscape is millions of glacially formed depressions, or wetlands (Tiner, 2003), also referred to as prairie potholes. These depressions provide ideal breeding habitat for migratory birds (Pardieck and Sauer, 2007), and habits for resident birds and mammals (Johnson et al. 1994).

The PPR is notorious for its extreme and variable climate, punctuated by severe droughts and precipitation deluges that influence both natural and human-dominated ecosystems (Woodhouse and Overpeck 1998; Johnson et al., 2005). For example, Winter and Rosenberry (1998) recorded a drought period in Cottonwood Lake area, North Dakota during the period of 1988 to 1992, then a wet period afterwards. Based on the Palmer Hydrological Drought Index, the Northern Glaciated Plains has switched from extreme drought in 1991 to extreme wet conditions by 2001 (Todhunter and Rundquist, 2008).

Climate variability such as natural wet or dry spell of extreme magnitude and duration act as a direct factor that contribute to the land use change (Drummond et al., 2012; Werner et al., 2013). Flooding of wetlands and the formation of larger lakes has occurred in the northern glaciated ecoregions. For example, in the Devils Lake Basin of North Dakota, the Stump Lake has increased by 53% in size, while the rural wetland ponds has increased by 426% (Todhunter and Rundquist, 2004). Shapley et al. (2005) also recorded the historically unprecedented high water levels in the Waubay Lakes complex, eastern South Dakota in 1990s. On semi-permanent and permanent wetland located at Prairie Pothole Region of North Dakota, McCauley et al. (2015) found current surface water areas (2003-2010) were 86% greater than historical water surface areas (1937-1969).

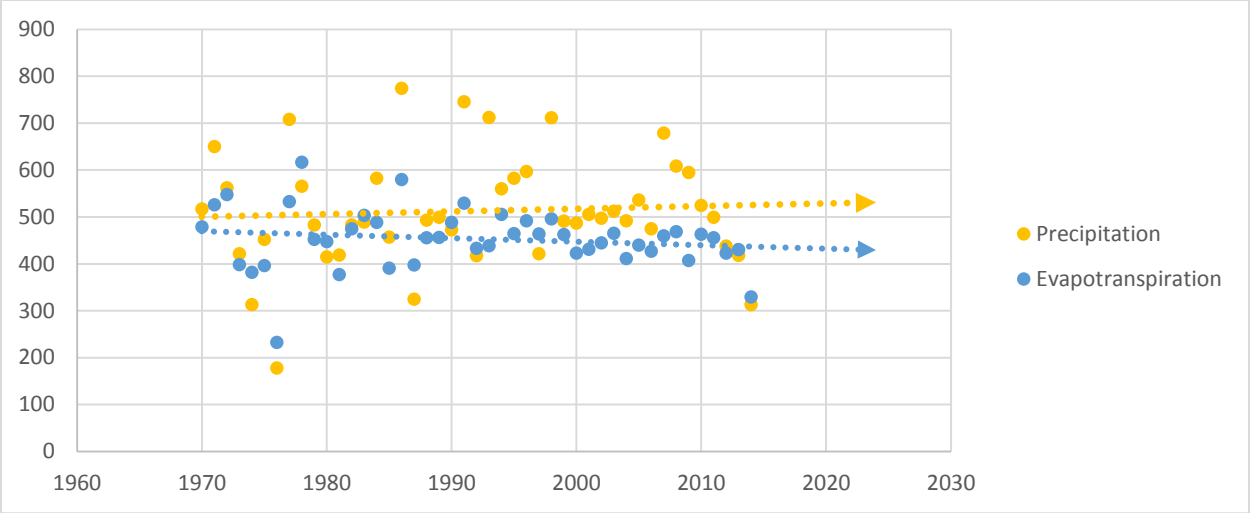

Figure 1. Annual Precipitation and estimated evapotranspiration at Waubay NWR (mm) using the Hargreaves-Samani (1985) equation for crop evapotranspiration

Climate extremes have strong negative effects on agricultural productivity and vegetation cover (Johnson et al. 2004). It has been suggested that deluges starting from the 1990s caused rising lakes and wetlands and flooded farms, towns and roads (Winter and Rosenberry 1998, Shapley et al. 2005). But more precisely, an estimated long-term imbalance between precipitations and evapotranspiration may be the primary contributing factor to changes in the water balances in the area (See Figure 1). Besides climate extremes, drainage is cited as a factor that has increased the risk of flooding (Smith and Ward, 1998). McCauley et al. (2015) also attributed the surface water increase to consolidation of drainage, due to water surface areas on extensively drained wetlands being 197% greater than those with no drainage.

Rural wetland flooding, though largely unrecognized, can be widespread and bring extremely harmful effects to the region's agricultural economic base (Todhunter and Rundquist, 2004). Furthermore, water drainage and water management upstream or downstream can result in economic externalities, and market distorting transaction costs, that require social-ecological systems (SES) to economize to maintain resource sustainability (Ostrom, 2007). This is particularly prevalent when watershed externalities are not harmonious with political governance boundaries, which can result in inefficient resource use or resource destruction.

Examples of current resource programs offered by government institutions for rural flooding include crop insurance or to enroll in the land retirement programs offered through the NRCS. Todhunter and Rundquist (2008) investigated the indemnity payments and found that from 1992 to 2001, flood-related crop claims accounted for 87.5% of all crop insurance claims.

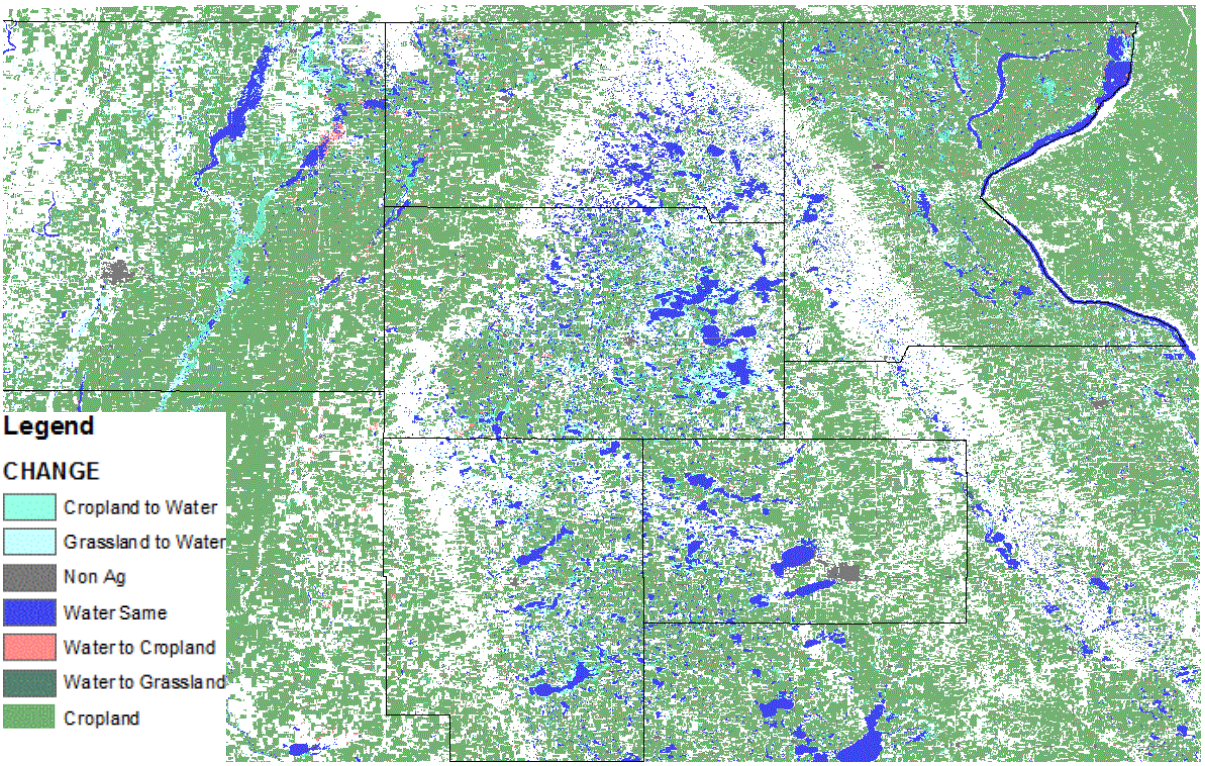

Figure 2. Study area and changes in surface water from 1992 to 2011 (NLCD).

Based on North Dakota Agricultural Statistics, Todhunter and Rundquist (2008) compared the

cropland planted, cash receipts and government payments for Nelson County from 1992 to 2001, to evaluate the effects of flooding on agricultural production. They found marked growth in northern prairie wetlands and the waterfowl has spurred significant growth for hunting and fishing, as well as in tourism and recreation opportunities. Bangsund et al. (2004), however, concluded that net increase in recreation spending can only offset 11% of the lost revenue on agricultural production.

Despite the evidence of the ongoing increase in surface waters in Dakotas PPR region (Todhunter and Rundquist, 2004, 2008; Shapley et al., 2005), the existing literature in the area has focused on conversion of wetland to cropland by human alteration or drainage. Absent from the literature is a complete accounting for both economic losses and gains in agriculture land in the PPR. For example, Johnsgard (2012) commented that "most of these wetlands have now been drained and converted to grainfields, subdivisions, or have otherwise been subjected to environmental changes that have degraded or destroyed their wildlife values" (pp. 9). Johnson et al. (1997) also remarked on the future insecurity of remaining wetland resources, as only 25% of wetlands are protected by easements or fee-title ownership. Johnston (2013) studied the rate of wetland losses in the PPR of North and South Dakota. Areas that were historically mapped by National Wetland Inventory (NWI) or National Land Cover Database (NLCD) of 2001 as wetlands, but classified as cropland by Cropland Data Layer (CDL) in 2011, were considered as wetland losses. Based on this method, Johnston (2013) concluded that the NWI wetland loss rate was 5,203 ha/yr and NLCD wetland loss rate was 6,223 ha/yr. In doing so, however, the areas that were previously cropland and later became annually, or perennially, covered by water were not considered.

In this paper we will focus on six counties in South Dakota PPR region, which are Brown, Clark, Codington, Day, Marshall and Roberts. Our goal is to establish the lost economic revenues caused by land use change in these six counties. To achieve this purpose, we will first measure the net changing rates between agricultural land and surface water, considering both diminishing surface water from potential drainage compared to the loss of agricultural land due to surface water increases from climate and or other contributing factors. We will determine the soil characteristics and dominant management of agriculture land in this area that was lost or gained from surface water changes. We will use the Agriculture Policy Environmental Extender model (APEX) (e.g. Gasman et al., 2010) to estimate crop and range production using historical weather trends for these areas. Instead of focusing on wetland change, our focus is the areas that have changed in surface water during the growing season that can result in economic impact to the entire study area. Surface water includes pond, lake, stream, river and a subset of wetlands that is likely to possess surface water for extended periods of time[1].

[1] As described by Cowardin et al. (p. 3), "Wetlands are lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water."

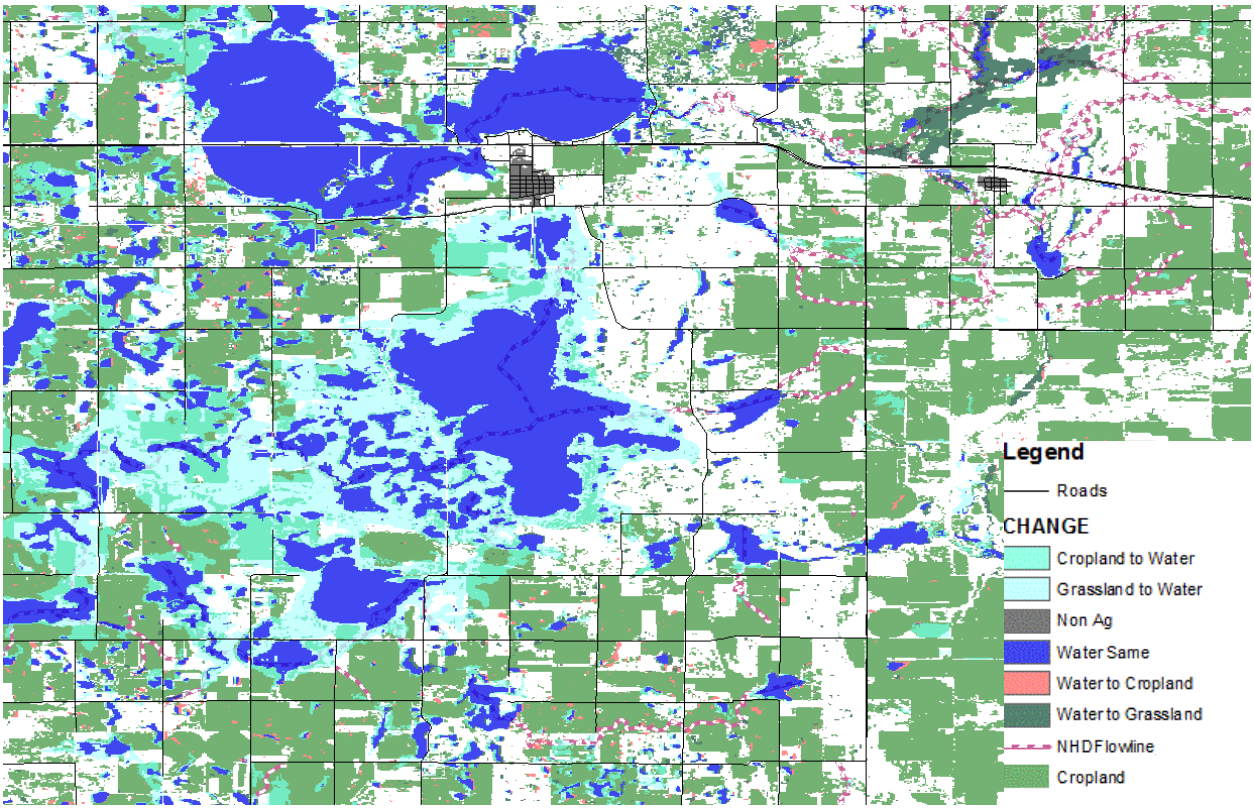

Figure 3. Change in surface water south of Waubay, South Dakota (NLCD) with National Hydrology flow lines identified.

Landscape Mapping using Landsat Data

High spatial resolution data at 16-day interval using the Landsat Multi-Spectral Scanner (MSS) and Thematic Mapper (TM) have been used to map water extent since it became available in 1972. Both are passive sensors since they receive energy naturally emitted from the earth's surface (Smith, 1997). Kingsford et al. (1997) used Landsat MSS data to map wetlands over part of the Murray-Darling Basin. For the supervised maximum likelihood classification method, the accuracy rate was 90% when checking 200 random water bodies with aerial photography. The project was then extended to the entire basin using unsupervised classification procedure.

According to France and Hedges (1986), the minimum detectable lake areas are 0.6 ha for TM and 2.4 ha for MSS. Of all the early studies that use Landsat MSS data, Smith (1997) concluded that MSS band 7 was most useful to distinguish water from dry soil or vegetated surfaces due to its strong absorption of water in the near-infrared range. When comparing the MSS band 7 distinguished water bodies with that derived from digitized aerial photography, Bennett (1987) found that the MSS data underestimated the area of water by around 40 percent.

By comparing satellite information with the true image, Johnston and Barson (1993) found that mid-infrared band 5 successfully detected the lake, pond and wetland areas with a classification accuracy of 95 percent. However, it failed to map the riverine wetlands adequately. Frazier and Page (2000) used Landsat TM data to map water bodies of Murrumbidgee River and its floodplain in Australia. They concluded that the infrared wavelengths, mostly absorbed by water bodies, are most useful for water mapping. For example, mid-infrared band 5 proved as successful as multispectral classification in achieving the overall accuracy of 96.9%. However, it tends to over-estimate water areas with a user accuracy of 64.5%. The visible bands are typically less adequate for classification due to the similarity between the brightness of the turbid water to that of the surrounding land cover (Frazier and Page, 2000).

To map vegetation cover and monitor its changes, most commonly used vegetation indices are normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI). NDVI measures the propensity for plant vegetation during photosynthesis to be highly reflective in the near infrared and highly absorptive in the visible red, resulting in the greenness of the vegetation (Wang and Tenhunen, 2004). Among the two indicators, EVI has been recommended due to its improved sensitivity to high biomass through its reduction in atmospheric influences and de-coupling of the canopy background signal.

Rather than single date observation, dynamic NDVI values from multiple dates are utilized to identify particular vegetation groups, such as grassland and cropland, through their unique phenology (Lenney et al., 1996). On cool and warm-season grasslands discriminant analysis, Guo et al. (2003) also showed that the use of three-date Landsat TM image dataset spanning spring, summer and fall season has significantly improved the classification accuracy over the single date method.

Study Area Description

This region is mainly dependent on agricultural production, and the land use changes we examine will make up a relatively small portion of the changes of land use in the study area (See Figure3). However, the small changes in acreage can have a larger economic impact given lost annual direct revenue potential, and indirect economic impacts.

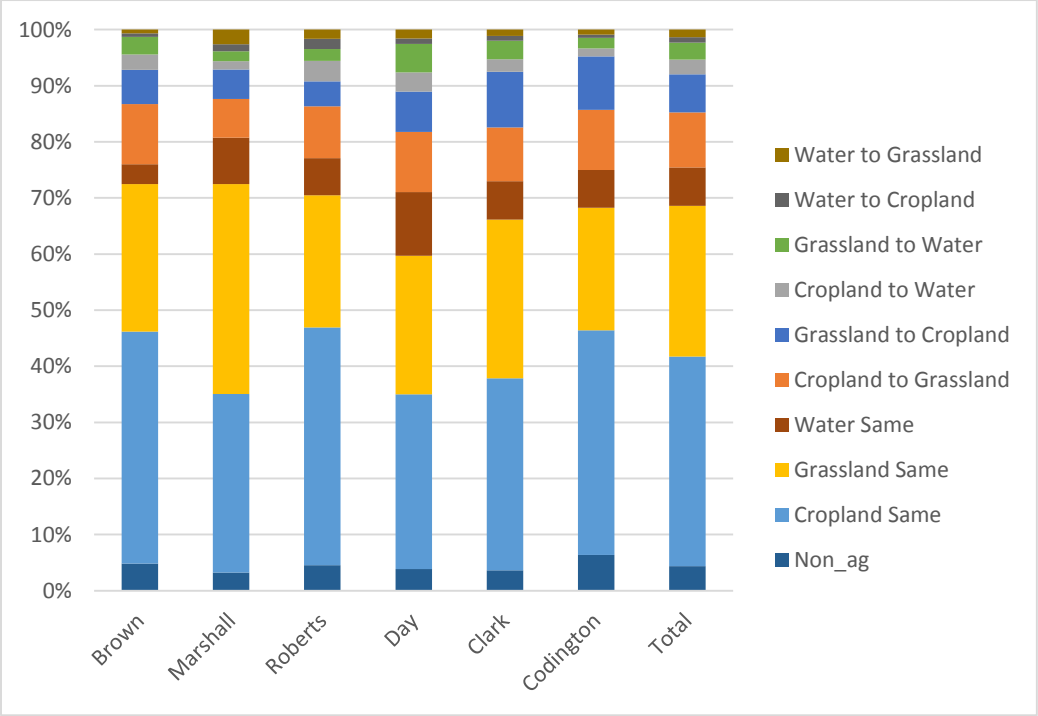

Figure 4. Percentage of land cover changes using the NLCD from 1992 to 2011.

Method

Our paper differs from existing literature in that we consider both changes to land use which includes *a)* land initially covered by water that subsequently reverted back to agricultural land; and *b)* initial agricultural land that subsequently became submerged by water. To detect land use change, and discriminate actual land use changes from error, we use the most straightforward method of comparing land cover classifications from two dates and additional ground information (Loveland et al., 2002).

I. Method to measure surface water change over time

For each study period, we collect approximately 200 random as training data, and classify them into three land use categories (cropland, grassland and water) based on the aerial photography image. Surface water for year 1990, 2000 and 2010 were identified to investigate the trend of land cover change over time.

In the discriminant analysis, the dependent variable (Y) is the land use category and the independent variables (X) are the variables that characterize the land properties, including EVI, NDVI, ponding, depth to water, productivity, capability, slope, focal direction, hydrology characteristics, etc. A complete description of these variables we use will be described in the Data Description section. We assume that the three land use categories are separable using a linear combination of the independent variables.

Assuming that for category i, the probability function of X is multivariate normal with mean vector μ_i and variable-covariance matrix Σ:

$$P(X|i) = \frac{1}{(2\pi)^{m/2}|\Sigma|^{1/2}} \exp\left[-\frac{1}{2}(X-\mu_i)'\Sigma^{-1}(X-\mu_i)\right] \quad (1)$$

Note that m denotes the number of independent variables.

By Bayes' rule, we will assign the observation to the category that has the highest conditional probability. That is, $P(i|X) > P(j|X)$. In our context we will assign the observation with measurement $X = (x_1, x_2, \cdots, x_m)$ to category i that has the highest score according to the linear score function:

$$s_i^L(X) = -\frac{1}{2}\mu_i'\Sigma^{-1}\mu_i + \mu_i'\Sigma^{-1}X + \log p_i = d_{i0} + \sum_{j=1}^{n} d_{ij}x_j + \log p_i \quad (2)$$

The linear score function is estimated for each category. The prior probability p_i is obtained by the proportion of each categories in the training data. For example, if the number of samples that belong to cropland, grassland and water are n_c, n_g and n_w, then the prior probabilities for them will be n_c / N, n_g / N and n_w / N respectively, with $N = n_c + n_g + n_w$. The population means μ_i can be estimated by the sample mean vectors $E(X|i)$ and the variance-covariance matrix Σ can estimated by $\mathrm{var}(X|i)$. Note that the linear score function will be estimated from the training data, and then apply to the large population.

To check the classification accuracy for the large sample, we randomly select samples and compare the classified data with the high resolution aerial photography to validate our results.

To make most optimal comparison, two alternative classification methods may be used: the (1) Linear Discriminant Analysis (DA) to best weight the transformation of our dataset, and

(2) a decision tree or vector support algorithm to classify our data with an additional training sample.

II. Method to calculate economic profit loss due to loss of cropland/grassland

Two methods were applied to calculate the lost revenue from agricultural production. The first method is based on our land use change estimation and location from our classification. The second method uses the land use changes to simulate lost or gained agricultural revenue based. The second method uses simulation of the land changes given the soil characteristics, dominant management types, topography, simulated prices, and historical weather data using the APEX model.

Data Description (to be finished)

Depth to Water- measures the distance from the surface to the water table, or where the soil is completely saturated. Water cannot drain when soils are completely saturated, and will instead pond on the surface, result in surface runoff, or subsurface lateral flow if partially drained but reaches a sub layer that is saturated.

Productivity- measures the ability for a soil to produce crops as defined by the NRCS. Certain soils contain properties that make it more productive in producing crops and/or range grasses.

Capability- measures the likelihood of erosion of a soil when cropped and other components of soil that determine the capability for cropping. Erosion is likely to increase with greater degrees of slopes, therefore capability generally decreases with increasing percentage of slopes.

EVI- Enhanced vegetation index measures the level of near infra-red relative to visible light reflection during the growing season while controlling for background reflection. Plants in the process of photosynthesis absorb visible light and reflect near- infrared light. This measurement is taken at different periods during the growing season to discriminate types of crops, and or grassland production, and level of productivity. For example, an EVI for crop land during early spring, when very little vegetation exists on bare soil, should have little difference in infra-red light reflection relative to visible light reflectance. Later, during the peak of growing season, cropland will have a higher level of visible light absorption relative to near infrared.

For year 1992, we chose EVI of four different cloud free dates, which are day 127 (May 6th), 175 (June 23rd), 223 (August 10th) and 230 (August 17th) respectively. Similarly, cloud-free dates are chosen for year 2010, which are day 128 (May 8th), 240 (August 28th), 256 (September 13th) and 288 (October 15th). .

Slope- is a measurement of the degree the area changes in elevation relative to nearby areas.

Focal Direction- is a measurement of the lowest value in a study area, or the minimum elevation point. This measurement gives indication of lateral surface water flow paths, if not resisted or drained through surface soil layers.

Results (pending)

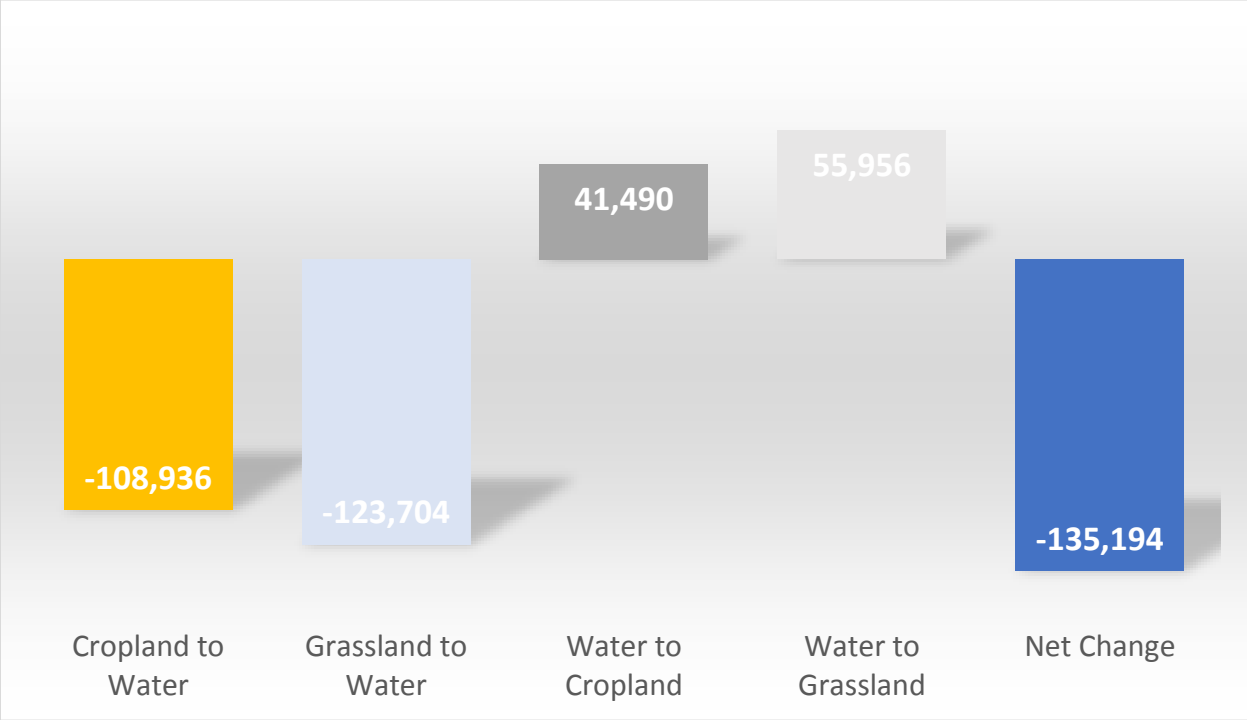

Figure 5. Preliminary results of acre changes using the NLCD in the study area.

Discussion (to be finished)

As pointed out by Loveland et al. (2002), our ability to correctly map and cover land cover is constrained by the moderate-resolution imageries, and by the local and regional landscape characteristics that blur the contrast of different land cover.

If possible, some sensitivity analysis may be done.

Further, we discuss and report lost revenues for local government from property taxes when cropland is inundated with water for 3 or more years and is allowed an adjustment for lower property tax assessment. We will also discuss possible water management institutions and/or

changes in property rights for land use for cropland when there is a changing definitions to use rights given governance jurisdiction and ‘adjacency to surface water’.

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