Environmentally sustainable second generation biofuel production through optimal land use planning

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Problem Statement

Biomass has emerged as a major source of energy production in many countries. In the United States, the Energy Independence and Security Act (EISA) of 2007 has envisaged a major share of fuel requirement of the country to be met from biofuel, by targeting a production of 36 billion gallons of biofuel by 2022 (Cibin et al., 2012). Ethanol production using corn and soybean causes unhealthy competition among food and fuel, and hence EISA has suggested to put an upper cap on such grain-based ethanol production and to meet the remaining bio energy requirement from second generation biofeedstocks such as crop residues (corn stover, wheat straw, etc.) and perennial grasses (Switchgrass and Miscanthus). In the present scenario, use of fertilizers and pesticides in corn and soybean fields has resulted in huge amount of nutrients being delivered to downstream rivers. Introduction of perennial grasses can improve the in-stream water quality compared to the row cropped systems. However, these grasses are associated with high production cost and hence less established. In such a situation, a simulation-optimization framework can be employed to develop optimal economic cropping patterns that can be adopted in the watershed to improve water quality, simultaneously achieving grain and biofuel production targets.

Objectives

- Calibrate and validate SWAT model for simulating stream flow, sediment and water quality simulations for the study area.
- Develop a simple exponential decay based in-stream process model for the watershed to loose-couple with the calibrated SWAT model.
- Develop a pseudo model representation of the calibrated SWAT model and to link it with the exponential decay based in-stream process model
- Develop optimal cropping pattern aiming at sustainable bio-energy production scenarios using a multi-objective simulation-optimization framework considering economic and water quality attributes, and food security constraints.

Methodology

STUDY AREA

-St. Joseph watershed encompasses an area of around 2830 km² in northeas Indiana, northwest Ohio and south central Michigan

-Major land use is agriculture ,dominated by corn/soybean (39%) and pasture (25%)

-SWAT model setup was done for the watershed with 47 sub basins and 940

-Model calibration was done with stream flow data from USGS (United States Geological Survey) and water quality data from ST. Joseph River Watershed Initiative (SJRWI)

-16 parameters were selected by sensitivity analysis for flow calibration

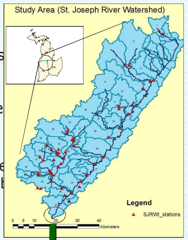

Figure 1: St Joseph Watershed delineated using SWAT

Model Calibration and Validation

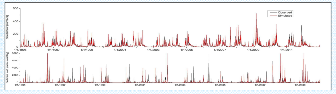

Figure 2: Plot of simulated and observed stream flow and sediment loads for the calibrated SWAT model.

Variable	Calibration			Validation		
	Period	R-square	NSE	Period	R-Square	NSE
Stream flow (daily)	1995-2004	0.80	0.80	2005-2012	0.74	0.74
Sediment (monthly)	2001-2005	0.63	0.40	2006-2009	0.89	0.86

Table 1: Calibration and validation statistics for stream flow and sediment

- Instead of the SWAT in-built in-stream model (QUAL2E) , an external exponential decay model was loose coupled with SWAT for simulating nutrient transport in streams. This simple coupled model slightly better performance compared to the default model.

Nitrate transport

(Smith et. al, 1993)

$$C = C_0 e^{-kx}$$

C:Downstream nutrient load
C_0 : Upstream nutrient load
k: Distance decay coefficient
x : Reach distance

Total Phosphorus transport

(Smith et. al,1997)

$$C = C_0 e^{-kt}$$

C:Downstream nutrient load
C_0 : Upstream nutrient load
k : Decay coefficient
t : Reach travel time

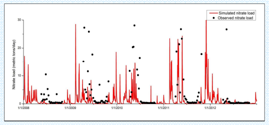

Figure 3:Simulated & observed nitrate for coupled model

Nutrient load(kg)	With in-built QUAL2E model			With exponential decay model		
	Period	R-Square	Modified NSE*	Period	R-Square	Modified NSE*
Nitrate	2008-2010	0.85	0.27	2008-2010	0.88	0.27
TP	1996-2005	0.49	0.76	1996-2005	0.49	0.76

Table 2: Comparison of QUAL2E and exponential models

OPTIMISATION

A multi-objective simulation optimisation framework was developed by linking coupled SWAT model with AMALGAM optimisation algorithm (Vrugt and Robinson, 2007)

Objective functions:

1. Minimize $OF1^{**} = \frac{Nitrate\_outlet}{Nitbase\_outlet} + \frac{phosphorus\_outlet}{phosbase\_outlet}$
2. Minimize $OF2 = \sum C_{HRU} * A_{HRU}$

C: Biomass Production Cost($/acre); A: Area(acre);
$Nitrate\_outlet$: mean daily nitrate load for new scenario;
$Nitbase\_outlet$: mean daily nitrate load for baseline

Constraints:

(1)Corn grain yield reduction should be less than 10%
(2)A minimum of 100 million gallon of bioenergy is to be produced

Variables: Corn, Soybean and Pasture areas

Placement Options: Switchgrass, Miscanthus, corn stover removal (30% and 50%)

Scenario	Biomass Production Cost ($/acre)	Yearly Corn Grain yield (x10⁵ tons)	Total Biomass yield (x10⁵ tons)	Daily Mean nitrate at outlet (tons)	Daily Mean Phosphorus at outlet (tons)
Baseline	0.0	8.52	0.0	9.15	1.99
Corn Stover Removal (30%)	18.3	8.51	3.18	8.79	1.69
Corn stover Removal (50%)	34.0	8.50	5.29	8.38	1.69
Switchgrass	555.0	0.0	12.75	5.35	0.29
Miscanthus	933.0	0.0	32.50	4.25	0.29

Table 2: Impacts of biofuel production when energy crops are placed in all Corn/Soybean and/or Pasture land uses (extreme case scenarios)

*To account for uncertainties in management practice dates, a simulated band is considered instead of discrete values(Cibin et.al,2012)

**Aggregate Pollutant Value (APV) Index (Cibin, 2013)

Results and Discussion

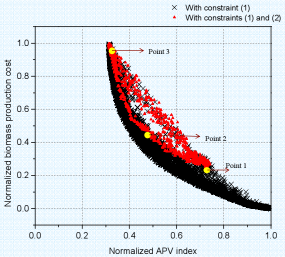

Figure 4: Optimal front obtained after optimization

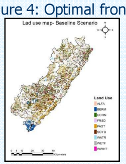

Figure 5:Baseline scenario

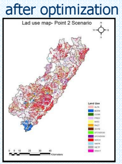

Figure 6: Spatial pattern for optimal solution

	Scenario	Baseline	Point 1	Point 2	Point 3
% of watershed area	Corn	16.9	1.5	**0.2**	0
	Soy bean	22.1	1.5	**0.8**	0
	Pasture	24.6	1.6	**0.5**	0
	30% stover	0	5.7	**4.4**	0
	50% stover	0	14.6	**11.4**	8.6
	Switch grass	0	34.4	**40.4**	2.2
	Misc-anthus	0	4.2	**5.8**	52.9
Mean nitrate (tons/day)		9.15	7.59	**5.91**	4.25
Mean TP (tons/day)		1.99	1.29	**0.58**	0.32
BPC ($)		0	23684	**28328**	58409

Table 3: Land use changes before and after optimization

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Conclusions

- Replacing the current cropping practices with Switchgrass and *Miscanthus* reduces downstream nutrient delivery in comparison to the baseline scenario. Moreover, this ensures sufficient biomass production.
- Stover removal options can improve the biomass potential of the watershed with minimum impacts on corn grain yield reduction.
- Optimization results provides options for economically and environmentally sustainable biofuel production from the watershed with various cropping patterns.

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