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Research article

Optimization of bioenergy crop selection and placement based on a stream health indicator using an evolutionary algorithm

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ABSTRACT

The emission of greenhouse gases continues to amplify the impacts of global climate change. This has led to the increased focus on using renewable energy sources, such as biofuels, due to their lower impact on the environment. However, the production of biofuels can still have negative impacts on water resources. This study introduces a new strategy to optimize bioenergy landscapes while improving stream health for the region. To accomplish this, several hydrological models including the Soil and Water Assessment Tool, Hydrologic Integrity Tool, and Adaptive Neruro Fuzzy Inference System, were linked to develop stream health predictor models. These models are capable of estimating stream health scores based on the Index of Biological Integrity. The coupling of the aforementioned models was used to guide a genetic algorithm to design watershed-scale bioenergy landscapes. Thirteen bioenergy managements were considered based on the high probability of adaptation by farmers in the study area. Results from two thousand runs identified an optimum bioenergy crops placement that maximized the stream health for the Flint River Watershed in Michigan. The final overall stream health score was 50.93, which was improved from the current stream health score of 48.19. This was shown to be a significant improvement at the 1% significant level. For this final bioenergy landscape the most often used management was miscanthus (27.07%), followed by corn-soybean-rye (19.00%), corn stover-soybean (18.09%), and corn-soybean (16.43%). The technique introduced in this study can be successfully modified for use in different regions and can be used by stakeholders and decision makers to develop bioenergy landscapes that maximize stream health in the area of interest.

1. Introduction

With the recent concern for the impacts of increased greenhouse gas emissions on climate change, renewable energy sources have gained popularity due to the fact that they have a much lower environmental impact than fossil fuels. Among the renewable energy sources, perhaps biofuel has been promoted most significantly in the recent decade. This is due to the many benefits that biofuels represent, such as reduced CO_2 emissions and supporting local agriculture (Farrell et al., 2006; Goldemberg, 2007; Groom et al., 2008; Ragauskas et al., 2006). However, there are many negative impacts associated with biofuel production. Altering forest and grassland landuse to allow for the production of bioenergy crops has been shown to increase CO_2 emissions (Searchinger et al., 2008). Furthermore the growth of bioenergy crops has led to the increase of nutrient and chemical loading in nearby water systems, which can impact the health of both the ecosystems and humans (Landis et al., 2008; Love et al., 2011; Nyakatawa et al., 2006). Therefore, decision makers need to take into account both the positive and negative impacts of biofuel production when deciding how to best apply bioenergy crops to a region.

Many studies have been conducted to evaluate the impacts of expanding bioenergy crop production on water quality and quantity. First generation bioenergy crops, such as corn, were the first plants used for biofuel production due to their easily processed starches (Goldemberg, 2007). However, studies have indicated that relying on starch crops increases the chemical, nutrient, and sediment loads to nearby water systems (Egbendewe-Mondzozo et al.,

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2013; Love et al., 2011; Thomas et al., 2014; Wu and Liu, 2012). Furthermore, first generation bioenergy crops require more water, which increases the amount of water needed for irrigation (Gasparatos et al., 2013; Wu and Liu, 2012). In order to mitigate these disadvantages, second generation bioenergy crops were introduced. These included lignocellulosic crops such as popular and miscanthus (Wu and Liu, 2012). Compared to the implementation of first generation bioenergy crops, the use of second generation bioenergy crops these crops reduces both the pollutant loadings in nearby water systems and the water yield (Love et al., 2011; Thomas et al., 2014; Wu and Liu, 2012). However, applying second generation bioenergy crops to natural environments, such as forests or grassland, could lead to increased pollutants loads and greater water demands (Wu and Liu, 2012).

To monitor the environmental impacts of anthropogenic activities, stream health is often used (Karr and Dudley, 1981; Pander and Geist, 2013; Walters et al., 2009). Stream health can be defined as the chemical, physical, and biological condition of a stream (Karr, 1999; Maddock, 1999). Biological indictors are often used when determining stream health due to their ability to not only represent not only the biotic characteristics of stream but also the physical and chemical (abiotic) characteristics (Brazner et al., 2007; Leigh et al., 2013; Pelletier et al., 2012). Furthermore, stream health can be modeled and calculated for all stream segments within a watershed (Einheuser et al., 2012). This allows environmental resource managers to use stream health scores to identify degraded regions and allocate resources to restore the ecosystems with the greatest needs (Butcher et al., 2003; Pelletier et al., 2012; Walters et al., 2009).

To minimize the environmental impacts of large scale bioenergy crop expansion, it is important to optimize the design of the bioenergy crop landscape for the study area. One approach is to examine a landscape design and monitor it for several years to determine which design is the best for the region. However, this approach is impractical due to cost and time constraints. Therefore, modeling approaches are typically preferred, which are inexpensive and faster alternatives to monitoring (Arabi et al., 2006; Einheuser et al., 2013a; Giri et al., 2012). However, modeling still has its own limitations. Access to detailed datasets and computational power are required when using models (Einheuser et al., 2013a).

As presented above, with respect to evaluating bioenergy crop expansion, numerous studies have been done but to the best of our knowledge, this is the first study that combines the concept of stream health for optimizing the placements of different bioenergy crops. This will be completed through the main objectives, which are: (1) predict stream health conditions beyond the monitoring points of a biological indicator, and (2) develop a series of bioenergy crop management scenarios that maximize stream health within a watershed.

2. Materials and methods

2.1. Study area

The region used for this study was the Flint River Watershed in Michigan (Fig. 1). This is an 8-digit hydrologic unit code (HUC 04080204) and is part of the Saginaw River Watershed, which has been identified as an area of concern due to bacteria, excessive nutrients, habitat loss, and hazardous chemicals, which has led to the degradation of the environmental conditions in the region (MSU Planning & Zoning Center, 2012). The Flint River Watershed discharges into the Shiawassee River, with the final outlet for the region discharging into Lake Huron at the mouth of the Saginaw River. The region has a total area of 3445 km^2, and is dominated by forest (40%), followed by agricultural land (25%), pasture (18%), urban (16%), and finally wetland and water (both 1%). While the largest individual landuse type is forest (40%), anthropogenic activities (agriculture, pasture, and urban) impact over half the region (59%).

2.2. Data collection

2.2.1. Physiographic data

To develop the stream health models for the Flint River Watershed, several spatial and temporal datasets were obtained. These datasets included topography, land use, soil characteristics, climate data, and management practices. Thirty-meter spatial resolution National Elevation Data was used to represent the topography of the region and was obtained from the US Geological Survey (USGS) (NED, 2014). Thirty-meter spatial resolution 2012 Cropland Data Layer (CDL) was used to represent the landuse in the study area and was obtained from the United States Department of Agriculture-National Agricultural Statistics Service (USDA_NASS) (NASS, 2012). Soil characteristics data was obtained from the Natural Resources Conservation Service (NRCS) Soil Survey Geographic (SSURGO) database at a scale of 1:250,000 (NRCS, 2014). Precipitation and temperature data were obtained from the National Climatic Data Center (NCDC). Within the Flint River Watershed, six precipitation and six temperature stations were used to supply daily climatological information from 1998 to 2005. Other climate data such as relative humidity, solar radiation, and wind speed were obtained from the SWAT weather generator (Neitsch et al., 2011). The stream network and subbasins were created from a 1:24,000 National Hydrography Dataset plus (NHDPlus) and refined by the Michigan Institute for Fisheries Research for stream health studies. Each of the 3807 subbasins from this dataset contains an individual stream and is considered to be physicochemically, geomorphologically, and biologically unique (Einheuser et al., 2013a). Bioenergy management operations, schedules, and crop rotations were obtained from the Michigan State University Extension, as presented by Love and Nejadhashemi (2011) for the study area.

2.2.2. Biological data

Fish are a commonly used biological indicator of stream health. This is due to their wide distribution and sensitivity to a variety of stressors (Karr, 1981; Mack, 2007; Zhu and Chang, 2008; Navarro-Llácer et al., 2010; Krause et al., 2013; Herman and Nejadhashemi, 2015). Furthermore, due to their life cycles and seasonal migrations they are used to provide regional scale views of stream conditions (Karr, 1981). For this study, the Index of Biotic Integrity (IBI) was used to evaluate stream health conditions. First introduced by Karr (1981), the IBI is a multi-metric index that evaluates stream health by utilizing twelve metrics that can be broadly grouped into three categories: species diversity, trophic composition, and abundance of fish communities. However, to better represent the regional fish communities, a modified IBI was introduced by Lyons (1992) in which the metrics and scoring system were updated. The ten metrics in the new system were given a score of 0–10, with 10 representing non-disturbed conditions within a stream (Lyons, 1992). These were summed just to calculate the overall IBI score. However, the final score should be adjusted under a certain ecological conditions (number of individuals per 300 m^2 is less than 50 or percent of deformities, eroded fins, lesions, or tumors in fish is greater or equal to 4%) using the correction factors, which can reduce the overall IBI score up to 20 (Lyons, 1992). After rounding any negative IBI scores to 0, the final stream health IBI scores