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Watershed-scale modeling of the water quality effects of cropland conversion to short-rotation woody crops

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Abstract

The conversion of cropland to the production of woody biomass, or short-rotation woody crops (SRWCs), has the potential to provide an economic alternative to Midwestern farmers, while simultaneously offering an environmental dividend in the form of reduced erosion and nutrient pollution of streams. However, notwithstanding a wealth of plot-scale and anecdotal data suggestive of these benefits, there are few watershed-scale integrated analyses on which to base regional policy decisions regarding incentives to convert fields to SRWCs. This study applied a field-scale runoff, sediment and nutrient transport model (Agricultural Drainage and Pesticide Transport, ADAPT) to a simulation of 10, 20 and 30% cropland conversion to SRWCs, grown on a 5-year rotation, in a representative Minnesota River sub-watershed. While the generation of a highly precise simulation would require extensive calibration of the model, its application with parameters previously calibrated to neighboring, similar watersheds provided reasonably robust results that indicated real differences resulting from cropland conversion. At the highest conversion level, mean annual runoff was reduced by up to 9%, sediment loads by 28% and nitrogen (N) loads by 15%, although total phosphorus (P) loads increased by 2% relative to the no-SRWC scenario. However, the relative benefits of conversion at the field level were contingent on soil type, drainage status and the alternative crop. These differences provide useful insights with respect to the targeting of possible conversion incentives.

Key words: ADAPT, nitrate, sediment, short-rotation woody crops, watershed models

Introduction

Short-rotation woody crop (SRWC) production systems have been the focus of much recent research, both because of their commercial potential and because of the perceived environmental dividend compared to conventional cropping systems. The production of biomass crops has the potential to provide an economic alternative for farmers faced with low prices for row crops. Biomass crops and residues already constitute the most significant proportion of the US renewable energy supply, and woody biomass crops may provide a feasible alternative source of fiber for an evolving forest products industry. Perennial cropping systems also tend to perform much better than annual crops with respect to nutrient sequestration and soil stabilization. These benefits have been cited as justification for some degree of public investment, in the form of subsidies or incentives to farmers, to reduce private risk and to encourage cropland conversion to trees[1].

Potential reductions in erosion and agricultural runoff, with commensurate improvements in surface water quality, are important considerations in most US cropland conservation programs, including the Conservation Reserve Program (CRP) and the Environmental Quality Incentives Program (EQIP). Excessive sediment loads can lead to high water-treatment costs and large expenditures on culvert, ditch and reservoir maintenance. The positive economic impact of water-quality improvement on recreational values has been documented extensively[2–5].

Systematic evaluations of the environmental and social benefits of cropland conversion to SRWCs have been constrained by the relative novelty of SRWC systems, which represent a synthesis of farming and forestry. A number of relevant regional- or national-scale modeling and valuation exercises have been conducted to assess the water-quality impacts of the CRP[6,7]. The information resulting from these studies has generally been too broad in scope to be useful for region-specific policy development.

Because of the prominence of surface water quality as an environmental issue in the Minnesota River Basin, which is heavily agricultural, the sediment and nutrient loading effects of converting land in row crops to trees are of immediate concern to policy makers. Field- and plot-scale studies of trees planted in cropland with and without cover crops have demonstrated reductions in sediment and nutrient delivery to streams, ranging from nonsignificant to as much as 64%[8,9].

However, there are few watershed-scale integrated evaluations of this effect. Notable exceptions include a study by Licht[10], who reported a 69% reduction in NO_3-N losses based on a paired-watershed comparison of in-field and riparian tree plantings with conventional crops in Iowa. In a study comparing conventional corn with agroforestry (oak, *Quercus* spp.) and contour grass strips, initial measurements indicated that the grass strips retained about 18% more nutrients and sediment than the (widely spaced) trees[11]. The data emerging from these studies are as yet too limited and site-specific to serve as a basis for policy decisions.

The study described in this paper was part of a broader analysis of the environmental impact of cropland conversion to hybrid poplar (*Populus* spp.) SRWCs. Its objective was to provide data that were geographically specific but also generalized enough to be scalable to the river-basin level, thereby constituting a policy-relevant analysis with respect to a major farming region of Minnesota. This report will focus on the watershed-scale modeling of cropland conversion to SRWCs, and the water-quality predictions that resulted from it.

Methods

Watershed location

The High Island Creek (HIC) watershed is one of the few rural sub-watersheds of the Lower Minnesota River in southern Minnesota (44°N, 94°W). High Island Creek, a second-order stream, and its major tributary, Buffalo Creek, are 91 and 25 km long, respectively. The topography of the watershed is mostly flat to gently rolling, but the eastern portion consists of steep hills and bluffs bordering the Minnesota River Valley. Nearly 85% of the 62,023-ha watershed is in row crops (corn, soybeans, small grains and forage), with an additional 5% in pasture or hay, 5% forested, 3% urban and 2.5% water or wetland[12]. An estimated 49% of the cropland has tile drainage installed[13]. The 1998 MN 305(b) Assessment of Stream Water Quality rated most of HIC as 'threatened' or 'partially supporting' with respect to support of aquatic life and various indicators, including oxygen depletion, turbidity, habitat alteration and bacteria[14]. Seven lakes in the HIC watershed have some type of public access. The two for which lake water-quality data were available from the Minnesota Pollution Control Agency (MPCA) were classified as 'non-supporting' with respect to swimming, although all lakes support some level of fishing.

Watershed modeling

The ADAPT (Agricultural Drainage and Pesticide Transport) model[15] is a field-scale water-table management model that was developed by enhancing GLEAMS[16], a root-zone water-quality model, with the subsurface drainage algorithms from DRAINMOD, a subsurface drainage and deep seepage model[17]. Its consequent ability to predict tile drainage contributions to runoff, nutrient and pesticide loads make it particularly valuable in the midwestern US, where nearly 30% of agricultural land has been modified by drainage[18]. Watershed-scale methodology and water-routing algorithms were developed by Gowda et al.[19]. The model is comprised of hydrology, erosion, nutrient and pesticide modules. The hydrology component simulates major surface and subsurface hydrologic processes, including snowmelt, infiltration, surface runoff, evapotranspiration, subsurface drainage, subirrigation and deep seepage. Model outputs included total runoff and loadings of sediment, nutrients and pesticides on daily, monthly or annual timesteps.

Model input. Climatic inputs to the ADAPT model included daily precipitation, temperature, humidity, wind velocity and solar radiation data for the simulation period (1996–2000). The 5-year period was selected to evaluate the water-quality impacts of a complete rotation of hybrid poplar, as proposed for a biomass power project near St. Peter, MN[20]. Precipitation data were obtained from four stations dispersed around the watershed. In the model simulation, a simple median precipitation value was used as it gave better runoff predictions during initial tests than simple average or Theissen polygon methods[13].

Generalized agricultural management data[21–24] were incorporated into crop data files originally developed by Dalzell[13]. These included crop rotations for corn, soybeans and wheat, planting and harvesting dates, tillage and fertilizer operations. Parameter files were also provided for noncrop land uses, such as pasture, forest and urban development.

Plant growth parameters for hybrid poplar, such as seasonal changes in leaf area index (LAI), rooting depth, biomass accumulation and carbon:nitrogen (C:N) and nitrogen:phosphorus (N:P) ratios were generalized from an extensive literature on poplar growth physiology, largely from the North Central region of the US[25–29]. Leaf litter returns to the soil were simulated by adjusting the model's yield ratio parameter.

Management parameters for hybrid poplar were based on local guidelines for farm-scale production of hybrid poplar in Minnesota[30]. Model parameters assumed fall tillage (including an application of glyphosate), with further tillage and planting the following spring. Weed control included herbicide applications in the spring of the first 3 years, and mechanical weed control (rotary hoe tillage) seven times in the first year and twice in the second and third years. N fertilizer was applied at a rate of 168 kg N ha^{-1} in the third year. Tillage and fertilizer inputs for conventional crops and hybrid poplar are compared in Table 1.

The ADAPT runoff routing module operates on hydrologic response units (HRUs), which are hydrologically unique polygons composed of geographically indexed overlays of soil type, land use, slope, crop and tillage information. The HIC watershed includes four STATSGO (State Soil Geographic Database) soil map units (Table 2), with average slope ranging from 3 to 17% and in texture classes from fine argillic to sandy. Identical HRUs were aggregated to form transformed HRUs, or THRUs. It should be noted that THRUs do not retain the positional information initially present in the HRUs. This data arrangement is based on the assumption that the time of concentration in the study watershed is less than 24 h, the time-step resolution of the model. This assumption is valid for the HIC watershed. Geographic information system (GIS) overlay analysis of land use, tillage, soil and slope layers for the HIC watershed resulted in 36 THRUs.

Table 1. Management inputs for major cropping systems included in the simulation, summed over the 5-year SRWC rotation. The first ‘priming’ year of the simulation has no SRWCs and is excluded.

Crop rotation[1]	Number of tillage operations	Fertilizer (kg NO_3/NH_4 ha^{-1})
Conventional tillage		
Corn	15	644.3
Wheat	15	382.7
Corn/soy/corn	15	424.3
Soy/corn/soy	15	299.8
SRWC[2]	11	168.0
Reduced tillage		
Corn	10	644.3
Wheat	10	382.7
Corn/soy/corn	10	424.3
Soy/corn/soy	10	299.8
SRWC	1	168.0

[1] Corn and soybean rotations are simulated separately, as: ‘corn/soy/corn’ indicates that the rotation begins with corn, while ‘soy/corn/soy’ indicates that it begins with soybeans.

[2] SRWC, short-rotation woody crop.

Cropland conversion to SRWCs was simulated at rates of approximately 10, 20 and 30% (4665, 9664 and 14,645 ha) of the base-case cropland area, respectively. We assumed that less productive and more erosive (higher slope) HRUs were the most likely to be taken out of crop production. Similarly, conventionally tilled HRUs were converted by preference over HRUs already in conservation tillage, in order to avoid increasing erosion rates. No pasture, grass or forested land was converted to SRWCs.

In the absence of information with respect to the spatial distribution of tile drainage, THRUs were assigned to the drained or undrained categories with reference to the STATSGO cropland ratings (see Table 2). For example, all THRUs of the Lester-Hawick-Terril (LHT) soil group were assumed undrained, as these soils are coarser and more sloping than the other soil groups in the watershed. Further, it was considered most likely that higher-value cropland (rated ‘prime’) would have drainage installed. No drained THRUs were converted to SRWCs except at the 30% conversion level. The final distribution of THRUs for each simulation was such that 49% of the THRUs were always classified as ‘drained’, in conformance with the 49% drainage rate estimated for this watershed. ADAPT apportions runoff differently if drainage is present. Therefore the model is run independently for drained and undrained THRUs, and the results are summed to determine the watershed response at the outlet.

The simulation was run for 6 years, with the first year serving to ‘prime’ the model and allow site preparation impacts to be included. Fall site preparation impacts were assumed to manifest as sediment delivered during the second year of the simulation.

Graphic analyses and *t*-tests for differences between means were performed in the package R[31].

Results and Discussion

Notwithstanding substantial inter-annual variability in modeled runoff and loading levels, ADAPT consistently simulated end-of-rotation reductions in sediment and nitrogen loadings—both at the field-scale and at the

Table 2. Descriptive data for STATSGO soil map units in the High Island Creek watershed.

Abbreviation	Series	Mean slope	Texture range
CNG	Canisteo-Nicollet-Glencoe	0.031	Fine loamy–sandy
LCC	Lester-Cordova-Canisteo	0.040	Fine argillic–sandy
CMC	Chaska-Minneiska-Colo	0.069	Fine silty–coarse loamy
LHT	Lester-Hawick-Terril	0.170	Fine loamy–sandy

Table 3. Percent change in annual runoff and nutrient yield compared to the default (no short-rotation woody crops, SRWC) cropping configuration. Negative values indicate a decrease compared to the default. The actual modeled values for the default simulation are presented for context.

Year	Runoff ($m^3 \times 10^6$)	Sediment (Mg)	Nitrogen (Mg)	Phosphorus (Mg)
Default yield and loading values				
1996	62	18677	198	122
1997	107	47582	307	326
1998	64	4551	33	55
1999	101	4983	39	46
2000	56	5202	39	33
Mean	78	16199	123	116
Percent change from default				
10% Conversion				
1996	–1.5	–21.8	–3.9	0.2
1997	–3.6	–44.1	–15.3	–0.4
1998	6.9	–19.7	4.3	–1.9
1999	–5.9	13.0	–1.2	21.8
2000	–13.1	1.7	–7.4	7.9
Mean	–3.4	–14.2	–4.7	5.5
20% Conversion				
1996	–3.6	–25.5	–3.3	1.4
1997	–6.5	–56.2	–26.8	–0.4
1998	18.2	–19.3	12.3	0.9
1999	–16.6	–2.9	–19.9	29.1
2000	–29.0	–13.2	–25.5	5.2
Mean	–7.5	–23.4	–12.6	6.9
30% Conversion				
1996	–5.6	–26.9	–8.1	2.7
1997	–15.1	–65.1	–35.4	–7.6
1998	12.8	–26.6	3.3	–10.4
1999	–8.7	–4.9	–22.5	17.4
2000	–28.4	–17.8	–12.4	9.5
Mean	–9.0	–28.2	–15.0	2.3

watershed scale—resulting from conversion of cropland to SRWCs. This was not true with respect to phosphorus loading. The magnitude of these reductions grew as increasing proportions of cropland were converted to SRWCs (Table 3).

Model validation

Flow predictions were compared with long-term stream monitoring data collected by the US Geologic Survey (USGS)[32].

Deviations of modeled annual flow values (which averaged 77.8 million m^3) from annual USGS flow estimates (average 87.4 million m^3) ranged from 6 to 292%, with the latter high value occurring in 2000, an unusually dry year. High Island Creek in its lower reaches passes over coarse streambed sediments that effectively result in subsurface flow during dry periods (see documentation of subsurface flow in the Minnesota River passing over similar sediments just upstream of its confluence with High Island Creek[33]). This effect likely skews the flow-monitoring data. Average deviation from measured annual flows, excluding 2000, was 13%. ADAPT underpredicted total annual flows in 1995–1998 and overpredicted in 1999–2000.

Excluding the subsurface flow issue, the largest deviation in the annual flow predictions from observed data is partly due to the lack of spatial variability in modeled precipitation across the watershed. In the Minnesota River Basin, the intensity of precipitation usually varies from west to east and a single median precipitation value, based on four stations scattered over the watershed, may not have captured extreme events that occurred, for example, in 2000. Monthly observed precipitation values from four dispersed stations deviated by 69–97%, on average, from the median value over the 1997–2000 period. An area-weighted averaging method (such as the Thiessen polygon approach), might have achieved a better approximation of watershed-wide rainfall, given the apparent strong precipitation gradient across the watershed and the nonuniform distribution of gauge stations. Initial comparisons of median and Thiessen-weighted average values did not suggest that the latter method would substantially improve flow predictions, but these comparisons were not made for all years of the simulation.

When the median precipitation values supplied to the model are superimposed on plots of total monthly runoff generated by ADAPT and measured by the USGS at Henderson (Fig. 1), it is clear that the modeled runoff conforms more closely to modeled rainfall than do the observed trends, supporting the proposition that rainfall variability is largely responsible for the observed disagreements between modeled and measured runoff. Because the model appeared to respond as expected to its climatic data inputs, its performance was judged adequate for the current application, in which we were interested in relative differences rather than absolute amounts. Previous calibrations of the ADAPT model for the neighboring similar watersheds, such as Sand Creek and Bevens Creek, determined that its performance criteria with respect to flow, nitrate and sediment predictions were comparable to those of other similar models[13,34]. The model performed the most poorly during periods of high rainfall variability, and also with respect to the prediction of sediment loads when streambank erosion was an important factor.

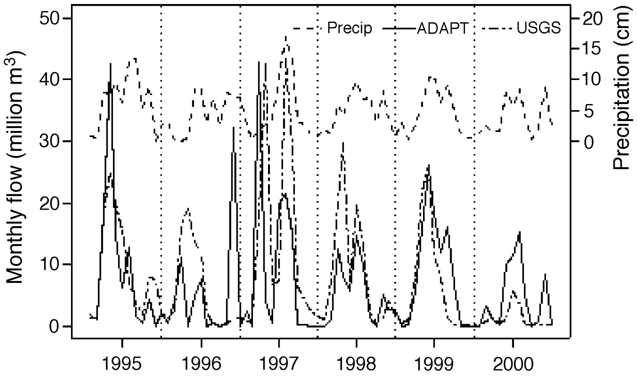

Figure 1. Monthly runoff values, with monthly precipitation superimposed, measured by the USGS at Henderson and modeled by the Agricultural Drainage and Pesticide Transport model (ADAPT). The largest absolute deviations occurred in 1997 and 1998, and are largely due to early and mid-season underpredictions by ADAPT, possibly in response to extreme events not captured by the median precipitation data (see discussion in text).

Sensitivity to parameter values

Rooting depth, productivity and fertilizer parameters were varied by ±50% to assess their effect on field-level nutrient and sediment delivery. These tests were conducted almost exclusively with respect to the SRWC THRUs, rather than for conventional crops.

While the greater rooting depth of SRWCs supposedly provides an advantage over annual crops with respect to N uptake[35], nutrient and sediment yields both proved insensitive to variations in a rooting depth parameter. This may reflect imperfections in model simulations of perennial root development (with progressive increases in root biomass) rather than an actual insensitivity to rooting depth.

The effect of differing productivity levels was tested by varying LAI curve parameterizations. However, there was no consistent correlation between modeled productivity and nutrient uptake by the crop and modeled losses to runoff and drainage. ADAPT is fairly limited with respect to its ability to simulate perennial crop growth and biomass accretion. Better simulation of these phenomena would likely have resulted in larger differences between the annual and perennial crop simulations. As it is, the observed reductions in sediment and nitrate loading most likely result simply from the reduced soil disturbance, absent annual tillage, and the greater (defined) biomass and cover of the tree crop. Levels and timing of fertilizer application can be important controls of nutrient losses from crops. Tests of 50% of the default level of N application reduced N export by 8–24% on drained THRUs and by 0.1–12% on undrained THRUs, while doubling N application rates increased N export by 16–34% on drained and by 2–18% percent on undrained THRUs. The sensitivity to N-fertilizer application rates and timing is not unique to tree crops (see Dalzell[13]), and merely serves to highlight the importance of careful fertilizer management to minimize the potential for nutrient losses in runoff.

Field-level effects of crop system, soil and drainage

Annual model outputs for each THRU were examined to assess the specific impacts of soil, crop and management inputs (Table 4). The SRWC rotation produced by far the lowest amounts of sediment per unit area of both drained and undrained cropland, compared to annual crops, on all soil groups. Results with respect to nutrient export were contingent on crop and drainage category.

Conservation tillage management reduced sediment and nutrient yields for all crops. In general, the benefits of converting conventionally tilled cropland to SRWCs were more marked than those gained from converting reduced-tillage cropland. While no-till management is not generally recommended for farm-scale SRWC systems, due to its productivity costs, we simulated a no-till system for the SRWC rotation in order to have a more complete assessment of tillage effects. Eliminating weed-control tillage operations and adjusting the USLE C-factors to reflect grass cover reduced modeled sediment yields by up to 85% relative to the conventional system, while P yields fell by 93%. In split-plot SRWC experiments in Alabama, Malik et al.[9] recorded a 64% reduction in sediment loss from tree plots two seasons after planting a rye grass cover, relative to plots with no cover crop. Because at the THRU level ADAPT models at the field scale, the modeled sediment loss values should be fairly comparable to measured plot-level values (i.e., not accounting for actual sediment delivery to the stream). Dissolved N yields were not sensitive to tillage.

The benefits of conversion also varied depending on soil type. For example, switching from conventional corn to

SRWC reduced total sediment yield by 92% on drained CNG soils, but only by 84% on CMC soils (Fig. 2). A similar switch on drained CMC fields reduced P yield by 81%, compared to an increase of 32% on LCC soils (Table 4).

The presence of subsurface drainage generally reduced modeled sediment losses attributable to overland runoff, but increased soluble nutrient (mainly NO_3-N) losses from fields. Consequently, modeled reductions in sediment yield (under SRWC) tended to be higher on drained land, while average modeled reductions in P yield were generally more substantial on undrained croplands. However, the difference in NO_3-N losses between corn and SRWC was similar on drained and undrained cropland; in fact the undrained

Table 4. Comparative modeled 5-year total nutrient and sediment yield for different transformed hydrologic response units (THRUs) by drainage status.

	Undrained cropland			**Drained cropland**		
Crop rotation	**Sediment ($Mg\ ha^{-1}$)**	**NO_3-N ($kg\ ha^{-1}$)**	**Total P ($kg\ ha^{-1}$)**	**Sediment ($Mg\ ha^{-1}$)**	**NO_3-N ($kg\ ha^{-1}$)**	**Total P ($kg\ ha^{-1}$)**
Canisteo-Nicollet-Glencoe (CNG)						
Corn, CT	5.5	0.5	73.9	4.9	16.2	70.0
Corn, RT	3.1	0.5	54.9	2.8	21	55.7
Soy, CT	3.7	0.8	50.3	3.4	1.3	49.9
Soy, RT	2.8	1.7	57.1	2.5	4.2	64.3
Wheat, CT	3.7	1.4	61.4	2.7	24.4	56.1
Wheat, RT	2.1	2.3	59.7	1.4	21.5	48.0
SRWC, CT	1.8	1.6	34.2	0.4	10.6	14.4
SRWC, RT	0.6	1.6	9.2	0.1	10.7	12.4
Grass	0.1	0.1	16.2			
Lester-Hawick-Terril (LHT)						
Corn, CT	135.0	0.7	912.2	103.6	23.8	873.6
Corn, RT	85.8	0.7	829.6	67.0	32.8	906.5
Soy, CT	99.2	0.6	814.4	66.7	4.5	668.7
Soy, RT	74.5	1	973.4	57.3	7.9	881.1
Wheat, CT	85.4	0.5	797.0	45.7	34.7	615.4
Wheat, RT	52.6	0.9	801.8	20.0	33.8	360.1
SRWC, CT	40.4	1.7	368.0	11.8	14.3	161.4
SRWC, RT	10.2	1.7	181.6	4.9	14.7	96.2
Grass	1.2	0.2	36.3			
Lester-Cordova-Canisteo (LCC)						
Corn, CT	10.4	0.2	22.3	10.2	9.1	20.9
Corn, RT	7.1	0.1	17.9	7	1.41	17.9
Soy, CT	10.1	0.4	19.3	11.1	8.3	22.1
Soy, RT	7.5	1.5	17.1	7.4	11.1	18.1
Wheat, CT	4.6	0.6	9.9	4.3	25.5	10.3
Wheat, RT	2.8	0.3	7.3	2.8	19.6	8
SRWC, CT	3.5	0.1	6.7	0.8	4.1	2
SRWC, RT	0.7	0.1	2.4	0.3	4.1	1.4
Grass	0.1	0.1	1.1			
Chaska-Minneista-Colo (CMC)						
Corn, CT	93.5	13.1	972.3	91.1	18.4	1099.5
Corn, RT	56.1	14.1	757.4	50.2	19.4	754.7
Soy, CT	80.2	1.6	1134.1	84.6	9.6	1081.7
Soy, RT	59.4	1.5	803.9	57	9.9	832.2
Wheat, CT	21	1.2	274.3	62	22	909
Wheat, RT	13.7	2.1	236.7	39.1	16.8	620.4
SRWC, CT	19.6	2.4	185.5	14.1	3.6	207.3
SRWC, RT	2.9	2.5	56.6	11.9	3.6	203.3
Grass	1	4.7	25.7			

Short-rotation woody crops (SRWC) and grass THRUs are included for contrast only; SRWC never replaced grass, and only conventionally tilled SRWC THRUs were included in the main simulation. The suffixes ‘CT’ and ‘RT’ indicate conventional and reduced tillage, respectively.

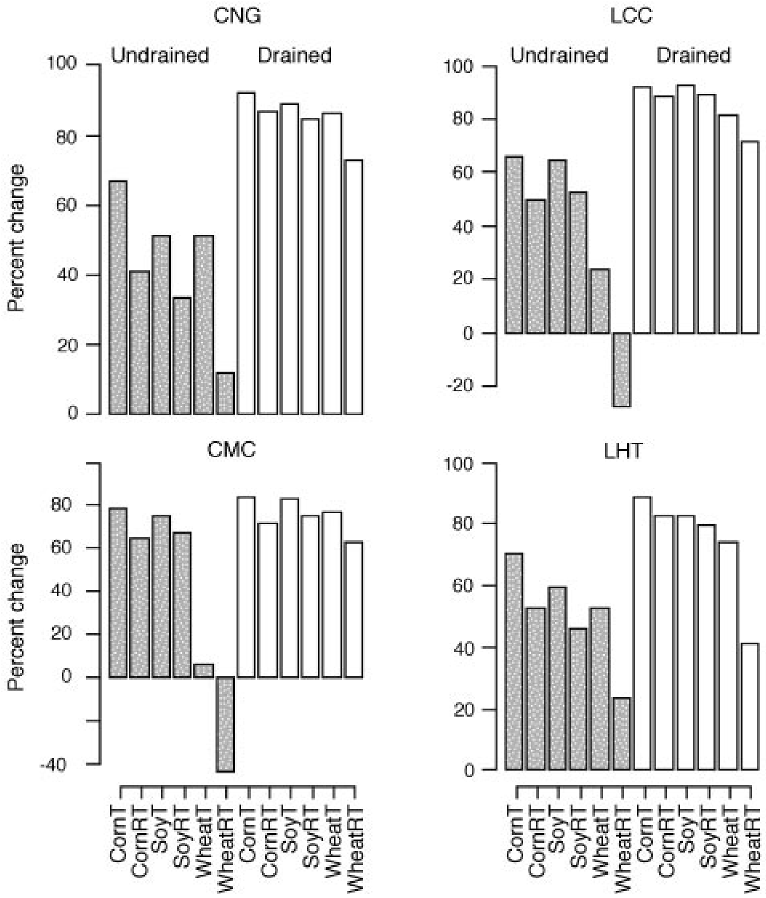

Figure 2. Percent reduction in 5-year modeled sediment yield (Mg ha^{-1}) of short-rotation woody crops (SRWC) relative to other crop/tillage systems, by soil group and drainage status. The suffix 'T' (e.g., CornT) indicates conventional tillage, while 'RT' indicates reduced tillage. The increases in sediment relative to RT wheat on LCC and CMC are probably due to the better ground cover provided by wheat stubble on these poorly drained soils, which are more sloping than CNG soils and finer-textured than LHT soils. See Table 2 for an explanation of CNG, LCC, CMC and LHT.

SRWC THRUs actually exported more dissolved N than corn or soybeans on some of the soil groups. This may be due to lower initial uptake rates by the young trees, or an indirect consequence of litter accumulation, which could result in higher levels of soluble nutrients being held at the surface and thus susceptible to runoff removal. In most cases the ratio of dissolved (as reported in Table 4) to sediment-associated N was at least a factor of 10 higher for SRWCs than for other crops; dissolved plus sediment N export was almost always lower from SRWCs than from any other crop. The model does not report litter accumulation, and the overwhelming influence of rainfall and spring runoff patterns on annual variations in nutrient export made it difficult to document a trend of increasing dissolved N export with stand development; further, such a detailed analysis of model behavior is beyond the scope of this paper.

In sum, the largest overall erosion benefits were realized by replacing corn with SRWCs on either drained or undrained soils, but the picture with respect to nutrients was more complicated. The largest NO_3-N reductions could be realized by replacing wheat on some drained soils, but the largest P reductions tended to result from the replacement of either corn or soybeans, depending on soil and drainage status. To reduce sediment yields, one would certainly want to displace conventionally tilled corn.

Watershed-level effects of SRWC conversion

The effects of 10, 20 and 30% cropland conversion to SRWC on annual runoff, sediment and nutrient delivery at the watershed outlet are summarized in Table 3. The largest proportional reductions in sediment and nitrate yield, which tended to occur in 1997 (a wet year), did not always correspond to the largest reductions in total runoff, which occurred in 2000 (a dry year). During some years sediment and nutrient delivery were actually higher in the SRWC scenarios than they were in the default; this was particularly true of P delivery, which tended to increase following conversion to SRWC. However, under the 20 and 30% conversion scenarios sediment delivery consistently declined relative to the default. It is notable that the greatest incremental reductions in sediment delivery were achieved at the 10 and 20% conversion levels, where the largest

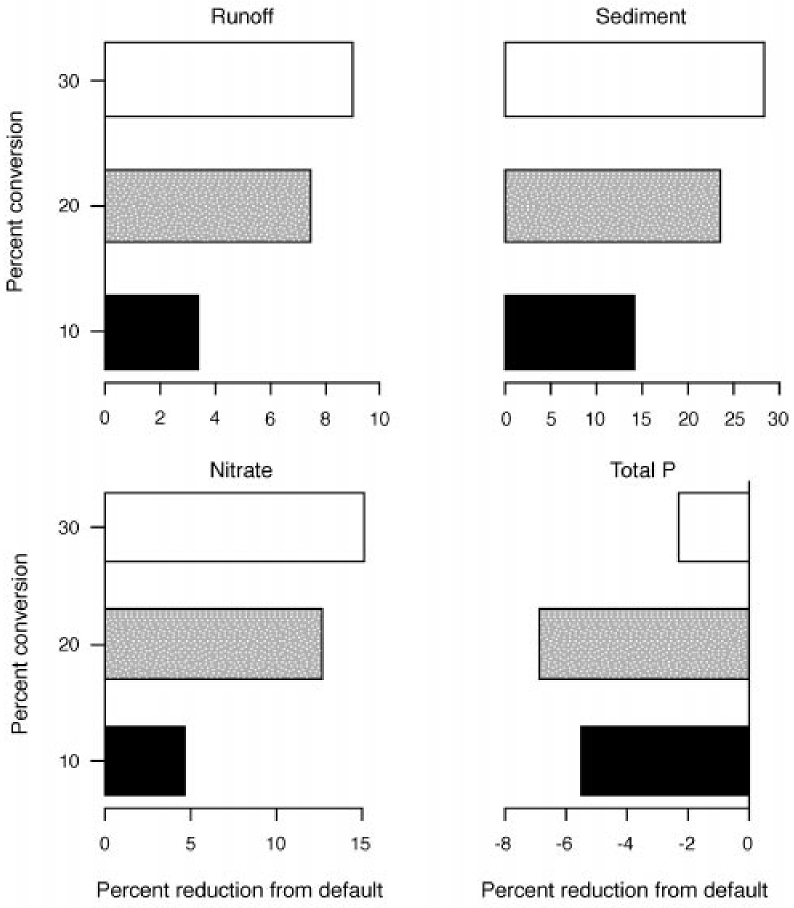

Figure 3. Summary of percent changes in modeled mean annual runoff and loadings (Mg) of sediment, nitrate and phosphorus (P) relative to the default (no short-rotation woody crops, SRWC) watershed condition. 'Percent conversion' refers to the modeled conversion scenario, as in Table 3.

proportion of the most erosive land and crop systems were moved into SRWC production.

Peak flows (annual maximum flow rates, which ranged from 50 to 372 $m^3 s^{-1}$ in the default and from 33 to 373 $m^3 s^{-1}$ in the 30% conversion scenario) did not vary significantly among scenarios ($P_t > 0.05$), but were highest in the default scenario during every year except 1995 and 1998. Annualized standard deviations were higher in 4 of the 6 years in the default scenario, compared to 30% conversion (range 5–24 versus 4–20 $m^3 s^{-1}$), although the differences were not significant, based on pairwise *t*-tests ($P_t > 0.2$). The slight moderating effect of conversion to SRWCs on peak flows, possibly due to their longer growing season and increasing transpirative capacity, supports the conclusions of a 2-year study in the Red River Valley[36], that mature hybrid poplar plantations behave hydrologically more like natural forests than like annual crops. The potential for hydrograph moderation may be an important consideration in flood-prone areas.

Similarly, the differences among scenarios in annual total nutrient and sediment yields were not significant ($P_t >$ 0.05). However, the lack of significance may be due in part to the very small sample size (4 points per comparison). Average modeled reductions in sediment yield over the entire rotation ranged from 14% for 10% conversion to 28% for 30% conversion. Mean annual NO_3-N yields fell by up to 15% (Fig. 3). By contrast, mean P yields actually increased by up to 7% following conversion.

Although total P export from SRWC THRUs was generally lower than from other crops, the ratio of dissolved to sediment-associated nutrients (see discussion above) tended to be a factor of 10–100 higher in SRWCs. Because only about 18% of the sediment exported from a field actually enters the stream, dissolved nutrients comprise a much higher proportion of the nutrient load leaving the watershed. Therefore the relative nutrient contribution of SRWC fields to the nutrient load is higher than from fields that export primarily sediment-associated N and P. This would be especially true at the 30% conversion level, in which some drained THRUs were converted to SRWCs. As noted above, the higher relative concentrations of dissolved P and N may result from leaf litter decomposition, since the model parameters were modified to simulate the litter component. Tolbert et al.[8] speculated that increased P export following canopy closure in sweetgum (*Liquidambar styraciflua* L.) plots in

Alabama might be attributable to an increase in the availability of organically bound P in the litter. In sum, the relatively higher dissolved phosphorus and nitrogen losses may partially account for the fact that reductions in sediment yield under SRWCs were much more marked compared to rowcrop HRUs.

Conclusions

The model results unequivocally indicate reductions in peak flows, as well as in annual sediment and nitrate delivery to the Minnesota river, following conversion of agricultural lands to SRWC production. Conversion of at least 10% of the cropland could theoretically produce sediment reductions in excess of the MPCA goal of 10% reduction in 10-year average sediment discharge rates by 2010 for the Minnesota River[37]. However, the goal of a 30% reduction in average NO_3-N discharge would not be achieved under any of the conversion scenarios, although annual reductions as high as 35% were achieved in some years with 30% cropland conversion. While the comparison suffers from incomplete data (the MPCA discharge reductions are relative to 1980–1996 averages, which we did not model), the results do suggest that more comprehensive land use and management changes would have to be implemented to achieve the MPCA goal for this watershed. Conversion to SRWCs with less intensive management, and particularly with lower N fertilization rates, could be more effective in reducing nutrient losses. The acceleration of dissolved nutrient transport by tile drainage may also constrain the beneficial effect of cropland conversion to SRWC.

On the whole, the model results suggest that while cropland conversion to SRWCs may be very effective at reducing sediment delivery to streams, its effect on nutrient delivery will likely be contingent on overall management and by the extent to which drainage remains an important factor in this watershed. Our interpretations of model results were limited by model shortcomings with respect to the simulation of perennial cropping systems. The incorporation of more sophisticated vegetation and crop parameterizations, such as those implemented in the REMM model for riparian zones[38] would substantially improve the usefulness of the model with respect to perennial crops. An additional, and related, issue is the limited ability of ADAPT to properly simulate nutrient movement within and among vegetation compartments, particularly when a perennial below-ground component is involved. Finally, the aggregation of THRUs and the limits of our spatial resolution meant that it was not possible to specify, for example, riparian planting locations for SRWCs. The special functions of forested riparian zones[39–41] make the location of SRWC plantings relative to streams of particular interest, and it would be useful to explore this.

Notwithstanding these limitations, the modeling results with respect to relative changes in nutrient and sediment delivery were sufficiently consistent and robust to be useful for policy guidance. The field-level results highlighted the importance of targeted incentives to optimize the water-quality benefits of cropland conversion to SRWC. Maximum sediment reduction benefits would be derived, for example, from the conversion of conventionally tilled corn on undrained, erosive soils. No-till or reduced-tillage management would further optimize the benefit of conversion: the no-till simulation produced much greater reductions in nutrient and sediment export, relative to the intensively managed SRWC (Table 4).

Policy decisions such as those regarding land-use incentive programs need to be based on the best information available. This project has demonstrated that useful information can be obtained from existing models and data when the resources for complete calibration and re-parameterization of models are not available. At the same time, it is important to recognize that such information can serve only as a qualitative guide.

Modeling results suggest that cropland conversion to SRWCs might be a viable and cost-effective approach to reducing agricultural sediment and nutrient runoff in the Minnesota River watershed. Modeled differences in relative benefits depending on soil type and physiography, as well as on the alternative management system, can provide guidance for possible targeting of incentives to farmers in order to optimize the benefits of cropland conversion.

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