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Simulating stream health sensitivity to landscape changes due to bioenergy crops expansion

Matthew D. Einheuser [a], A. Pouyan Nejadhashemi [a,b,*], Sean A. Woznicki [b]

[a] Department of Plant, Soil, and Microbial Sciences, Plant and Soil Sciences Building, 1066 Bogue Street, Room A286, Michigan State University, East Lansing, MI 48824, USA

[b] Department of Biosystems and Agricultural Engineering, 524 S. Shaw Lane, 225 Farrall Hall, Michigan State University, East Lansing, MI 48824, USA

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ABSTRACT

In order to study the impacts of bioenergy crop expansions on stream health the adaptive neural-fuzzy inference system (ANFIS) was used to simulate three macroinvertebrate and one fish stream health measure. Macroinvertebrate measures considered were the Hilsenhoff Biotic Index (HBI), Family Index of Biological Integrity (Family IBI), and Number of Ephemeroptera, Plecoptera, and Trichoptera taxa (EPT taxa) and the fish measure used was the Index of Biological Integrity (IBI). Water quality and quantity variables obtained from a high-resolution biophysical model (Soil and Water Assessment Tool) were considered as inputs to the stream health predictive models. In order to examine the potential impacts of bioenergy crop expansions on stream health measures, 20 different rotations were examined in the Saginaw Bay basin. Overall, for the second-generation of biofuel crops, improvement in water quality was associated with less intensive agricultural activities, while traditional intensive row crops generated more pollution than current landuse conditions. Regarding the impacts of landuse changes on stream health measures, all three macroinvertebrate measures were negatively impacted under intensive row crops scenario while these measures were improved under perennial crops. However, for the fish measures, the expansion of native grass, switchgrass, and miscanthus resulted in negative impacts on IBI compared to first-generation row crops.

1. Introduction

Biofuels can provide many benefits such as lowering CO_2 emissions and supporting local agriculture [1], however; some evidence has shown that greenhouse gas emissions can as much as double with landuse changes driven by corn-based ethanol production [2]. Additionally, other negative effects of biofuel production may occur when considering ecological aspects and biodiversity. Agricultural activities often result in increased nutrient and chemical loadings in nearby waters, which can lead to adverse impacts on human and aquatic ecosystems health [3,4]. Therefore, when determining

Abbreviations: SFLOW, average seasonal flow; SOrgP, average seasonal organic phosphorus concentration; SNo3, average seasonal nitrate concentration; SNo2, average seasonal nitrite concentration; STN, average seasonal total nitrogen concentration; AFLOW, average annual flow; AOrgP, average annual organic phosphorus concentration; AOrgN, average annual organic nitrogen concentration; ANH4, average annual ammonium concentration; ANo2, average annual nitrite concentration.

* *Corresponding author*. Department of Biosystems and Agricultural Engineering, 524 S. Shaw Lane, 225 Farrall Hall, Michigan State University, East Lansing, MI 48824, USA. Tel.: +1 517 432 7653; fax: +1 517 432 2892.

E-mail address: pouyan@msu.edu (A.P. Nejadhashemi).

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whether biofuels are a sustainable and cost-effective replacement of current production methods, both positive and negative aspects of large-scale bioenergy crop production are important to consider [5]. Policies and decision making regarding biofuel production need to incorporate an inclusive understanding of how potential shifts in landuse can affect ecological systems [6,1].

Agricultural production impacts on streams, such as altered flow [7,8], sediment loading [7,9–11], nutrient levels [12–14], and pesticide concentrations [4,15], can be further be mirrored in ecological health, whether it is fish communities, macroinvertebrates, and/or ecological systems all together. Integrating biological assessment information into management decisions can support water quality management programs, such as the Clean Water Act, which aims to "restore and maintain the chemical, physical, and biological integrity of the Nation's waters" [16]. The term "integrity" refers to a quality or state, when compared to an initial condition and is often synonymous with stream health [17]. Biological indicators, commonly fish or macroinvertebrates [18–21], are frequently used to quantify ecological health or integrity. Ideally, a comprehensive representation of integrity would simultaneously include fish and macroinvertebrates because they can reflect conditions at different scales and react differently to varying stressors [19,20,22–24]. For example, in general, fish tend to respond to broader scale factors like flow and landuse, due to their range of movement and lifespan [18,22], while macroinvertebrates tend to respond to more localized habitat factors [23].

Multiple approaches have been used in linking disturbances and stream variables to aquatic biota [25–27]. However, researchers face numerous key challenges when trying to explore and model these complex ecological processes. One of these challenges is the lack of high resolution and complete landscape datasets, which complicates attempts at linking anthropogenic disturbances in watersheds with in-stream physicochemical and biological conditions [28]. Additionally, the collection of data over long periods of time and for hypothetical conditions is often impractical. However, biophysical models can minimize these challenges. This is exhibited through the efforts by the Conservation Effects Assessment Project (CEAP), which aims to quantify the ecological effects of agricultural practices through modeling applications and tools [8,29].

Based on these concerns, the specific objectives of this study were to: 1) employ a biophysical model to create high resolution and complete water quality and quantity variables; 2) develop predictive models to estimate ecological integrity based on fish and macroinvertebrate communities; 3) calculate the water quality and quantity effects of large scale landuse change due to biofuel crop production; (4) project the ecological impacts of large scale biofuel crop expansion throughout the Saginaw Bay basin in Michigan.

2. Materials and methods

2.1. *Study area*

The study area for this research is the Saginaw River watershed (040802), which is Michigan's largest 6-digit HUC (hydrologic unit code) watershed (Fig. 1). This 16,000 km^2 basin consists of the following six 8-digit HUC watersheds: the Tittabawassee (04080201), Pine (04080202), Shiawassee (04080203), Flint (04080204), Cass (04080205), and Saginaw (04080206). Landuse within the Saginaw River watershed largely consists of agricultural lands, primarily corn and soybean. With approximately 43% of the basin comprising of agricultural lands and an additional 14% urbanized, it is apparent that human disturbance is largely responsible for many segments of the river system being designated as areas of concern by the EPA [30].

2.2. *Biophysical model*

Physically based hydrologic models, such as the Soil and Water Assessment Tool (SWAT), are reliable tools for acquiring high resolution stream water quality and quantity conditions. The SWAT model (ArcSWAT 2005 v.2.3.4) was developed by the U.S. Department of Agriculture-Agricultural Research Service (USDA-ARS) Temple, Texas and was designed to determine the impacts of landuse changes on water quantity and quality at the watershed scale. The model simulates several watershed processes including water movement, sediment transport, crop growth, nutrient cycling, etc. [31]. The SWAT model is built using detailed climatic, topographic, soil, and landuse information [32,33].

SWAT partitions a watershed into subbasins, which are further divided into areas of homogeneous landuse, soil, and slope called hydrologic response units (HRU) [31]. It is here at the HRU level where the hydrologic balance, erosion, and nutrient losses are calculated. Within the model, the Modified Universal Soil Loss Equation (MUSLE) is used to calculate erosion and sediment yields, which are routed within the reach and controlled through deposition and degradation [31]. Both nitrogen (N) and phosphorus (P) are simulated through their respective nutrient cycles. This includes uptake and losses through several processes such as crop/plant uptake [40]. Specifically, plant uptake is controlled by a supply and demand approach and can be introduced into the system through fertilization and residue [33]. Nitrogen and phosphorus are represented in several forms (e.g. organic N and P) within the model, which can further dictate the processes and routing that takes place, both on land and within the channel [33]. Neitsch et al. [31] provide a complete description of SWAT model processes.

2.3. *SWAT model setup*

Model setup includes several input datasets that reflect physiographic (landuse, soils, and topography) and climatic characteristics of the watershed. Soil data was obtained from the USDA State Soil Geographic dataset (STATSGO) database [34]. A 30 m resolution USGS National Elevation Dataset (NED) was used for topography data and was acquired through the Better Assessment Science Integrating point and Nonpoint Sources (BASINS) software, version 4.0. Both the stream network and subbasins were predefined layers based on 1:24k National Hydrography Dataset plus (NHDPlus) obtained through the Michigan Institute for Fisheries Research. This high resolution dataset delineates the entire basin into 13,831subbasins that each contain a single reach, representing a stretch of river with homogenous features (physicochemical, geomorphological,