Impacts of land-use change on hydrologic responses in the Great Lakes region

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SUMMARY

Human activities have historically affected hydrology in the upper Midwestern United States, specifically through the conversion of forests and prairie grasslands to agricultural uses. The hydrologic impacts of land-use change due to settlement on the water balance of three Great Lakes states: Minnesota, Wisconsin, and Michigan were analyzed using the Variable Infiltration Capacity (VIC) large-scale hydrology model, and changes in the spatial distribution of vegetation types were studied. Point model simulations demonstrated that the VIC model simulated changes in average annual and monthly evapotranspiration (ET) and total runoff response were in the same direction and had similar magnitudes to values from other published land-use change studies. At regional scales, simulated changes resulting from land-use modifications varied spatially and seasonally, but were strongly correlated to the type of vegetation conversion and the geographic location of the land-use type centroid. Deforestation was most dramatic in the central part of the study domain where five million hectares of deciduous forest have been converted to wooded grasslands and row crop agriculture, which resulted in a 5–15% decrease in ET and a 10–30% increase in total runoff. Northern areas, where land-use change was primarily from majority evergreen wooded grasslands and row crop agriculture, which resulted in a 5–15% decrease in ET and a 10–30% increase in total runoff. The southern and western parts of the study domain were dominated by a conversion from prairie to majority deciduous forest, experienced decreases of 5–10% in ET and increases of 20–40% in total runoff. Northern areas, where land-use change was primarily from majority evergreen wooded grasslands and row crop agriculture, which resulted in a 5–15% decrease in ET and a 10–30% decrease in total runoff.

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Introduction

Land cover plays a significant role in influencing the water and energy balance at the land surface via its effect on transpiration, interception, and evaporation from canopy leaves. Though the physical properties of soils are important and have a strong influence on the nature of hydrologic response (Dunn and Mackey, 1995), changes in vegetation cover can alter surface roughness and Leaf Area Index (LAI), thus influencing the surface energy balance and evapotranspiration (ET) (Pielke and Avissar, 1990; Greene et al., 1999). These influences may significantly affect the timing and magnitude of evaporative losses to the atmosphere and the amount of water yield that governs soil moisture content, runoff and baseflow patterns of regional hydrologic responses (Henderson-Sellers et al., 1993; Niehoff et al., 2002; Jones and Post, 2004), and lead to increased streamflow through vegetation species replacement and deforestation (Matheussen et al., 2000; VanShaar et al., 2002). Furthermore, land-use modifications can also affect flood frequency (Bultot et al., 1990; Brath et al., 2006) and regional climate (Copeland et al., 1996; Bonan, 1997; Greene et al., 1999; Pan et al., 1999).

Human activity is one of the major driving forces leading to changes in land cover characteristics and subsequently hydrologic processes. Substantial changes in land cover have occurred over North America in the past two centuries with the spread of settlement and increasing use of land resources for agriculture and economic development (Copeland et al., 1996). In the Great Lakes region, the main difference between current and pre-settlement land-use is that forest and grass prairie have been replaced by cropland. Modern forest covers 40% less area as compared to their pre-settlement (mid-1800s) extent (Cole et al., 1998). Much of the original hardwood forest has been converted to agricultural land or successional forest (Copeland et al., 1996). Parts of the Great Lakes region have experienced increased precipitation, earlier snow melt, more frequent large flood events, and greater sedimentation due to land cover change (Knox, 2001). Given the fact that changes in forest extent in the Great Lakes region during the past 150 years were far greater than the changes recorded over the preceding 1000 years (Cole et al., 1998), it serves as an unprecedented test case for studying the effects of land-use management as an essential component for sustainable development in the region.

Several previous studies have focused on how climate and land cover interact (e.g., Copeland et al., 1996; Bonan, 1997; Pan et al.,
Spatial variability of infiltration, and therefore soil moisture, is represented by the variable infiltration capacity curve. It represents the spatial variability in soil properties and topographic effects at scales smaller than the grid cell without assigning infiltration parameters to specific sub-grid locations, through an empirically based infiltration curve that is expressed as:

$$i = i_m[1 - (1 - A)^{1/b}]$$

(1)

where $i$ and $i_m$ are the infiltration capacity and maximum infiltration capacity, respectively, $A$ is the fraction of area within the grid cell, or within a vegetation type, for which the infiltration capacity is less than $i$, and $b$ is the infiltration shape parameter, which is a measure of the spatial variability of the infiltration capacity, defined as the maximum amount of water that can be stored in the soil column. The value of A increases with the soil moisture of the top two soil layers, effectively representing the amount of saturated soil within a given grid cell.

The model uses the top two soil layers to represent the dynamic behavior of the soil column as it responds to rainfall events, with the thin surface layer used to improve the calculation of surface energy fluxes and the deeper second layer to improve infiltration dynamics. Water that cannot infiltrate is removed from the cell as runoff. Drainage from the first to the second and the second to the third soil layers is driven by gravity, with the bottom layer producing baseflow (or groundwater return flow) through a non-linear empirical relationship based on the soil moisture of the bottom layer (Liang et al., 1994). Water and energy fluxes, including runoff, baseflow and ET, are computed for each cover type and reported as a weighted sum over the grid cell based on soil, vegetation, and climate data input. Special attention has been paid to representation of cold season processes, including soil frost, snow accumulation and the interception of snow by forest canopies (Cherkauer and Lettenmaier, 1999; Cherkauer et al., 2003), which are significant in this part of the United States.

The VIC model has been refined and implemented on a number of large scale river basins under various climate conditions (Abdulla et al., 1996; Nijssen et al., 1997; Cherkauer and Lettenmaier, 1999; Matheussen et al., 2000). Tests of the VIC model at multiple locations, such as prairie grassland of the First International Satellite and Land Surface Climatology Project Field Experiment (FIFE) site in central Kansas (Liang et al., 1994), a tropical forest in mid-latitude grassland in Brazil (Liang et al., 1996), forested watersheds in the Pacific Northwest (Matheussen et al., 2000), and a high-latitude wooded grassland in northern Scandinavia (Bowling et al., 2003), have yielded consistently favorable comparisons between simulated and observed surface fluxes.

Much of the following analysis will focus on how ET is affected by changes in land-use. Therefore, the VIC model equations relating to ET are presented here to clarify the connections between vegetation parameters and ET estimates. ET in the VIC model is calculated from evaporation from canopy layer, and transpiration from vegetation class (Liang et al., 1994). Canopy evaporation for the nth surface cover, $E_v[n]$, is specified as

$$E_v[n] = \left[ \frac{W_f[n]}{W_m[n]} \right]^{2/3} E_p[n] \frac{r_w[n]}{r_w[n] + r_0[n]}$$

(2)

where $n$ refers to the vegetation surface cover class index, $W_f[n]$ is the amount of intercepted water in storage canopy layer, and $W_m[n]$ is the maximum amount of water the canopy can intercept. $E_p[n]$ is the potential evaporation from surface based on the Penman–Monteith equation with canopy resistance set to zero. Elements used to calculate $E_v[n]$ are obtained from model input meteorological and vegetation data. $r_w[n]$ and $r_0[n]$ are aerodynamic and architectural resistances, respectively. Values of $r_w[n]$ are determined using a function of wind speed, zero displacement height,
roughness length and measurement height, while \( r_c[n] \) is set to use default values predefined for each vegetation class. The calculation of canopy interception, \( W_{in}[n] \), is directly tied to LAI using

\[
W_{in}[n] = K \times LAI[n, m]
\]

(3)

where \( LAI[n, m] \) is the Leaf Area Index for the \( n \)th surface cover class in month \( m \), and \( K \) is a constant taken to be 0.2 mm following Dickinson (1984).

Transpiration from vegetation is calculated as:

\[
E_t[n] = \left[ 1 - \left( \frac{W_{in}[n]}{W_{sm}[n]} \right)^{2/3} \right] E_{r}[n] \frac{r_w[n]}{r_w[n] + r_o[n] + r_c[n]}
\]

(4)

with canopy resistance \( r_c[n] \) given by

\[
r_c[n] = \frac{r_{\min}[n] g_{sm}[n]}{LAI[n, m]}
\]

(5)

where \( r_{\min}[n] \) is the minimum canopy resistance, a function of stomatal resistance, \( g_{sm}[n] \) is a soil moisture stress factor based on water availability in the root zone. Vegetation height, albedo and LAI are all allowed to change monthly within the VIC model, though these monthly values remain constant during the simulation. Other vegetation parameters, such as stomatal resistance and root depth, can vary between vegetation types but remain constant during the year.

**Study region**

The study region covers three Great Lakes states: Minnesota, Wisconsin, and Michigan, a total area of about 494,000 km². Elevation of the region varies from less than 200 m above sea level along the lake shores to more than 500 m in the northern forested hills. According to the Land Use History of North America (LUHNA) study by Cole et al. (1998), land-use patterns in the Great Lakes region have changed significantly since European settlers arrived in the 1800s, and intensified mainly due to the introduction of agriculture and continuous economic development. The land-use change study conducted by Cole et al. (1998) focused on changes in forest type and area. Reconstruction of pre-settlement forestation relied on the survey records of the General Land Office from the mid-nineteenth century (1815–1866) as parcels were allotted, and location records were kept by noting the species of tree at each corner. Maps were developed and then digitized using a Geographic Information System (GIS). The modern vegetation classification was based on the US Forest Service’s Fourth Forest Inventory (made between 1977 and 1983). Vegetation classes from the LUHNA study were categorized into the less specific types (Table 1) commonly used by the VIC model: evergreen needleleaf forest, deciduous broadleaf forest, wooded grassland, grassland, and cropland. Since non-forest areas are not classified in the original maps, pre-settlement non-forest area was assumed to be undisturbed prairie grass. Default grassland parameters were updated to reflect prairie grasses rather than modern pasture. Modern non-forest area was categorized as cropland, or more specifically corn, due to its prevalence in this part of the United States. Based on the summarized area percentage of the categorized vegetation: pre-settlement land cover was nearly 80% forested with 39% deciduous, 23% coniferous, and 17% wooded grassland. The remaining 20% was mostly grassland concentrated in the southwest portion of Minnesota.

Since the start of settlement in the early 19th century, land cover patterns have changed significantly. From Fig. 1 it can be seen that most of northern Minnesota, Wisconsin and Michigan have converted from evergreen needleleaf forest to deciduous forest or wooded grasslands. Wooded regions in mid-central Minnesota, southern Wisconsin and the southern part of the Lower Michigan peninsula have been deforested from a mix of deciduous forest and wooded grassland. Cole et al. (1998) concludes that forest cover has declined to only 40% of the total land area in the region, and only 39% of the pre-settlement forests have not changed their major types since settlement. Drastic changes include the conversion of forest to agriculture and evergreen forest to deciduous broadleaf forest. Evergreen forested area has dropped from 23% of the region in pre-settlement to only 6% in modern times. Deciduous forest has experienced less of an overall change in area coverage, in part due to the conversion of traditional evergreen stands to deciduous forest (Fig. 1). Dramatic deforestation in the central part of the study domain removed around 5,000,000 ha of deciduous forest. The most noticeable change is in the southern part of the region, where non-forest area has increased from 20% to more than half of the total area of the region.

### Data sources

The VIC model is used to examine impacts of vegetation change on the hydrologic response of the study region using 50 years (1950–2000) of meteorological data for both pre-settlement and modern land-use maps. The entire study region was gridded to a spatial resolution of 1/8° (~10–15 km). Implementation of the VIC model requires three types of input data: characterizations of land cover and soil, and time-series of meteorological data.

As for vegetation input, the two scenarios used in this study were based on the pre-settlement and modern land-use maps described previously, but these have been gridded for use with the VIC model by calculating the fractional area of each vegetation type within each 1/8° grid cell. Fractional coverages of less than 1% were discarded and all other vegetation coverage fractions were rescaled to fill the area. Urban areas, which account for about 3.1% of the study domain in modern times, were ignored for this study as they do not appear in the original land cover datasets. While the impact of urbanization is likely to be significant locally, this study was focused on region-wide changes in hydrology due to deforestation and the introduction of agriculture.

The primary characteristic of land cover that affects hydrologic fluxes simulated by the VIC model is LAI. In this study, monthly LAI for each vegetation class in each grid cell were taken from Land Data Assimilation System (LDAS) dataset described by Maurer et al. (2002), in which monthly values of LAI were derived from the \( \frac{1}{4} \) gridded monthly global LAI database originally created by Myneni et al. (1997). Monthly LAI values for wooded grassland and grassland were adjusted to represent historic prairie grasses based on the studies of Twine et al. (2004) and Owensby et al. (2006). Monthly LAI values do not change from year to year in this implementation. Rooting depths were also specified for each land-use type based on Maurer et al. (2002).

Soil data used in the model were processed from soil texture data downloaded from the conterminous United States soil data set (CONUS-SOIL) (Miller and White, 1998). This dataset was based on the State Soil Geographic Data Base (STATSGO) database.
processed into a multi-layer soil characteristics dataset at a 1-km spatial resolution to improve its relevance for most environmental modeling applications. Soil hydraulic properties were estimated based on 16 soil texture classes and sand, clay, and silt content. Three soil layers were used in the VIC model, with depths of 0.1 m, 0.3 m and 0.6 m from top to bottom, respectively. All necessary parameters were then processed and aggregated into the VIC model resolution. For parameters not available from the CONUS-SOIL database, default values were obtained from those used by Maurer et al. (2002). This resulted in a consistent set of soil properties that included parameters required for the soil frost algorithm that was not used by Maurer et al. (2002).

Daily meteorological data from January 1949 to July 2000 developed by Maurer et al. (2002) were used to drive the model simulations. The year 1949 was reserved for model spin-up, which allows the water and energy storage terms in the model to reach equilibrium and reduces the influence of the initial parameter settings, before analysis starts in 1950.

**Simulation evaluations**

**Model calibration and evaluation**

Calibration of the VIC model typically involves comparing simulated streamflow with observations and adjusting soil parameters to improve the agreement. Once an acceptable set of parameters has been developed, they are evaluated against observed streamflow for watersheds or time periods that were not included in the calibration process. Five USGS gauged watersheds, spread throughout the study domain as shown in Fig. 2, were selected for this process. Streamflow was simulated at a specific location, usually a gage station location by routing runoff and baseflow from each grid cell using the method of Lohmann et al. (1998). Since the modern vegetation map was derived from data collected in the early 1980s, the model was calibrated using streamflow from water years 1975–1980 to minimize changes in land-use that invariably affect the discharge measurement as time passes, while maintaining a long enough simulation period to capture both wet
and dry years. The evaluation time period (water years 1980–1990) was selected to meet the same criteria. Simulations were made using a single set of soil parameters to control infiltration throughout the region. Streamflow analysis for selected watersheds is illustrated in Fig. 3 for the evaluation period. Coefficient of efficiency \( E \) and index of agreement \( d \) were used to measure the accuracy of the calibration. Nash and Sutcliffe (1970) defined the coefficient of efficiency as

\[
E = 1.0 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(O_i - \bar{O})^2}
\]

where \( O \) is the observed data and \( P \) is the model simulated data, and \( \bar{O} \) is the observed mean. Index of agreement \( d \) was proposed by Willmott (1981) to overcome the insensitivity of correlation-based measures to differences in the observed and predicted means and variances.

\[
d = 1.0 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(P_i - \bar{O})^2 + (O_i - \bar{O})^2}
\]

The VIC model simulation results were comparable with observations for the upper Mississippi, Chippewa, and Wisconsin River basins. Nash–Sutcliffe coefficients for those three watersheds are above 0.6. The Muskegon and Grand Rivers are located in Lower Peninsula Michigan with substantially different soils resulting in lower Nash–Sutcliffe coefficients, 0.355 and 0.492, respectively. The indexes of agreement, \( d \), of all watersheds used in the evaluation are close to 0.9. Overall, model performance is acceptable within the study domain. There are no available observations of pre-settlement meteorology or streamflow, so a similar streamflow comparison cannot be conducted. Changes to soil properties were assumed to be minimal between the two scenarios as soil formation occurs over even longer time scales. The potential exception to this would be surface changes caused by tillage and compaction, whose effect we neglected assuming that changes in vegetation type would dominate. Therefore, a single set of model parameters was used for all simulations.

**Sensitivity analysis**

To understand the sensitivity of hydrologic responses to vegetation type and to compare them to the findings of other land-use change studies, the VIC model simulations were run on a single cell (44.19°N, 90.56°W) using five vegetation types from Table 1, for a 20-year period (1975–1995). This period covered both dry and wet years, which were representative of regional climate variability. For these simulations, it was assumed that each vegetation type covered 100% of the grid cell, thus allowing for independent analysis of ET and runoff responses. According to the generalized water balance equation, precipitation equals the sum of ET, streamflow (surface runoff + baseflow) and changes in storage. ET and streamflow are especially important components of the balance as changes in storage become negligible over long periods of time. Average annual monthly and average annual simulated values for ET and runoff were analyzed for each land-use scenario. Impacts of land-use class conversions on annual average ET and total runoff (sum of surface runoff and baseflow) were calculated as an amount of change for each conversion scenario.

**Regional application**

Spatial simulations were conducted for the study domain to analyze the impact of land-use change on hydrologic responses. Pre-settlement and modern simulations were driven using the meteorological and soil datasets described in “Data sources” and “Model calibration and evaluation”. This minimizes the effects of climate on simulation results. Bulk soil properties change very slowly and are not expected to have changed significantly between the pre-settlement and modern periods. Analyses of patterns of modern soil properties, such as sand, silt and clay fractions, demonstrate strong correlation with pre-settlement land-use. What is affected within the time frame of this study are near surface conditions such as compaction, which influence infiltration. Running historic and current model simulations with a consistent set of soil parameters restricts simulated changes to those caused by changes in vegetation and vegetation location, including ET rates, interception of snow fall and changes in soil types associated with each vegetation type.

Analysis were focused on annual and seasonal average differences in regional hydrologic variables including ET, total runoff, snow water equivalent (SWE), and soil moisture between pre-settlement and modern land cover. Spatial patterns across the region were analyzed to study the impact of geographic shifts in land-use on hydrology either through changes to effective climate or soil type. Areas where the main land-use has been converted in bulk from one type to another were identified and analyzed in a fashion similar to that used in “Sensitivity analysis”. Conversion groups...
were limited to grid cells with more than 85% of their area covered by a single type of vegetation as this limits interference from other land-use types, while maximizing the number of grid cells in the analysis. If the land-use within a given cell switched from more than 85% of vegetation type A to more than 85% of type B, it was considered to be a conversion of type A to type B. Distributions of hydrologic response variables for each vegetation type in pre-settlement and modern conditions were analyzed to study the spatial distribution and range of variations between land-use scenarios of each vegetation type.

To understand how changes in the geographic extent of vegetation types have affected their hydrology, spatial analysis was used to identify the centroids, “center of gravity,” of each vegetation type’s geographic extent and how that has changed between pre-settlement and modern land-use maps. By testing for changes in hydrologic variables relative to those in soil type and climate variables related to the observed shifts in centroids, it was possible to assess the significance of spatial extent in controlling the hydrologic impacts of land-use change.

**Results and discussion**

**Single cell vegetation analysis**

Annual average monthly precipitation, snow depth, LAI, ET, total runoff response, and snow water equivalent (SWE) for the surface snowpack were compared between each vegetation type (Fig. 4). Monthly precipitation increased gradually from spring to a peak in summer before decreasing in fall and winter (Fig. 4a). Snow was mostly seen in winter and early spring, with annual average peak accumulations of almost 20 cm in February and significant melt between March and April. Evergreen needleleaf forest LAIs remained constant throughout the year, while LAI values for other vegetation classes changed from minimums of less than 0.5 m² m⁻² during winter and early spring to peaks of up to 5 m² m⁻² during the summer (Fig. 4b). This was related to the seasonal growth patterns of all vegetation types represented in the model. Deciduous forest LAIs were similar to those of non-forest vegetation in winter and early spring, but increased more quickly...
in April and remained 2–3 times that of the non-forest vegetation between May and October. Cropland, wooded grassland and grassland types were all slower to leaf out in the spring, reaching peak LAs only in July and August, and then slowly declining into September and October. The magnitudes of peak LAs were different, however with cropland being nearly twice that of grassland and almost the same as that of forest. Wooded grassland LAs were between those of cropland and grassland types.

LAI variations were directly reflected in the ET responses in Fig. 4c. All vegetation types showed bell-shaped ET trends throughout the year with low values in winter and late autumn, gradually increasing to peak values in the summer. Both evergreen and deciduous forests had similar ET patterns. ET started to increase in March, peaking in July, and then decreasing in autumn. Cropland in this region was assumed to be planted in April and reached maturity in late summer. During this time, it consumed large amounts of water. Its peak ET rate in late summer even exceeded forest ET by as much as 60 mm. This peak in ET was partly due to the lower stomatal resistance (80 s/m) of cropland vegetation as compared to the other vegetation types (Table 2). Grassland ET values were not as high as those of cropland. Wooded grassland showed a mixture of forested and grassland response as fits its definition.

Monthly variations in total runoff response (Fig. 4d) were computed from model output, but were clearly the residuals of the water balance with snow serving as the storage term. Peak annual total runoff occurred in the spring as snow melted (Fig. 4a), while summer precipitation was used primarily to refill soil moisture lost to ET. Total runoff increased again in the fall as ET decreased and soil moisture reserves were refilled. Winter total runoff was minimal as precipitation was stored on the land surface as snow.

Forests had the lowest spring total runoff, which was mainly due to higher annual ET that kept soil moisture levels low, leading to increased infiltration. During the winter the presence of a canopy reduced the accumulation of ground snow through interception and limited solar radiation penetration, which in turn retarded melt of the snow pack, increasing the likelihood that it would infiltrate into the soil. Though long wave radiation can be enhanced by the presence of a canopy, it was not enough to accelerate the melt rate in the vegetated area. Grasslands, wooded grasslands, and cropland had higher spring total runoffs because of their lower ET losses and the more rapid loss of winter snow cover. Grassland had the highest runoff yield over all other vegetation types as it has the lowest ET losses.

On an annual average basis (Fig. 4f–h and Table 3), forests evaporated more than cropland, and cropland more than grassland primarily because of differences in stomatal resistance and monthly LAs that control ET. These results correspond to other vegetation change analyses including the works of Twine et al. (2004), Bosch and Hewlett (1982), and Silberstein et al. (1999)). Though there was a distinct difference in peak monthly ET rates between deciduous forest and cropland, over an average year cropland had similar cumulative ET losses to those of the deciduous forest. Total cumulative total runoff amounts between vegetation types varied inversely with ET as was expected from the water balance analysis. Snowpack varied most between forested and non-forested areas as sublimation of intercepted snow significantly reduced ground snow accumulation. Under the same snow fall, a change in vegetation type from forest to non-forest vegetation type could have a drastic impact on SCE.

The impact of VIC model simulated vegetation conversions on ET, total runoff and SCE are summarized in Table 4. Evergreen needleleaf forest conversion to wooded grassland had the greatest (21% or 148 mm/yr) ET decrease among the vegetation change scenarios. Similarly, this change also triggered an increase, by 128% (150 mm/yr), in total runoff, and a 95% (88 mm/yr) increase in SCE. The conversion with the least impact on ET and runoff was that from deciduous broadleaf forest to cropland, with only a 1% (2 mm/yr) decrease in ET and a 3% (4 mm/yr) increase in total runoff as their cumulative annual values were similar. However, SCE increased by 132% (105 mm/yr) resulting in the largest simulated change, due to the difference in snow dynamics between forested and non-forested vegetation types. Because snow accumulation and melt processes were similar in wooded grassland, grassland and cropland, minimal change (2%) was seen in SCE for conversions between these types.

### Regional annual average fluxes

For these simulations, the VIC model was applied across the three state study domain for the full climatologic period of record (1949–2000) using both pre-settlement and modern land-use maps. Spatial differences between the modern and the pre-settlement land-use cases for four variables: ET, total runoff, snow water equivalent (SWE), and soil moisture content are plotted in Fig. 5. The most visible changes in these variables can be related directly to changes in vegetation from Fig. 1.

Annual average ET (Fig. 5a) decreased from 30–60 mm/yr (6–10%) in northern Minnesota and Wisconsin, where evergreen needleleaf forest had been converted to deciduous broadleaf forest. The largest decreases in ET, ranging from 120–180 mm/yr (20–30%), resulted from evergreen forest conversion to wooded grassland. Changing from deciduous forest to cropland in central and southeastern Minnesota, eastern Wisconsin and Lower Peninsula of Michigan yielded a 30–70 mm/yr (5–12%) net reduction in ET. Much of the wooded grassland in southern Wisconsin and Lower

### Table 2
Minimum stomatal resistance of different vegetation classes used in the VIC model.

<table>
<thead>
<tr>
<th>Vegetation type</th>
<th>Minimum stomatal resistance (s/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evergreen needleleaf</td>
<td>250</td>
</tr>
<tr>
<td>Deciduous broadleaf</td>
<td>250</td>
</tr>
<tr>
<td>Wooded grassland</td>
<td>150</td>
</tr>
<tr>
<td>Grassland</td>
<td>120</td>
</tr>
<tr>
<td>Cropland</td>
<td>80</td>
</tr>
</tbody>
</table>

### Table 3
Average annual ET and runoff of different vegetation classes based on single cell simulation with rainfall of 808 mm/yr.

<table>
<thead>
<tr>
<th>Vegetation conversion</th>
<th>ΔET (mm/yr)</th>
<th>ΔTotal runoff (mm/yr)</th>
<th>ΔSWE (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN to DBm</td>
<td>27</td>
<td>4</td>
<td>1.1</td>
</tr>
<tr>
<td>EN to WGm</td>
<td>148</td>
<td>21</td>
<td>7.4</td>
</tr>
<tr>
<td>ENp to NFc,m</td>
<td>29</td>
<td>4</td>
<td>7.4</td>
</tr>
<tr>
<td>DBp to WGm</td>
<td>121</td>
<td>18</td>
<td>8.5</td>
</tr>
<tr>
<td>DBp to NFc,m</td>
<td>2</td>
<td>4</td>
<td>8.8</td>
</tr>
<tr>
<td>WGp to NFc,m</td>
<td>119</td>
<td>21</td>
<td>0.3</td>
</tr>
<tr>
<td>NFg,p to NFc,m</td>
<td>124</td>
<td>22</td>
<td>0.3</td>
</tr>
</tbody>
</table>

### Table 4
Vegetation conversion and its impact on annual average ET and total runoff based on single cell simulations using 100% coverage of each vegetation type. Changes are calculated as the first vegetation minus the second vegetation (downward arrow means a decrease and an upward arrow means an increase). Vegetation types are defined in Table 1. p – pre-settlement and m – modern.
Peninsula of Michigan has been converted to cropland, yielding increases in ET from 60–120 mm/yr (10–25%). Replacement of prairie grasslands with cropland resulted in increases in ET of around 40–80 mm/yr (10–16%) in southern Minnesota.

Changes in annual total runoff (Fig. 5b) were opposite in magnitude to changes in ET (Fig. 5a) as expected. Forest type conversion resulted in small decreases ranging between 30–60 mm/yr (20–50%) in average annual total runoff. Evergreen forest conversion to wooded grassland in the northern part of Lower Peninsula of Michigan experienced the largest increases of between 140–180 mm/year (80–140%). Deciduous forest conversion to cropland in eastern Wisconsin and Michigan also led to the generation of higher total runoff by 30–70 mm/yr (15–30%). Where vegetation has shifted from wooded grassland to cropland, especially in southern Wisconsin and Michigan, total runoff has decreased by 30–100 mm/yr (10–30%). Grassland conversion to cropland generated 30–80 mm/yr (10–40%) less total runoff in the southern portions of the region. Minimal changes in total runoff occurred in the central part of the region where deciduous forest was converted to cropland, both of which have nearly identical cumulative ET.

Changes in SWE were greatest in the central portions of the study region (Fig. 5c) where deforestation has been most severe. Interception and sublimation of snow from the forest canopy reduced SWE in forested domains with respect to cropland by 7–11 mm/yr (100–160%). Forest type conversion from evergreen needleleaf to deciduous broadleaf in northern Minnesota yielded a decrease in SWE of only 2–5 mm/yr (20–30%). Conversion of forest types to wooded grassland, effectively opened the canopy, reduced interception and increased ground snow accumulation by 4–8 mm/yr (40–60%) in the northern part of the Lower Peninsula of Michigan.

Patterns of soil moisture content change for all soil layers (Fig. 5d) were very similar to those of total runoff (Fig. 5b), where
vegetation change produced lower ETs, soil remained wetter and contributed to higher total runoff. This was clearest for conversion from evergreen to deciduous forest which increased soil moisture by 0.02–0.05 mm/mm (15–20%). Conversely, areas where wooded grassland and grassland had been converted to cropland, soil moisture content decreased by 0.02–0.08 mm/mm (5–20%) and led to a decrease in total runoff.

Fig. 5e summarizes changes in hydrologic response over the study area by plotting the percent area that has experienced net positive and negative changes in the four hydrologic variables discussed previously. More than 50% of the study area experienced declines in ET and soil moisture leading to equivalent areas experiencing enhancement in total runoff. Sixty-three percent of the total domain experienced increased SWE. Under the same meteorology, the magnitude of changes in hydrologic responses and total area in deforested and southern part of the region outweighed conversions between forest types. Net increases in total runoff and SWE for the entire study region were calculated as 0.15%, and 10.01%, respectively. Meanwhile, ET and soil moisture content decreased by 0.50% and 1.11%.

Regional annual average seasonal fluxes

Annual average seasonal water fluxes were compared between the two vegetation scenarios to explore spatial changes of hydrologic responses in greater detail (Fig. 6). Seasonal ET maps for spring and summer (Fig. 6a) highlight the change from forested to non-forested cropland in central Minnesota, Wisconsin, and eastern Michigan. Specifically, spring ET decreased by 50–70 mm (30–50%) and summer ET increased by between 40–80 mm (15–20%). This reflected the earlier greening of perennial vegetation and the higher peak ET rate of summer crops. Minimal changes were seen throughout the year in the northern regions close to the lakes where forests are relatively undisturbed.

Deforestation increased spring total runoff (Fig. 6b) in the central and northern part of the study domain by 30–100 mm (30–140%) due to deforestation. This agreed with the earlier single cell analysis where forest spring ET was higher and total runoff lower than cropland. Without canopy interception and sublimation, cropland areas accumulated more snow than forested areas. Melt occurred more quickly in these regions without canopy shading leading to a higher spring total runoff. Conversion from prairie grassland to cropland in southwestern Minnesota slightly increased ET in spring, yielding lower spring total runoff. Because all vegetation types reached their ET peaks in summer, changes in total runoff were minimal. Conversion from evergreen needle-leaf forest to wooded grassland in the northern part of Lower Peninsula of Michigan caused increases in total runoff of 10–30 mm (80–160%) in autumn and winter, which was reflected by decreases in ET for those seasons.

Fig. 6c illustrates an increase, by 15–20 mm (80–250%), in SWE during spring and winter for the central portions of the study domain where deforestation occurs. This increase correlated with the annual average increases shown in Fig. 5c.

Changes in soil moisture were most significant in summer when differences in ET were greatest between cropland, and wooded grassland and grassland in the southern part of the domain (0.05–0.10 mm/mm or 10–15% decrease), and deforested areas in northern part of the Lower Peninsula of Michigan (0.10–0.20 mm/mm or 40–60% increase) (Fig. 6d). These differences were carried over into the autumn as drier soils require a longer time to recover from their summer ET losses. Winter differences decreased further as soil moisture continued to recover without significant ET. Soil moisture decreased 0.02–0.06 mm/mm (5–12%) in the
southern part and increased 0.08–0.15 mm/mm (20–35%) in northern Lower Peninsular Michigan. Spring differences were lowest in grassland conversion to cropland (0.01–0.05 mm/mm or 5–10% decrease) as increased spring melt helped fill any remaining deficits in soil storage.

Geographic shifts in land cover centers of gravity

As a result of land cover change, the center of gravity for each vegetation class shifted geographically between the pre-settlement and modern era (Fig. 7a). Evergreen needleleaf, deciduous broadleaf and wooded grassland land cover definitions were the same between modern and pre-settlement simulations, so differences in their hydrologic response were a function only of their change in geographic range. Non-forested areas experienced both a geographic shift and a change in type from prairie grass to cropland. The geographic center of evergreen needleleaf forest has moved northward by 83 km as most of the evergreen forests in the central and southern region have been converted to deciduous trees. The remaining clusters of evergreen needleleaf forest were scattered through northern Minnesota and Upper Peninsula Michigan (Fig. 1). Deforestation to the south and west and the conversion of historic evergreen needleleaf stands in the north led to a shift of the geographic center of deciduous broadleaf forest by 138 km to the northwest. Wooded grassland also shifted to the northwest, but only by 90 km, as a large cluster still exists in southwest Wisconsin. Non-forested areas experienced the largest change, moving to the east-southeast by 318 km due to significant deforestation. The directions of all observed trends in geographic shifts and a change in type from prairie grass to cropland. The geographic center of evergreen needleleaf forest has moved northward by 83 km as most of the evergreen forests in the central and southern region have been converted to deciduous trees. The remaining clusters of evergreen needleleaf forest were scattered through northern Minnesota and Upper Peninsula Michigan (Fig. 1). Deforestation to the south and west and the conversion of historic evergreen needleleaf stands in the north led to a shift of the geographic center of deciduous broadleaf forest by 138 km to the northwest. Wooded grassland also shifted to the northwest, but only by 90 km, as a large cluster still exists in southwest Wisconsin. Non-forested areas experienced the largest change, moving to the east-southeast by 318 km due to significant deforestation.

In general, shifts to the north decreased annual average air temperature (Fig. 7b) and shifts to the northwest led to a decrease in annual average precipitation (Fig. 7c). Annual average values for precipitation, air temperature, ET, total runoff and SWE were computed for each land-use class in both modern and pre-settlement periods. An ANOVA test was then applied to assess the effect of geographic shifts on regional climate for each class (Table 5). Evergreen needleleaf and wooded grassland experienced 9 mm/yr (1%) and 8 mm/yr (1%) decreases in precipitation due to the shift in geographic domain, respectively, but neither was statistically significant. Deciduous broadleaf experienced a statistically significant decrease (15 mm/yr or 2%) in precipitation while the non-forested regions had a significant increase (83 mm/yr or 13%). All vegetation types, except non-forested, had statistically significant decreases in annual average air temperature. Once again non-forested regions experienced an increase. The directions of all observed trends in air temperature and precipitation were expected based on the observed shifts in geographic center (Fig. 7) versus regional climate patterns.

Dominant soil types within a land-use type’s extent may also have changed with the geographic shift of vegetation. An analysis of soil texture using the previous method found that there were no significant changes in soil properties for evergreen needleleaf forests, whose extent was dominated by sandy loam soils under both pre-settlement and modern land-use. Average percent sand content and porosity in modern deciduous broadleaf forest covered regions were found to increase significantly as compared to pre-settlement, as it has shifted northward from predominantly loam to sandy loam soils. Since maximum infiltration capacity within the VIC model was a function of maximum soil moisture, infiltration capacity also increased. Wooded grassland regions experienced a similar shift in soil texture, but the observed increases in average percent sand content were not significant. Non-forested areas continued to be dominated by loam soils, but experienced a statistically significant increase in hydraulic conductivity.

Because of shifts in geographic extent, changes to the hydrologic variables in Table 5, for all but the non-forested class, were due to the effective change in climate and soil. Evergreen forest which experienced the smallest shift in geographic location had a decrease in ET and increase in total runoff, neither of which was statistically significant. There was, however, a statistically significant increase in SWE. This was due to the fact that its modern range is limited to the colder northern extremes of the study domain with an increased likelihood of snow accumulation. Additionally, the extent of evergreen forest was dominated by areas directly around the Great Lakes which experienced higher snowfalls due to additional atmospheric moisture provided by the lakes (Fig. 7c). Deciduous broadleaf ET responses were not significantly different, but the northwest shift resulted in a significant decrease in mean total runoff by 21 mm (8.5%) and increase in mean SWE by 3 mm (25%). Wooded grasslands that are now lim-
Conclusions

Simulated changes in hydrologic responses that are vegetation dependent depend on characteristics of plant growth such as changes in LAI, displacement and roughness heights, and the presence of a canopy. SWE was most highly influenced by the presence or absence of vegetation canopy, with canopy interception reducing accumulation on the ground surface while increasing the duration of the snowpack by shading it from direct shortwave radiation. On an average annual basis, the magnitude of simulated changes in ET and total runoff from single vegetation type conversions agreed with results from previous published studies. Existing minor differences can be attributed to differences in study location and model parameterization.

Deforestation from settlement and the large-scale establishment of agriculture dominated the land-use change process in the study region, leading to increases in total runoff and SWE in more than half of the study area, with central Minnesota, Wisconsin and the northern part of Lower Peninsula Michigan experiencing the greatest increases in total runoff and SWE. Seasonal changes in water balance variables were more strongly correlated to land-use type. The most substantial changes in hydrologic fluxes occurred in spring and summer in the deforested regions. In addition to more SWE in those areas, spring total runoff increases of 30–70% indicated a greater risk of flooding and soil erosion under modern land-use. Simulation results also suggested that changes in soil wetness in the northern part of the region are minimal where only forest species changes. The southern part of the study region was drier under human influences because of pre-settlement prairie grass conversion to cropland agriculture.

The magnitudes of hydrologic variables within each land cover class were affected by shifts in their geographic centroids resulting from changes between their pre-settlement and modern extents. These shifts have been generally to the north from pre-settlement to modern times with the exception of the non-forested class, which shifted significantly to the east-southeast. This led to significant increases in average SWE for forest related land cover types as their northward retreat concentrates them in areas with colder temperatures and greater snow accumulation. Soil infiltration capacity increased for deciduous forest and wooded grassland area because of changes in dominant soil types and resulted in an enhancement of porosity. Geographic shift also reduced annual average precipitation for these vegetation types, which should result in a decrease in total runoff generation. These areas experienced decreases indicating that a change in soil type and precipitation pattern may be influential in simulated hydrologic changes.

Finally, the largest changes to ET (25%) and total runoff (136%) came from evergreen needleleaf conversion to wooded grassland.

Table 5
Mean (μ), standard deviation (σ), and P-value of annual average precipitation (mm), temperature (°C), ET (mm), total runoff (mm), and SWE (mm) hydrologic fluxes of different vegetation classes using pre-settlement and modern land-use maps from ANOVA analysis (using 95% significance level). P-value < 0.0001 indicates that paired hydrologic responses significantly different from each other. ns – not significantly different, s – significantly different. Arrows in front of significant indicator represent increase (upward) and decrease (downward), respectively. Vegetation classes are defined in Table 1. Vegetation substitutions p and m represent pre-settlement and modern, respectively.

<table>
<thead>
<tr>
<th>Vegetation class</th>
<th>Precipitation (mm)</th>
<th>Temperature (°C)</th>
<th>ET (mm)</th>
<th>Total runoff (mm)</th>
<th>SWE (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>μ</td>
<td>σ</td>
<td>P</td>
<td>μ</td>
<td>σ</td>
</tr>
<tr>
<td>ENp to DBm</td>
<td>739</td>
<td>70</td>
<td>ns</td>
<td>4.84</td>
<td>1.37</td>
</tr>
<tr>
<td>ENm to DBm</td>
<td>730</td>
<td>71</td>
<td>s</td>
<td>4.07</td>
<td>1.20</td>
</tr>
<tr>
<td>DBp to WGm</td>
<td>778</td>
<td>64</td>
<td>s</td>
<td>5.96</td>
<td>1.70</td>
</tr>
<tr>
<td>DBm to WGm</td>
<td>763</td>
<td>64</td>
<td>s</td>
<td>4.75</td>
<td>1.09</td>
</tr>
<tr>
<td>WGp to NFg,p</td>
<td>822</td>
<td>52</td>
<td>ns</td>
<td>7.82</td>
<td>1.07</td>
</tr>
<tr>
<td>WGm to NFg,p</td>
<td>814</td>
<td>38</td>
<td>s</td>
<td>7.09</td>
<td>0.77</td>
</tr>
<tr>
<td>NFg,p to NFc,m</td>
<td>649</td>
<td>87</td>
<td>s</td>
<td>6.08</td>
<td>1.28</td>
</tr>
<tr>
<td>NFc,m to ENp</td>
<td>732</td>
<td>102</td>
<td>s</td>
<td>6.87</td>
<td>1.56</td>
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</tbody>
</table>

Table 6
Changes in hydrologic responses of different vegetation conversion cases over the region, (downward arrow in A means decrease and upward means increase).

<table>
<thead>
<tr>
<th>Vegetation conversion</th>
<th>ΔET (mm/yr)</th>
<th>ΔTotal runoff (mm/yr)</th>
<th>ΔSWE (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENp to DBm</td>
<td>50 9</td>
<td>49 37</td>
<td>2.6 18</td>
</tr>
<tr>
<td>ENp to WGm</td>
<td>166 25</td>
<td>166 136</td>
<td>5.5 45</td>
</tr>
<tr>
<td>ENp to NFc,m</td>
<td>48 10</td>
<td>50 44</td>
<td>5.5 50</td>
</tr>
<tr>
<td>DBp to WGm</td>
<td>75 14</td>
<td>77 30</td>
<td>7.3 104</td>
</tr>
<tr>
<td>DBp to NFc,m</td>
<td>31 6</td>
<td>32 13</td>
<td>6.6 111</td>
</tr>
<tr>
<td>WGp to NFc,m</td>
<td>61 13</td>
<td>61 18</td>
<td>0.2 2</td>
</tr>
<tr>
<td>NFg,p to NFc,m</td>
<td>37 9</td>
<td>36 14</td>
<td>0.1 1</td>
</tr>
</tbody>
</table>
and were related to the large differences in ET between these land cover classes. Conversion between forest species and from prairie grassland to cropland yielded smaller changes in hydrologic response. Historical land-use changes have had a significant impact on the hydrology of this region. Pressed by population growth and changing agricultural demands, land-use in the region will continue to change. Historic land-use changes resulting from the expansion of agriculture and the harvesting of forests by European settlers have significantly affected regional hydrology and provide insight into more sustainable management practices for the future.

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References


