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M. P. Russelle
Plant Science Research Unit, USDA-ARS, St. Paul, Minnesota

D. W. Kelley
University of St. Thomas, St. Paul, Minnesota

A. S. Birr
Minnesota Department of Agriculture, Rochester, MN

D. C. Tiffany
University of Minnesota - Twin Cities

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Published in *GIS Applications in Agriculture, Volume II: Nutrient Management for Energy Efficiency*, edited by David E. Clay & John F. Shanahan (Boca Raton: CRC Press, 2011), pp. 395-424.

M. P. Russelle
Plant Science Research Unit, USDA-ARS
St. Paul, Minnesota

D. W. Kelley
Department of Geography, University of St. Thomas, St. Paul, Minnesota

A. S. Birr
Minnesota Department of Agriculture, Pesticide and Fertilizer Management Division, Rochester, Minnesota

D. C. Tiffany
Department of Applied Economics, University of Minnesota,
St. Paul, Minnesota

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23 Spatial Ramifications of Crop Selection: Water Quality and Biomass Energy

M.P. Russelle, D.W. Kelley,
A.S. Birr, and D.G. Tiffany

CONTENTS

23.1 EXECUTIVE SUMMARY

The use of GIS in concert with simple or complex simulation modeling provides an unparalleled way to generate new data and to help a variety of audiences understand spatial patterns of data. From improved understanding, policy incentives can be crafted to reduce adverse environmental impacts of agricultural production at lower costs than would be necessary otherwise. In this chapter, two case studies demonstrate how GIS and modeling can be used to understand how crop selection and soils interact to effect environmental outcomes across an agricultural landscape.

We addressed the needs of two distinctly different audiences: (1) a public drinking water supplier faced with increasing nitrate in a ground water source and (2) a variety of stakeholders involved with planning a new biomass conversion facility to produce renewable fuels from grain or cellulosic feedstock. In both cases, the GIS output documents the benefits of the perennial legume alfalfa (*Medicago sativa* L.) in particular landscape areas, and provides a mechanism to compare alfalfa with corn (*Zea mays* L.) and soybean (*Glycine max* [L.] Merr.).

23.2 INTRODUCTION

Farmers usually know that particular crops perform better on some soils or landscape positions than on others. This knowledge accrues over years of observation, either directly or by previous generations who farmed that land. Although there are management approaches that can reduce such variation (e.g., fertilization, artificial drainage, irrigation, etc.), the fundamental basis for the variation remains—the soils and their characteristics, and how these interact with weather.[1]

However, crop yields affect less obvious outcomes, such as net energy production of various biofuel crops or nitrate leaching losses to shallow drinking water aquifers. Here we present two case studies as examples of ways GIS can be used to help an audience gain new understanding of problems it faces and to visualize how to achieve better solutions by growing different crops in the landscape. Diversifying cropping systems may increase management effort, equipment needs, and other costs, but alternative crops can offer significant advantages. The primary alternative crop we consider here is alfalfa, a legume that requires no fertilizer N, fits well into rotations with other crops, and provides a wide array of environmental services, in addition to high dry matter and protein yields.[2]

In the first case study, we developed maps of estimated nitrate leaching losses into a rural water drinking supply. These maps were used for targeting the "leakiest" fields for improved fertilizer management of corn or better crop rotation. In the second study, we analyzed the yield and net energy production of different biomass crops in a prospective fuelshed near a town interested in producing alternative transportation fuels.

23.3 CASE STUDY 1: ESTIMATING NONPOINT NITRATE FLUX INTO A SHALLOW AQUIFER

In many regions, drinking water is obtained from shallow aquifers that are subject to contamination from inputs on or near the soil surface. Nitrate impairment of drinking water aquifers has been related to agricultural practices (fertilizer and manure application), residential sources (leaking septic systems), industrial activities (leaking fertilizer storages or spills), and geologic sources. The risk of contaminant movement through the soil depends in large part on soil characteristics, including depth, slope, landscape position, texture, and density. These characteristics define how much water infiltrates, how much is held against gravity, how quickly it moves, and how long it will remain in the plant root zone. The risk of nitrate loss by leaching also depends on the management of inputs that affect the concentration of the potential contaminant in the soil solution (e.g., nitrogen [N] fertilizer or animal manure) and the soil water balance (i.e., rootzone water storage capacity, effective precipitation, and crop water use).

The probability of N loss generally increases with the intensity of agricultural production, which usually is related to greater water and N inputs and shorter crop rotations that include only annual crops, such as corn and soybean. Within a particular crop rotation, nitrate leaching loss can be minimized with a combination of optimum N rate and source, and of timing and method of fertilizer application;[3,4] but further reductions can be achieved only with altered cropping systems.[5,6] As these authors and others have shown, alfalfa can be particularly effective in reducing nitrate leaching.

The nitrate concentration of public drinking water is currently limited by the U.S. EPA to 10 mg nitrate–N L^{-1} (water.epa.gov/drink/contaminants/basicinformation/nitrate.cfm). As nitrate concentration in a public water supply approach this limit, the water supplier must institute one or more means to reduce the concentration. This can be done by dilution with water from less contaminated sources (e.g., from deeper wells or surface water) or by removal using reverse osmosis, ion exchange, or, rarely, distillation. These tactics all require energy and produce waste materials. In the case of reverse osmosis at one treatment facility, 10%–20% of the treated water volume is discharged to a local stream at nitrate concentrations five to ten times that of the influent water. In addition, the discharge contains other salts that were concentrated during reverse osmosis. The advisability and sustainability of this permitted activity could be questioned.

An alternate, preventative approach is to reduce the amount of contaminants transported into the wellhead protection area (WPA). The WPA is defined by the area of land that contributes recharge water to the aquifer (see www.health.state.mn.us/divs/eh/water/swp/whp/fs/swpadfs.html for a more complete description). Most wellfield operators have dealt with known point sources, but it is less common and more difficult to address the nonpoint sources from agricultural fields and feedlots, which are privately owned and managed. In this case study, we were part of a team that provided ideas to a rural water supplier that wanted to reduce nitrate flux into the aquifer from nonpoint sources.

23.3.1 METHODS

The subject of investigation was a drinking water supply management area (DWSMA) for the Holland wellfield near Pipestone, Minnesota. This DWSMA encompasses about 8800 ha with 30 soil series and 49 soil mapping units (Figure 23.1). The aquifer is outwash sand and gravel deposited in a glacial meltwater channel that formed in clayey deposits. Loamy surficial deposits cover most of the underlying materials (Figure 23.2). Water table depth usually is within 6 m of the soil surface, and low-lying soils near the creek often are saturated or flooded during late autumn through spring. Due to their drainage condition, most of these low-lying soils are either not farmed or are used for pasture.

Base maps were generated with (1) a soils layer, delineated using the U.S. Department of Agriculture-Natural Resource Conservation Service (USDA-NRCS)

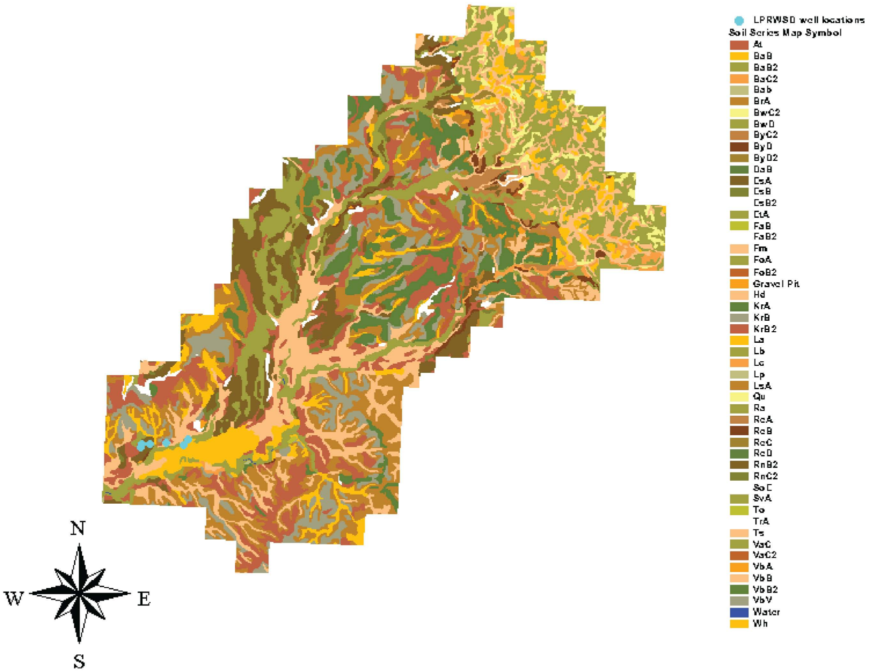

FIGURE 23.1 Soil units in the Holland, Minnesota, DWSMA. The DWSMA is comprised of 30 soil series and 49 mapping units.

Soil Survey Geographic (SSURGO) database for Pipestone county, Minnesota (www.soils.usda.gov/survey/geography/ssurgo/); (2) field boundaries estimated using 1991–1992 1 m USGS Digital Orthophoto Quad (DOQ) for the Holland (NE, NW, SE, SW) and Pipestone North (NE, NW, SE, SW) quadrants, Pipestone county, Minnesota (deli.dnr.state.mn.us/); (3) a subset of cultivated areas generated using Farm Service Agency information (confidential); (4) roads for Pipestone county, Minnesota (deli.dnr.state.mn.us/); and ancillary information.

The Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) modeling tool was used to provide one-dimensional, field-scale, continuous flow estimates to evaluate the effects of agricultural management systems on chemical and nutrient movement within and through the rootzone.[7] This software incorporates four distinct subroutines to predict hydrology, nutrients, erosion, and pesticide dynamics. The model considers chemical interactions, soil characteristics, weather, and management to arrive at selected output for soil, water, nutrient, or pesticide transport. Model input requirements include weather data (daily rainfall, temperature, solar radiation, and wind speed), soil characteristics, pesticide information, fertilizer and tillage data, and crop-specific information. Soil physical and chemical parameters are described for up to five soil genetic horizons, which are further distributed into seven distinct computational soil layers. GLEAMS output includes daily, monthly, or annual values for runoff, percolation volumes, sediment transport, pesticide mass and concentration, and plant nutrient mass and concentration.

The GLEAMS model utilizes the field capacity concept to simulate percolation of water through the computational soil layers. To estimate evapotranspiration

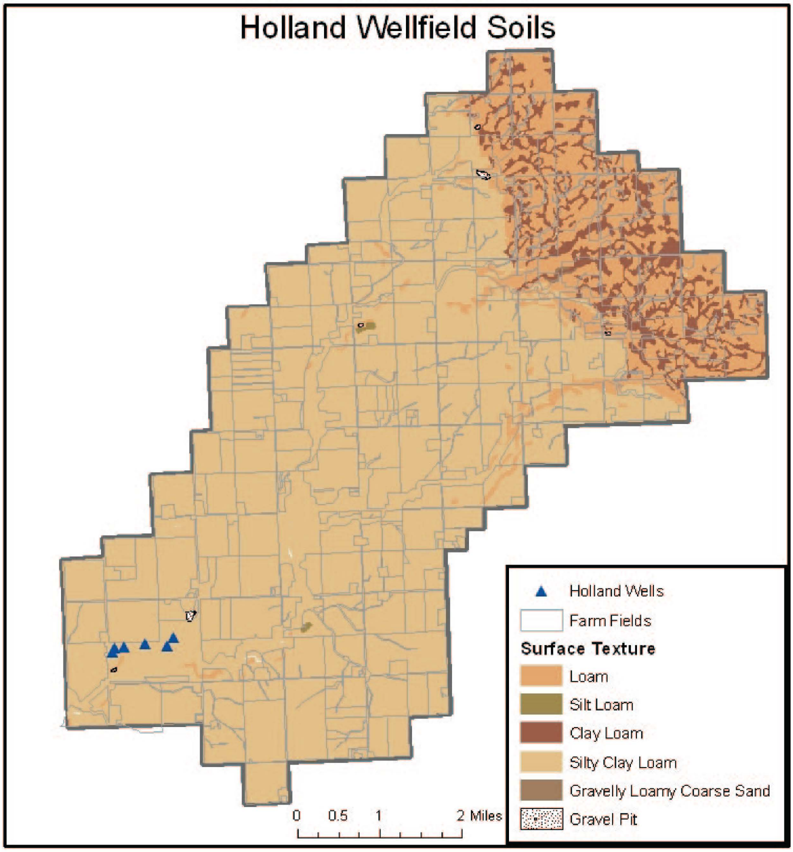

FIGURE 23.2 Generalized soil texture classes in the Holland, Minnesota, DWSMA.

rates and soil water content, model algorithms account for seasonal changes in leaf area index. Water percolation is calculated on a daily basis and is assumed to be zero unless the soil water stored above a given layer exceeds field capacity. Any nitrate available for leaching is transported deeper in the profile only when water moves between layers. In other words, the model ignores diffusive movement in unsaturated conditions. Nitrate leaching loss is assumed only when nitrate is present in the soil solution in the lowest computational layer and when deep percolation occurs out of this layer. We set the maximum depth of rooting to 1.5 m in this simulation for all crops, as information for deeper layers is not available for all soils included here.

23.3.1.1 Model Validation

Because of the number of soil types and the lack of observed data for each modeling case study, model calibration was impractical for each combination of soil, management, and crop. To substantiate the utility of GLEAMS to accurately predict nitrate leaching, we validated the model using observed field data from

TABLE 23.1
GLEAMS Model Validation Results

	Alfalfa		Continuous Corn		Corn–Soybean[a]	
Year	**Observed**	**Simulated**	**Observed**	**Simulated**	**Observed**	**Simulated**
			Nitrate–N Leached (kg N ha^{-1})			
1990	0	0	0	27	0	27
1991	1	5	70	63	81	55
1992	2	0	48	28	32	28
1993	4	6	84	88	67	52
Mean	1.8	2.7	50	51	46	40
% Error	—	54.7	—	1.6	—	(10)
			Percolation Volume (mm)			
1990	n/a[b]	0	20	80	19	80
1991	n/a	21	178	193	220	161
1992	n/a	0	131	92	124	92
1993	n/a	29	441	339	480	238
Mean	—	13	194	176	211	143
% Error	—	—	—	(9)	—	(32)

Source: Observed data obtained from Chung, S.W., *J. Environ. Qual.*, 30, 822, 2001.

[a] Corn grown in 1990 and 1992.

[b] n/a = not available.

the Southwest Research and Outreach Center of the University of Minnesota in Lamberton, Minnesota.[8] Climate data from the station were combined with site-specific field and crop management information to test the effectiveness of the GLEAMS model to predict nitrate losses, leachate percolation volumes, and crop yields for alfalfa, continuous corn, and corn–soybean in rotation (Table 23.1). The main parameter that was modified to achieve acceptable agreement between observed and predicted results was NRCS runoff curve number (CN2), which was set at 75 and 78 for alfalfa and corn, respectively[8] (see Ref. 9 for an in-depth evaluation of CN values).

Validation results were generally within 10% of the mean of observed data, with two exceptions. First, the small average difference between predicted and observed nitrate leaching under alfalfa was large in proportion to the small leaching values, but this error would not be biologically significant. Second, deep percolation under a corn–soybean rotation was underpredicted by 32%. Although this is a large difference for the cropping system, predicted percolation volumes were considerably larger for annual crops than alfalfa, as one would expect given the different temporal and total water demands of these crops. There were no significant differences between the other observed and predicted means (paired *t*-test, $p > 0.05$). For our purposes, we concluded that the model was adequate for predicting percolation volumes below these three crops.

23.3.1.2 Model Application

Following validation, the model was applied to each soil type using the following parameter files for each:

1. Nutrient: current standard management practices for each crop (fertility, timing, field operations) based on a survey of farm management practices[10]
2. Hydrology: predominant soil parameters, mean monthly maximum and minimum air temperatures, planting and harvest dates, irrigation parameters, daily precipitation summaries
3. Erosion: field parameters (slope, contour, CN, % cover, soil erodibility factor)

The effective rooting depth, texture of each soil horizon, effective saturated conductivity of each horizon, soil evaporation parameter based on surface soil texture, and saturated conductivity of each horizon were identified for the typifying pedon of the dominant soil textural class for each polygon. These selections were based upon the SSURGO attribute database and the Official Soil Series Descriptions (ortho.ftw.nrcs.usda.gov/osd/osd.html). Soil textural parameters such as bulk density, porosity, field capacity, permanent wilting point, and hydrologic soil group were also considered.

Mean monthly maximum and minimum air temperatures (°C), solar radiation (MJ m^{-2}), wind speed (km day^{-1}), and dew point temperatures (°C) were input from the GLEAMS climate database, along with the elevation and latitude of Pipestone. Daily data for the 10-year weather records (1989–1998) and daily precipitation and air temperature data for input to the GLEAMS model were obtained from the Minnesota Climatological Working Group Historical Records site (climate.umn.edu/doc/historical.htm) for Pipestone. Daily solar radiation, wind movement, and dew point temperatures were obtained from the GLEAMS model climate database.

Fertility for the corn production simulations consisted of applying urea with a nitrification inhibitor and incorporating to 15 cm 1 week before planting. The rate of N application varied with the crop rotation, and we included two rates for the continuous corn simulation to discern the potential impact of excessive fertilizer rates on nitrate leaching. No N fertilizer was applied to soybean or alfalfa, and we assumed the alfalfa was an established crop. Other essential nutrients were assumed to be optimal.

23.3.1.3 GIS Application

A soil map from the SSURGO database for Pipestone county was used to extract soil characteristics at a mapping scale of 1:24,000. Topology and attribute data were obtained from the USDA-NRCS Soil Data Mart site as SSURGO data in ArcView Shapefile format. These data are at a level of mapping designed for use by landowners and by township and county natural resource planners and managers.

The GLEAMS model output was extended to the individual polygons of the GIS coverages using ArcMap to produce the final map products, which depicted areas of high, moderate, and low nitrate leaching risks.

23.3.2 RESULTS

Predicted nitrate leaching was much lower under alfalfa than under the corn and soybean rotation or continuous corn with higher fertilizer N rates (Figure 23.3). It is evident from the maps that nitrate leaching was substantially higher when continuous corn received higher, rather than lower, fertilizer N rates, especially on the "leakier" soils. The model predicted similar yields for both of these N rates, as supported by current recommendations.[11]

A few fields in the DWSMA are irrigated, which reduces yield loss risks due to drought and often increases the crop yield potential. We ran GLEAMS for the entire DWSMA for irrigated situations, based on the "checkbook" method.[12] Predicted nitrate leaching increased under irrigation for all cropping and N rates (data not shown). This is a recognized risk of irrigation because the soil profile is maintained with more plant-available water and, therefore, has less remaining storage capacity for natural precipitation.

Water quality is improved most rapidly by altering land management within the 10-year time-of-travel area, rather than in other areas of the DWSMA, unless surface water provides a significant input to ground water.[13] The 10-year time-of-travel area usually is delineated using dye tracing and hydrologic modeling during wellhead protection development. In order to help the water utility focus incentives for

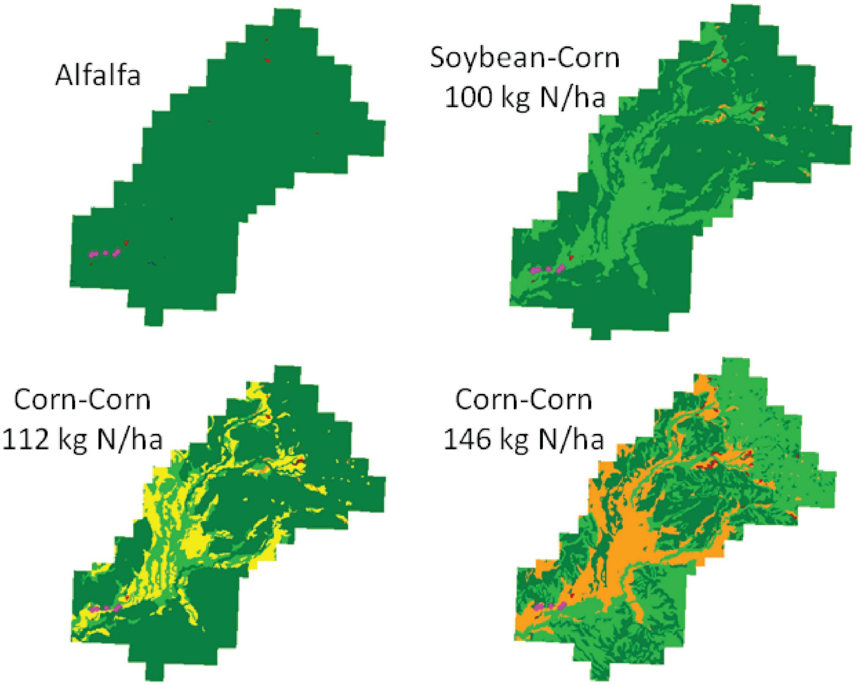

FIGURE 23.3 Effect of crop species and fertilizer N addition on estimated nitrate leaching in the Holland, Minnesota, DWSMA. The grayscale increments, increasing from light gray to black, are <2, 2–4, 4–9, 9–18, and >18 kg NO_3–N ha^{-1}; black circles indicate the wells at the wellhead.

changing cropping practices on these fields, we generated additional maps showing the relative decrease in nitrate leaching for areas within the 10-year time of travel (Figure 23.4). Some fields were characterized into a single category, whereas others were not. The water utility should focus on the fields in which the largest reductions could occur with improved fertilizer or manure management or rotation to a short-lived perennial, such as alfalfa. Conversion of the nearest of these fields will provide the fastest water quality improvement.

However, it is clear from Figure 23.4 that altering land management based on proximity alone is as likely to produce unsatisfactory reductions in nitrate leaching as basing the decision solely on either soil series (Figure 23.1) or soil texture (Figure 23.2). Other functional soil, crop, and management characteristics must be considered. As a case in point, the quarter section of land (about 65 ha) immediately north of the wellhead had been planted to native perennial grasses and forbs a few years before our team began this project. The water suppliers reasoned correctly that this conversion from annuals to perennials would reduce nitrate leaching. As is evident in

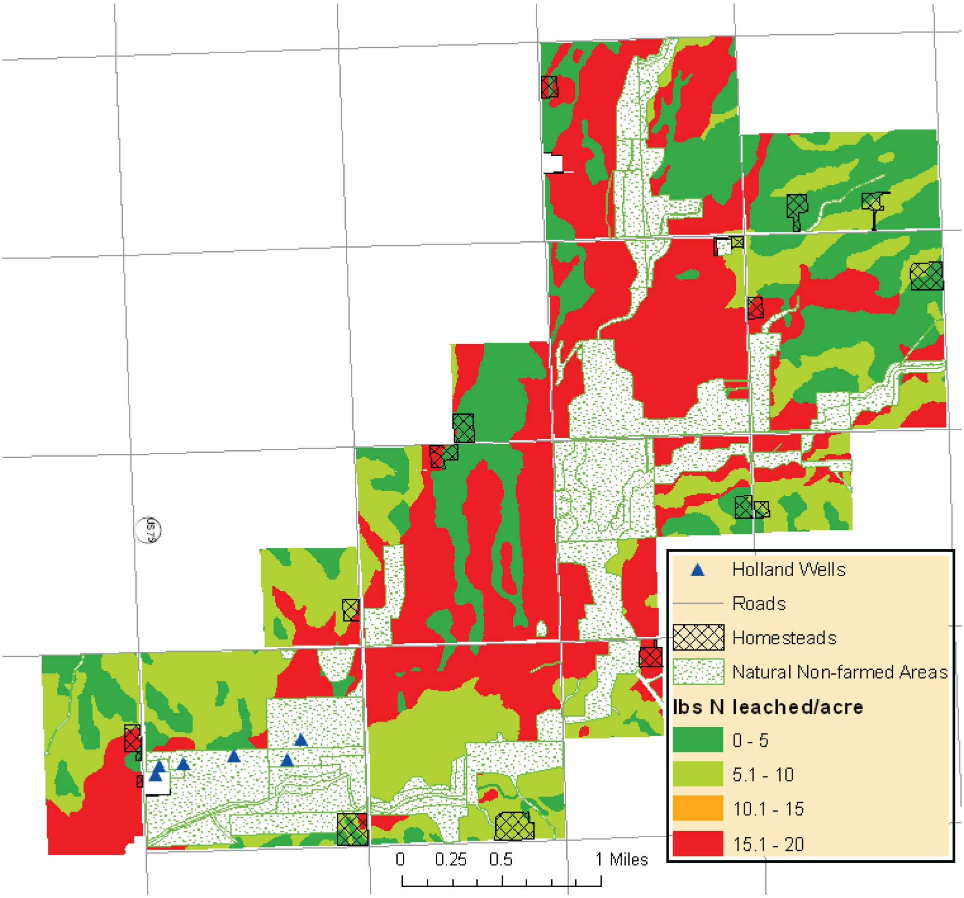

FIGURE 23.4 Reduction in nitrate–N loading estimated in GLEAMS by changing from continuous corn with annual applications of 180 kg N ha^{-1} to a well-adapted perennial crop that does not require N fertilizer.

Figure 23.4, however, nitrate leaching under corn was probably relatively small from these soils compared to other areas of the DWSMA.

Management of private land may be altered by encouraging voluntary changes (e.g., appealing to the manager's sense of public responsibility and providing research results that demonstrate good economic returns for a practice), supporting desired changes with payments (such as leases or per area payments for contracts) or in-kind contributions (seed, soil sampling, etc.), or regulation (such as penalties for excessive manure or fertilizer application rates). The option(s) selected will depend on many conditions we do not address here, such as legal authority, sociological considerations, and access to funds to incentivize improvements.

Sophistication and precision are sacrificed for the visualization of spatial patterns in many cases where GIS is employed, particularly when a rigorous process-based model is not used. But even when process-based models are used, a valid question is whether modeled predictions are reliable and accurate. One can use lookup tables, equations based on simplifying assumptions, or simulation models to estimate the amount of nitrate leaching that may occur. Although results from GLEAMS may not have been accurate for the annual crops, based on the dataset used in our validation process (described above), it is reasonable to expect that more reliable estimates will be provided by models that include crop management and weather variables along with soil characteristics. For the purposes of this project, the combination of simulation modeling and GIS was used to visualize nitrate leaching risks.

23.4 CASE STUDY 2: ESTIMATED BIOMASS FEEDSTOCK YIELD AND NET ENERGY DELIVERY IN A FUELSHED

Ethyl alcohol was the original fuel used by the internal combustion engines in the early to mid-1800s, and both Henry Ford and Charles Kettering promoted the development of cellulosic ethanol for use in automobiles.[14] However, this effort was stopped by the convergence of economic and political conditions offering cheap gasoline from crude oil.[14] And now, again, biomass crops as feedstocks for biofuels are catching fire—metaphorically, at least. Fuel and oxygen have been added by the DOE-USDA "Billion Ton" report,[15] the U.S. Energy Policy Act of 2005 (P.L. 109-58), the Energy Independence and Security Act of 2007 (P.L. 110-140), President Bush's "Biofuels Initiative," and President Obama's establishment of a top-level Biofuels Interagency Working Group, while review articles, editorials, and commentaries have added heat.[16,17] The extent to which herbaceous and woody biomass can provide cellulosic feedstock to replace fossil fuels is contentious, but the fact they will play a role is not.

Currently, only two principal grain crop–product combinations for biofuels have been commercialized in the United States (corn grain ethanol and soybean biodiesel), but sorghum (*Sorghum bicolor* [L.] Moench), wheat (*Triticum aestivum* L.), sugarcane (*Saccharum officinarum* L.) bagasse, and brewery waste are used in some of the 182 facilities operating in early 2010.[18] Of these, 21 were in Minnesota, with 3 using biomass as an additional source of heat and power.[19] Minnesota also hosted three biodiesel production facilities.[19]

Cellulosic plant materials may be converted with fermentation, pyrolysis, or other processes, but decisions about *what* crop to grow for cellulosic biomass will be guided by yield, cost of production, product requirements,[20] the potential to produce valuable coproducts (fats, oils, proteins), agricultural infrastructure, and agronomic capability. In the case of alfalfa, stems can be used as the biomass feedstock and leaves can provide additional income as a high-protein livestock feed.[21] Crop selection should also maximize ancillary environmental benefits and net energy production,[22,23] and alfalfa also fits these criteria.[24]

It is reasonable to expect the U.S. cellulosic biomass industry will be based on a variety of plant species and that facilities will be sited near feedstock production areas because of high transportation costs for this lower-density material. Because crop yields vary on different soils, highest efficiencies and lowest risk can be achieved by growing the selected crop on productive soils nearest the facility. Specific environmental goals (e.g., reduced nitrate leaching or lower risk of soil erosion) may be achieved most reliably by growing the appropriate crop on certain soils or landscape positions. To demonstrate this fuelshed planning approach, we analyzed a hypothetical, 80 km diameter area around Madelia, Minnesota, where a consortium of interests is developing plans for bio-based economic growth.[25,26]

23.4.1 METHODS

The subject area comprised about 420,000 ha of cultivated land. A base map was generated with a soils layer, delineated using the SSURGO database, and coverages of roads, municipal areas, and rivers were added. Corn grain and stover (assumed to be 1:1 on a dry matter basis), soybean, and smooth brome grass (*Bromus inermis* L.)-alfalfa yields were provided in the SSURGO database by soil series and county, based on a simple model driven by location and soil series (J. Floren, 1992, internal document, USDA-NRCS). This model was developed with data from field-level crop yields and extended to soils with similar characteristics. In this model, yield potential declines according to a climatology factor that combined growing degree days and growing season precipitation.[27] The model estimated yields for a smooth brome–alfalfa mixture because that was a common practice at the time (latter half of the twentieth century). Currently, it is more common for alfalfa to be grown as a pure stand when it is grown for hay or haylage. In most fields, yields from pure alfalfa stands likely would be similar to the mixture, except on poorly drained soils where the alfalfa would not persist.

This simple approach to predicting yields was appropriate for our purpose and helped us develop maps quickly. Alternatively, the Web Soil Survey tool (websoilsurvey.nrcs.usda.gov) now includes a National Commodity Crop Productivity Index and/or estimated yields for several primary crops in some states. As demonstrated in the first case study, one also could select more detailed crop growth models that are validated for the crop species of interest.

We translated yield into higher heating value (HHV) energy content[28] as delivered to the facility and reduced this by subtracting the energy used in typical crop production inputs in the fuelshed (Table 23.2). Typical and desirable crop production practices were outlined along with best estimates of fuel requirements and amounts of products used. These inputs were assigned HHV for materials utilized (fuels, fertilizers, lime, seed, and pesticides).[29–34] Some of these inputs varied with

TABLE 23.2
Inputs for Production of Corn Grain and Stover, Soybean, and Alfalfa (see Excel Workbook in Appendix)

		Requirement by Crop			
Operation or Material Applied	**Input**	**Corn**	**Corn Stover**[b]	**Soybean**	**Alfalfa**[c]
Tillage and Field Operations					
Dry fertilizer application (Urea + P + K)	Diesel fuel (L ha^{-1})	1.4		1.4	0.7
Lime application	Diesel fuel (L ha^{-1})				**1.8**
Field cultivator	Diesel fuel (L ha^{-1})	3.0		3.0	**0.8**
Roller harrow	Diesel fuel (L ha^{-1})				**0.8**
Planting	Diesel fuel (L ha^{-1})	3.2		3.2	**0.8**
Herbicide application	Diesel fuel (L ha^{-1})	0.9		1.4	**0.2**
Insecticide application	Diesel fuel (L ha^{-1})				0.9
Cultivation	Diesel fuel (L ha^{-1})	4.1		1.6	
Combine grain	Diesel fuel (L ha^{-1})	18.0		18.0	
Stalk raking	Diesel fuel (L ha^{-1})		4.7		
Baling: Large round bales	Diesel fuel (L ha^{-1})		7.2		
Swathing	Diesel fuel (L ha^{-1})				7.8
Raking	Diesel fuel (L ha^{-1})				9.4
Baling: Large square bales	Diesel fuel (L ha^{-1})				6.6
Stalk shredding	Diesel fuel (L ha^{-1})	6.9			
Chisel plow	Diesel fuel (L ha^{-1})			5.6	
Combined disk and V ripper	Diesel fuel (L ha^{-1})	13.7			
Moldboard plow	Diesel fuel (L ha^{-1})				***12.0***
Pickup use (supplies, repairs, etc.)	Gasoline fuel (L ha^{-1})	*9.3*		*9.3*	*9.3*

Seed, Fertilizer and Chemicals Applied					
Seed	Seed (kg ha^{-1})	19.9		87.4	**4.2**
Limestone	Aglime (kg ha^{-1})				**840.0**
Nitrogen[a]	N (kg ha^{-1})	112.0	*11.0*		
Phosphate[a]	P_2O_5 (kg ha^{-1})	*56.0*	*25.3*	*48.8*	*55.9*
Potash[a]	K_2O (kg ha^{-1})	*76.8*	*43.0*	*56.0*	*224.0*
Herbicides	Product (kg ha^{-1})	2.23		1.2	**0.56**
Insecticides	Product (kg ha^{-1})	0.08			0.28
Post Harvest					
Transport of grain or biomass from field to farm	Diesel fuel (L [Mg-km]$^{-1}$)	0.0281	0.0281	0.0281	0.0281
Drying of wet grain	Propane (L Mg^{-1} per % water)	2.97			
Drying of wet grain	Electricity (kJ Mg^{-1} per % water)	1.41			
Transport of feedstock from farm to facility	Diesel fuel (L [Mg-km]$^{-1}$)	0.0178	0.0178	0.0178	0.0178

[a] For purposes of illustration, yield-dependent inputs (italics) are shown for assumed static yields of 11.3, 4.8, 3.4, and 9.0 Mg ha^{-1} for corn grain, corn stover, soybean, and alfalfa, respectively.

[b] Corn grain inputs also apply to stover, with additional inputs required for nutrient replacement and stover collection and transport.

[c] One-time inputs for alfalfa are amortized over the 4-year life of the stand (bold-face).

yield (e.g., diesel required to haul biomass), whereas others were constant per unit area (e.g., diesel use for tillage). See the Appendix for the Excel spreadsheets showing these calculations.

Two harvests per year were assumed for alfalfa biomass.[21] Minnesota guidelines were used for N fertilizer rate assuming corn followed soybean and the price ratio of N to corn grain was 0.15.[11] We assumed replacement of phosphorus (P) and potassium (K) based on the amount of removed biomass of all crops and that lime would be required to prevent soil pH decline during alfalfa production. In most states, P and K recommendations are made on the basis of soil test results rather than on replacement. Furthermore, the availability of added P and K varies with soil chemistry. Therefore, better site-specific estimates could be made by taking these considerations into account. Here, we assumed that soil test levels were optimum and used the University of Wisconsin recommendations to maintain those levels.[35]

Corn grown after alfalfa needs less fertilizer N and insecticide than corn grown after soybean, so these energy savings were assigned to alfalfa. We included only the variable energy inputs rather than the embedded energy in the farm equipment and trucks, which already are part of the food, feed, and fiber production systems. Because end products from each crop varies with technology, we did not include processing energy beyond that required to produce and deliver the crop at a moisture content suitable for storage. We assumed that corn grain and stover were harvested in separate operations and restricted removal of corn stover to 50% in order to sustain soil organic matter (SOM) levels.[36] This removal rate might not be sustainable in a corn–soybean rotation, however, because SOM declines during bean production. On the other hand, sustainable stover removal rates may be higher in rotation with alfalfa, which improves soil carbon storage.[37]

Mean distance between fields and a farmstead was assumed to be 6.4 km (based on unpublished research in southern Minnesota by the senior author). To account for typical rectilinear road patterns, transportation distance to the processing facility was calculated as twice the square root of 2 multiplied by the vector distance of the field to Madelia. To simplify this calculation, we estimated energy required to transport each crop from concentric rings of 1 mile (1.6 km) radius. Inputs were aggregated and expressed in the relevant units, i.e., per unit area, mass, or distance. After calculating total yield, net energy (delivered), and net energy value for each cultivated hectare, corresponding coverages were produced using ArcGIS. All associated shapefiles and ancillary data layers are provided in the Appendix.

23.4.2 RESULTS

Energy input for corn production is considerably higher than for the legumes, soybean, or alfalfa, mainly because of N fertilizer requirements and the need to artificially dry corn grain most years (Figure 23.5). More than one-third of the energy input to corn receiving 112 kg N ha^{-1} in a corn–soybean rotation is due to the N fertilizer and nearly one-fifth of the input is due to grain drying. The figure for grain drying would vary widely with the weather conditions in autumn and the timing of harvest. Transportation is a small contributor to the net energy balance compared to the energy inputs of fertilizer, but was a larger factor for the cellulosic crops

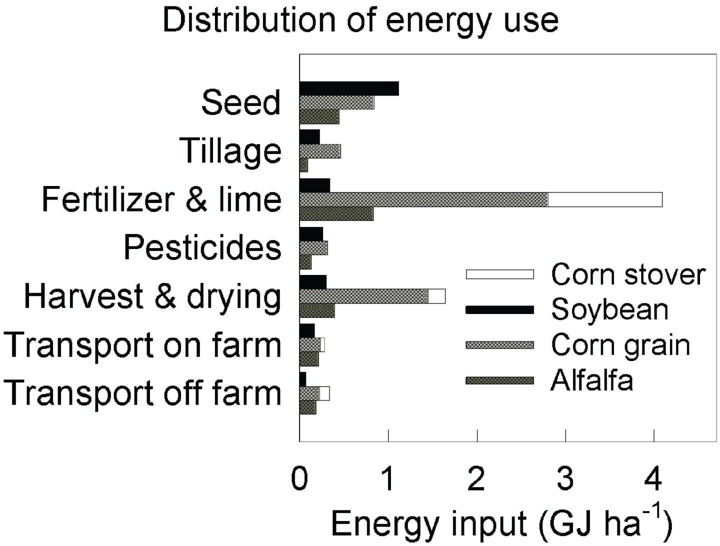

FIGURE 23.5 Energy use in different inputs for corn, soybean, and alfalfa production at assumed yields of 11.3, 3.4, and 9.0 Mg ha^{-1}, respectively.

(about 8% for alfalfa and 5% for the extra energy input to produce corn stover) than for grain (4% for corn and 3% for soybean). Note that the values in Figure 23.5 are static figures based on selected yields.

Unlike analyses that use static figures, such as those above and in most regional and national reports, our use of GIS provided products that showed how the energy required to produce and deliver biomass crops varied with soil type and distance to the biofuel manufacturing facility. Across the fuelshed, net energy yields of soybean ranged from 14 to 58 GJ ha^{-1}, corn grain from 33 to 206 GJ ha^{-1}, and alfalfa from 41 to 226 GJ ha^{-1}. Maps of the entire fuelshed are included in the Appendix, but the variability due to soils can be seen in an example subarea (Figure 23.6). The maps

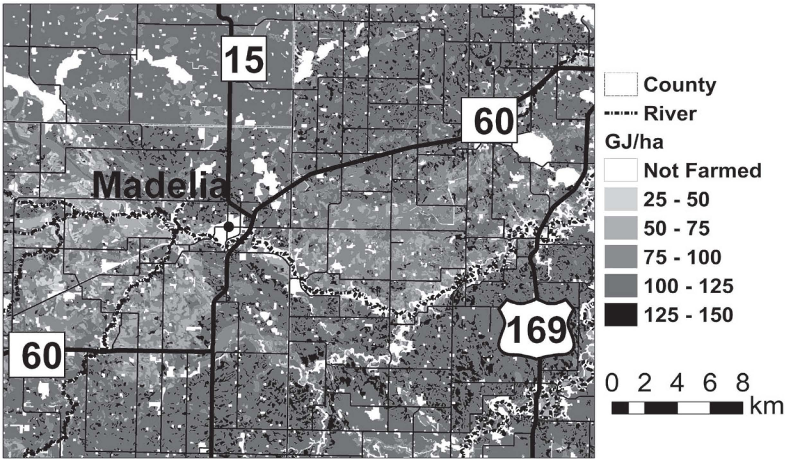

FIGURE 23.6 Spatial variation in net energy yield of corn grown on soils around Madelia, Minnesota.

TABLE 23.3
Examples of Energy Input and Output for Several Biomass Crops, Assuming a Fixed Yield and Distance (24 km) from a Processing Facility in Madelia, Minnesota

Crop (Yield)	Energy Input (GJ ha^{-1})	Delivered Energy (GJ ha^{-1})	Net Energy (GJ ha^{-1})	Output-to-Input Energy Ratio
Soybean (3.36 Mg ha^{-1})	5.4	54.3	48.9	9.0
Corn grain (11.3 Mg ha^{-1})	15.6	138.0	122.4	7.8
Corn grain + stover (11.3 Mg ha^{-1} and 4.8 Mg ha^{-1} stover dry matter)	20.1	211.9	191.7	9.5
Alfalfa (13.4 Mg ha^{-1})	6.6	192.1	185.4	27.9

illustrate that fields to the North and South of Madelia can be expected to produce higher net energy yields than those to the East and West. Further enlargements of net energy yield can assist in field-level decision making (examples for alfalfa and soybean are included in the Appendix).

Biofuel facility planners can minimize costs and maximize energy production by contracting with farmers on high-producing soils (Figure 23.6). Although the effect of transportation distance is small in terms of energy balance, it directly reduces the net yield of liquid fuel (not calculated here), so selecting farms based on productivity and proximity would help achieve the national goals expressed in several public laws.

The large amount of input energy needed for corn production concerns some authors.[22] In this fuelshed, alfalfa was about three times more efficient in producing energy per unit input than either corn or soybean, although gross and net energy production were similar for alfalfa and corn grain plus 50% stover (Table 23.3). This does not imply that alfalfa should be grown on all land parcels, but rather that its inclusion in crop rotations would improve net energy production in the fuelshed, in addition to providing many environmental benefits (e.g., better water, soil, and air quality, and improved wildlife habitat). Our analysis shows that alfalfa grown in riparian areas west of Madelia yield three to four times more net energy than soybean (Figure 23.7) while contributing to improved water quality.

Requirements for liquid fuels and natural gas vary among the crops, and these energy sources differ in their economic costs.[38] Economic costs of energy inputs were set at \$9.00 GJ^{-1} for liquid fuels, \$6.73 GJ^{-1} for natural gas, and \$22.75 GJ^{-1} for electricity. Using these prices, the net energy delivered per dollar of energy input ranged from 570 to 800 MJ \$$^{-1}$ for soybean, 380 to 1020 MJ \$$^{-1}$ for corn grain, and 790 to 2540 MJ \$$^{-1}$ for alfalfa. Fine-scale maps covering about 1550 ha are included in the Appendix to illustrate how this information might be used at the farm scale. However, these maps were not intended for within-field management decisions. The inherent variability within the soil series polygons (due to inclusions and indistinct borders) and the effects of past field management (erosion, manure application, etc.) limits the utility of these broad-scale maps to larger areas.

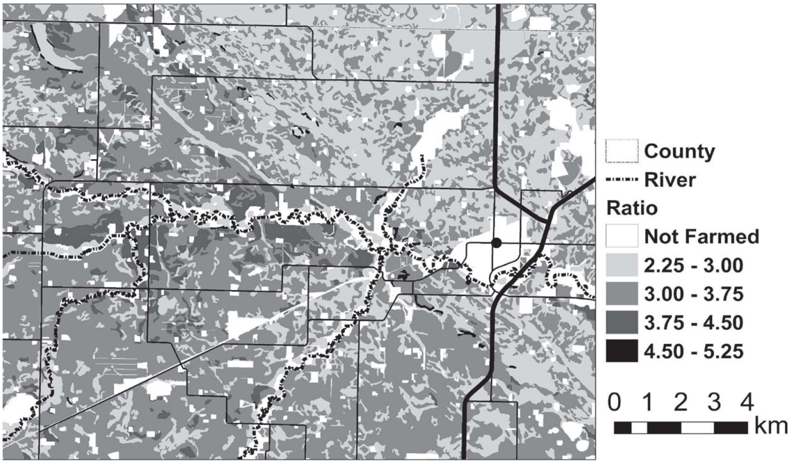

FIGURE 23.7 Relative net energy yield of alfalfa compared to soybean delivered to a hypothetical facility in Madelia, Minnesota.

As stated earlier, other considerations should be taken into account when deciding which biomass crop to select and where to grow it in the landscape. Data layers (digital elevation models, location of shallow aquifers, estimates of greenhouse gas emissions, etc.) can be added to these GIS-based analyses.[39,40]

For the grain crops and eventually for lignocellulosic crops, the land area required per megaliter of ethanol or biodiesel may be calculated from mapped yields,[41] allowing more complete life-cycle assessment of selected scenarios. Predicted net energy yields can be validated by long-term local records of crop yields, when available. Such maps and data layers may also help regional, state, and federal policy makers evaluate how they might encourage particular biomass production systems to achieve policy goals.

23.5 CONCLUSIONS

Soil information can be used to guide decision making when public water supply managers, biomass fuelshed operators, and others are selecting crop species, but only after the information is synthesized to produce interpretable outputs. Soil units are defined by a number of characteristics that do not necessarily relate to the problem of interest. The importance of particular soil characteristics, however, depends on the crop species and management, which are taken into account in simulation models. GIS allows us to aggregate the model output into categories, making the map product easy to interpret. In the DWSMA, specific fields were highlighted to help the managers prioritize their prevention activities and note which fields are not likely contributing to the problem of excess ground water nitrate. In the prospective biomass fuelshed, planners could visualize which areas of the fuelshed could supply feedstock most efficiently, assess how feedstock selection will affect net energy production, and consider areas where additional environmental payments may be available to improve farm profitability.

ACKNOWLEDGMENTS

The wellhead protection area research was supported in part by the Legislative Commission on Minnesota Resources (#L3916016101). In-house funding from USDA-ARS supported both projects. Dr. Prasanna Gowda, Kyle J. Symoniak, and Kyle Kvien assisted with other portions of the DWSMA mapping. We appreciate the editorial reviews by Ryan Maher and Ginger Walker. Results of these two studies have been published previously only as abstracts of technical presentations. Mention of specific commercial products was made for the purposes of completeness and does not imply endorsement by the organizations involved in this research.

APPENDIX

Primary Folder	**Contents**
Holland_DWSMA	Contains each of the following folders and files required for data generation and mapping as described in this chapter.
Subfolder	
Color figures	Color versions of Figures 23.1 through 23.4.
Holland_DWSMA_GISfiles	
Subfolder/file	
DOQ_color	Color digital orthoquads of the DWSMA area.
DWSMA	Arc shapefiles for the DWSMA.
Excel_files	MS Excel workbooks containing the GLEAMS model output for the different crop–soil management scenarios used in the study.
Fields	Arc shapefiles for field boundaries, natural areas, and nonfarmed areas.
GLEAMS	Simulation program files, including the modified version we used in the research, and the required input files, including the 10 year weather file (Pip10pcp.dat), crop-specific management parameter input files, by crop, soil type, and irrigation (present or absent), and in the case of corn, N fertilizer timing and rate. These files may be read and modified using a text editor, such as Notepad. The .par files that end in "e" include erosion parameters, "h" are hydrology parameters, and "n" are nutrient parameters. Output files also are included for each scenario. In order to understand these files, users must have some familiarity with the file structure required and produced by GLEAMS; documentation is provided within the GLEAMS_Program folder.

mn117_pipestone_mn	Arc shapefiles for the NRCS digital soil survey SSURGO soils for Pipestone COUNTY, Minnesota.
N_Leaching	Arc shapefiles for nitrate–N leaching losses as predicted by GLEAMS. The three shapefile groups are 1_N_leach (<2 lb/ac), 4_N_Leach (2–4 lb/ac), and 8_N_Leach (8–16 lb/ac).
Soildata	Arc shapefiles for soil polygons and for soil attributes joined to GLEAMS output for corn and alfalfa and the nitrate–N reductions achieved by converting from corn to alfalfa.
Support	Arc shapefiles for Minnesota counties, DWSMA wells, roads, and the area.

HollandDWSMA_crop_modeling.mxd

The Arc map document file that contains data frames for:

1. Holland Wellfield Landcover—location of Pipestone COUNTY, Minnesota; the DWSMA; farm fields; unfarmed areas; roads; wells.
2. Holland Landcover Imagery—Farm Services Administration Color Orthophotos 2003–2004; the DWSMA; roads; wells.
3. Holland Wellfield Soils—NRCS digital soil survey (SSURGO soils) for Pipestone COUNTY, Minnesota; the DWSMA; farm fields; wells.
4. N Loading Reductions with Management—SSURGO soils joined to GLEAMS model output; the DWSMA; farm fields; unfarmed areas; roads; wells.

Madelia_fuelshed	Contains each of the following folders and files required for data generation and mapping as described in this chapter.
Subfolder/file	
Color figures	Color versions of Figures 23.5 through 23.7, and additional figures of the entire fuelshed, by crop, of (1) net energy at the farm (without transport to Madelia), (2) net energy with transport delivered to Madelia, and (3) total energy delivered per dollar cost of energy invested.
Net energy calculations.xlsx	Annotated Excel workbook with separate worksheets for each crop to calculate energy input, energy output, and net energy production at a defined yield, moisture content, and hauling distance. Typical U.S. units are given for most operations.

Madelia_fuelshed_GISfiles

All GIS files are in the following coordinate system:
UTM
Zone 15
Nad83
Meters

Alfalfa_shapefiles

Layer: alfalfa_energy2010.shp

Overview: The spatial boundaries of this layer are comprised of SSURGO soil map units, Minnesota 1990s census of the land use boundaries, and 1 mile (1.6 km) concentric circles surrounding the city of Madelia. The following attributes are the resulting energy calculations associated with the alfalfa yields derived from the SSURGO data. Example values are presented in parentheses.

Field	**Description**
AREA	Polygon area in m^2 (1,127.64550420000).
PERIMETER	Polygon perimeter m (280.32763887900).
MALFYLDLU_	Polygon id (2).
MUSYM	SSURGO map unit symbol (386).
MUKEY	SSURGO map unit key (400,598).
MUSYMNAME	SSURGO map unit symbol name (OKOBOJI M).
BROMALFHUN	Bromegrass–alfalfa yield units normalized by acres (Tons).
BROMALFHYL	Bromegrass–alfalfa yield (3.00000000000).
ENERGYHAY	Harvested energy content of alfalfa in kcal/ac = BROMALFHYL × 3,551,020 (10,653,060.00000000000).
LUSE_CODE	Minnesota 1990s census of the land use code (21 = cultivated land).
DISTANCE	Concentric circle distance in m (40,225.00000000000).
ALFOUTENG	Output energy from alfalfa in kcal/ac = 12,481,200 BTU/ton/ac × BROMALFAHYL × 0.252 (9,435,787.19999999000).
ALFIN1ENG	Input energy associated with field operations and seed in kcal/ac = 1,198,466 BTU/ac × 0.252 (302,013.43200000000).
ALFIN2ENG	Input energy associated with nutrients and transportation in kcal/ac = 195,276 BTU/ton/ac × BROMALFHYL × 0.252 (147,628.65599999900).
ALFIN3ENG	Input energy associated with transportation to the plant in kcal/ac = 2,842 BTU/ton/mile × BROMALFHYL × (DISTANCE/1609 m/mile) (53,713.80000000000).
ALFNETENG	Net energy after accounting for transport energy associated with transport to the plant in kcal/ac = (ALFOUTENG + ALFOUT2ENG) − (ALFIN1ENG + ALFIN2ENG + ALFIN3ENG) (9,771,334.52399999000).

ALFNETENG2	Net energy without transport energy associated with transport to the plant in kcal/ac = (ALFOUTENG + ALFOUT2ENG) − (ALFIN1ENG + ALFIN2ENG) (13,142,617.48000000000).
ALFYLDMET	BROMALFHYL expressed in Mg/ha = BROMALFHYL × 2.24 (6.72000000000).
ALFNETMET	ALFNETENG expressed in GJ/ha = ALFNETENG × 1.0341396 × 10^{-5} (101.04923976116).
ALFNETMET2	ALFNETENG2 expressed in GJ/ha = ALFNETENG2 × 1.0341396 × 10^{-5} (135.91301183720).
ALFNETMETJ	Total net energy for each concentric circle in TJ = (ALFNETMET × (AREA/10,000))/1,000 (0.01139477209).
ALFOUT2ENG	Energy associated with nitrogen fertilizer benefit to next two corn crops and insecticide benefit to next corn crop in kcal/ac = 3,328,981 BTU/ac × 0.252 (838,903.21200000000).
ALFIN1DOL	Input costs associated with field operations and seed in $/ac = $14.52810000000.
ALFIN2DOL	Input costs associated with nutrients and transportation in $/ac = $2.5567 × BROMALFHYL (8.57010000000).
ALFIN3DOL	Input costs associated with transportation to the plant in $/ac = $0.0270 × BROMALFHYL × (DISTANCE/1,609 m/mile) (2.02500000000).
ALFINDOL	Input costs after accounting for transport energy associated with transport to the plant in $/ac = (ALFIN1DOL + ALFIN2DOL + ALFIN3DOL) (25.12320000000).
ALFINDOLM	ALFINDOL expressed as $/ha = ALFINDOL × 2.47 (62.05430400000).
ALFMJDOL	Output energy delivered per value total energy input in MJ/$ = (ALFOUTENG × 0.01033448)/ALFINDOLM (1,571.42934199465).
ALFOUTMETJ	Total harvested energy for each concentric circle in TJ = (ALFOUTMEN × (AREA/10,000))/1,000 (0.01100347597).
ALFINDOLMT	Total value of input costs for each concentric circle in $ = (ALFINDOLM × (AREA/10,000))/1,000 (0.00699752569).
ALFOUTMET	ALFOUTENG expressed as GJ/ha = ALFOUTENG × 1.0341396 × 10^{-5} (97.57921200693).

Corn_shapefiles

Layer: corn_energy2010.shp

Overview: The spatial boundaries of this layer are comprised of SSURGO soil map units, Minnesota 1990s census of the land use boundaries, and 1 mile (1.6 km) concentric circles surrounding the city of Madelia. The following attributes are the resulting energy calculations associated with the corn yields derived from the SSURGO data. Example values are presented in parentheses.

Field	Description
AREA	Polygon area in m^2 (1127.64550420000).
PERIMETER	Polygon perimeter m (280.32763887900).
MCORYLDLU_	Polygon id (2).
MUSYM	SSURGO map unit symbol (386).
MUKEY	SSURGO map unit key (400598).
MUSYMNAME	SSURGO map unit symbol name (OKOBOJI M).
CORNUNIT	Corn yield units normalized by acres (bu).
CORNYLD	Corn grain yield (136.00000000000).
ENERGYCORN	Harvested energy content of corn grain + stover in kcal/ac = CORNYLD × 190,996.8 (25,975,565.00000000000).
ENERGYCRNG	Harvested energy content of corn grain in kcal/ac = ENERGYCORN – ENERGYCRNS (12,841,854.00000000000).
ENERGYCRNS	Harvested energy content of corn stover in kcal/ac = CORNYLD × 96,571.4 (13,133,714.00000000000).
LUSE_CODE	Minnesota 1990s census of the land use code (21 = cultivated land).
DISTANCE	Concentric circle distance in m (40,225.00000000000).
CGSOUTENG	Output energy from corn grain and stover in kcal/ac = 494,612 BTU/bu/ac × CORNYLD × 0.252 (16,951,342.46400000000).
CGSIN1ENG	Input energy for corn grain and stover associated with field operations, seed, fertilizer, pesticides in kcal/ac = 4,409,879 BTU/ac × 0.252 (1,111,289.50799999000).
CGSIN2ENG	Input energy for corn grain and stover associated with drying, nutrients, and transportation to the farm in kcal/ac = 15,926 BTU/bu/ac × CORNYLD × 0.252 (545,815.87199999900).
CGSIN3ENG	Input energy for corn grain and stover associated with transportation to the plant in kcal/ac = 147 BTU/bu/mile/ac × CORNYLD × (DISTANCE/1609 m/mile) (856.80000000000).
CGSNETENG	Net energy for corn grain and stover after accounting for transport energy associated with transport to the plant in kcal/ac = (CGSOUTENG) – (CGSIN1ENG + CGSIN2ENG + CGSIN3ENG) (15,293,380.28400000000).
CGOUTENG	Output energy from corn grain in kcal/ac = 327,644 BTU/bu/ac × CORNYLD × 0.252 (11,229,015.16800000000).
CGIN1ENG	Input energy for corn grain associated with field operations, seed, fertilizer, pesticides in kcal/ac = 4,223,189 BTU/ac × 0.252 (1,064,243.62800000000).

CGIN2ENG	Input energy for corn grain associated with drying, nutrients, and transportation to the farm in kcal/acre = 8664 BTU/bu/acre × CORNYLD × 0.252 (296,932.60800000000).
CGIN3ENG	Input energy for corn grain associated with transportation to the plant in kcal/acre = 80 BTU/bu/mile/acre × CORNYLD × (DISTANCE/1609 m/mile) (68,544.00000000000).
CGNETENG	Net energy for corn grain after accounting for transport energy associated with transport to the plant in kcal/acre = (CGOUTENG) – (CGIN1ENG + CGIN2ENG + CGIN3ENG) (9,799,294.93200000000).
CGSNETENG2	Net energy for corn grain and stover without accounting for transport energy associated with transport to the plant in kcal/acre = (CGSOUTENG) – (CGSIN1ENG + CGSIN2ENG) (17,842,035.96000000000).
CGNETENG2	Net energy for corn grain without accounting for transport energy associated with transport to the plant in kcal/acre = (CGOUTENG) – (CGIN1ENG + CGIN2ENG) (11,844,721.98000000000).
CSNETENG	Net energy for corn stover after accounting for transport energy associated with transport to the plant in kcal/acre = CGSNETENG – CGNETENG (5,494,085.35200000000).
CSNETENG2	Net energy for corn stover without accounting for transport energy associated with transport to the plant in kcal/acre = CGSNETENG2 – CGNETENG2 (5,997,313.98000000000).
CORNYLDMET	CORNYLD expressed in Mg/ha = CORNYLD × 6.273 × 10^{-2} (8.53128000000).
CGSNETMET	CGSNETENG expressed in GJ/ha = CGSNETENG × 1.0341396 × 10^{-5} (158.15490169544).
CGSNETMET2	CGSNETENG2 expressed in GJ/ha = CGSNETENG2 × 1.0341396 × 10^{-5} (184.51155930860).
CGNETMET	CGNETENG expressed in GJ/ha = CGNETENG × 1.0341396 × 10^{-5} (101.33838941261).
CGNETMET2	CGSNETENG2 expressed in GJ/ha = CGSNETENG2 × 1.0341396 × 10^{-5} (122.49096050508).
CSNETMET	CSNETENG expressed in GJ/ha = CSNETENG × 1.0341396 × 10^{-5} (56.81651228283).
CSNETMET2	CSNETENG2 expressed in GJ/ha = CSNETENG2 × 1.0341396 × 10^{-5} (62.02059880352).
CGSNETMETJ	Total net energy for each concentric circle in TJ = (CGSNETMET × (AREA/10,000))/1,000 (0.01783426639).
CGNETMETJ	Total net energy for each concentric circle in TJ = (CGNETMET × (AREA/10,000))/1,000 (0.01142737792).

CSNETMETJ	Total net energy for each concentric circle in TJ = (CSNETMET × (AREA/10,000))/1,000 (0.00640688846).
CGSIN1DOL	Input costs associated with seed, nitrogen fertilizer, and pesticides in $/acre = 44.61910000000.
CGSIN2DOL	Input costs associated with nutrients and transportation in $/acre = $0.1471 × CORNYLD (20.00560000000).
CGSIN3DOL	Input costs associated with transportation to the plant in $/acre = $0.0014 × CORNYLD × (DISTANCE/1,609 m/mile) (4.76000000000).
CGSINDOL	Input costs after accounting for transport energy associated with transport to the plant in $/acre = (CGSIN1DOL + CGSIN2DOL + CGSIN3DOL) (69.38470000000).
CGIN1DOL	Input costs associated with seed, nitrogen fertilizer, and pesticides in $/acre = 42.84550000000.
CGIN2DOL	Input costs associated with nutrients and transportation in $/acre = $0.1471 × CORNYLD (11.12480000000).
CGIN3DOL	Input costs associated with transportation to the plant in $/acre = $0.0014 × CORNYLD × (DISTANCE/1,609 m/mile) (2.72000000000).
CGINDOL	Input costs after accounting for transport energy associated with transport to the plant in $/acre = (CGIN1DOL + CGIN2DOL + CGIN3DOL) (56.69030000000).
CSINDOL	Input costs after accounting for transport energy associated with transport to the plant in $/acre = (CGSINDOL – CGINDOL) (12.69440000000).
CGINDOLM	CGINDOL expressed as $/ha = CGINDOL × 2.47 (140.02504100000).
CGSINDOLM	CGSINDOL expressed as $/ha = CGSINDOL × 2.47 (171.38020900000).
CSINDOLM	CSINDOL expressed as $/ha = CSINDOL × 2.47 (31.35516800000).
CGSMJDOL	Output energy delivered per value total energy input in MJ/$ = (CGSOUTENG × 0.01033448)/CGSINDOLM (1,022.19101429243).
CGMJDOL	Output energy delivered per value total energy input in MJ/$ = (CGOUTENG × 0.01033448)/CGINDOLM (828.75199924700).
CGSOUTMETJ	Total harvested energy for each concentric circle in TJ = (CGSOUTMET × AREA/10,000))/1,000 (0.01976768716).
CGOUTMETJ	Total harvested energy for each concentric circle in TJ = (CGOUTMET × AREA/10,000))/1,000 (0.01309463598).
CGSINDOLMT	Total value of input costs for each concentric circle in $ = (CGSINDOLM × (AREA/10,000))/1,000 (0.01932561222).

CGINDOLMT	Total value of input costs for each concentric circle in \$ = (CGINDOLM × (AREA/10,000))/1,000 (0.01578986080).
CGSOUTMET	CGSOUTENG expressed as GJ/ha = CGSOUTENG × 1.0341396 × 10^{-5} (175.30054515184).
CGOUTMET	CGOUTENG expressed as GJ/ha = CGOUTENG × 1.0341396 × 10^{-5} (116.12369254229).
CSOUTMET	CSOUTENG expressed as GJ/ha = CSOUTENG × 1.0341396 × 10^{-5} (59.17685260955).

Soybean_shapefiles

Layer: soybean_energy2010.shp

Overview: The spatial boundaries of this layer are comprised of SSURGO soil map units, Minnesota 1990s census of the land use boundaries, and 1 mile (1.6 km) concentric circles surrounding the city of Madelia. The following attributes are the resulting energy calculations associated with the soybean yields derived from the SSURGO data. Example values are presented in parentheses.

Field	**Description**
AREA	Polygon area in m^2 (1,127.64550420000).
PERIMETER	Polygon perimeter m (280.32763887900).
MSOYYLDLU_	Polygon id (2).
MUSYM	SSURGO map unit symbol (386).
MUKEY	SSURGO map unit key (400,598).
MUSYMNAME	SSURGO map unit symbol name (OKOBOJI M).
SOYUNIT	Soybean yield units normalized by acres (bu).
SOYYLD	Soybean grain yield (38.00000000000).
ENERGYSOY	Harvested energy of soybeans in kcal/acre = SOYYLD × 130,204.1 (4,947,756.00000000000).
LUSE_CODE	Minnesota 1990s census of the land use code (21 = cultivated land).
DISTANCE	Concentric circle distance in m (40,225.00000000000).
SBOUTENG	Output energy from soybean grain in kcal/acre = 458,473 BTU/bu/acre × SOYYLD × 0.252 (4,390,337.44799999000).
SBIN1ENG	Input energy for soybean grain associated with field operations, seed, and pesticides in kcal/acre = 1,941,560 BTU/acre × 0.252 (489,273.12000000000).
SBIN2ENG	Input energy for soybean grain associated with drying, nutrients, and transportation to the farm in kcal/acre = 6,539 BTU/bu/acre × SOYYLD × 0.252 (62,617.46400000000).
SBIN3ENG	Input energy for soybean grain associated with transportation to the plant in kcal/acre = 83 BTU/bu/mile/acre × SOYYLD × (DISTANCE/1609 m/mile) (19,870.20000000000).

SBNETENG	Net energy for soybean grain after accounting for transport energy associated with transport to the plant in kcal/acre = (SBOUTENG) − (SBIN1ENG + SBIN2ENG + SBIN3ENG) (3,818,576.66399999000).
SBNETENG2	Net energy for soybean grain without accounting for transport energy associated with transport to the plant in kcal/acre = (SBOUTENG) − (SBIN1ENG + SBIN2ENG) (4,605,517.47599999000).
SOYYLDMET	SOYYLD expressed in Mg/ha = SOYYLD × 6.7211 × 10^{-2} (2.55401800000).
SBNETMET	SBNETENG expressed in GJ/ha = SBNETENG × 1.0341396 × 10^{-5} (39.48941343878).
SBNETMET2	SBNETENG2 expressed in GJ/ha = SBNETENG2 × 1.0341396 × 10^{-5} (47.62748000424).
SBNETMETJ	Total net energy for each concentric circle in TJ = (SBNETMET × (AREA/10,000))/1,000 (0.00445300595).
SBIN1DOL	Input costs associated with field operations, seed, and pesticides in $/acre = 26.83770000000.
SBIN2DOL	Input costs associated with nutrients and transportation in $/acre = $0.0973 × SOYYLD (3.69740000000).
SBIN3DOL	Input costs associated with transportation to the plant in $/acre = $0.0008 × SOYYLD × (DISTANCE/1609 m/mile) (0.76000000000).
SBINDOL	Input costs after accounting for transport energy associated with transport to the plant in $/acre = (SBIN1DOL + SBIN2DOL + SBIN3DOL) (31.29510000000).
SBINDOLM	SBINDOL expressed as $/ha = SBINDOL × 2.47 (77.29889700000).
SBMJDOL	Output energy delivered per value total energy input in MJ/$ = (SBOUTENG × 0.01033448)/SBINDOLM (586.96639034328).
SBOUTMETJ	Total harvested energy for each concentric circle in TJ = (SBOUTMET × AREA/10,000))/1,000 (0.00511976071).
SBINDOLMT	Total value of input costs for each concentric circle in $ = (SBINDOLM × (AREA/10,000))/1,000 (0.00871657537).
SBOUTMET	SBOUTENG expressed as GJ/ha = SBOUTENG × 1.0341396 × 10^{-5} (45.40221812340).

Net_energy_ratio_shapefiles

Layer: ratio_energy2010.shp

Overview: The spatial boundaries of this layer are comprised of SSURGO soil map units, Minnesota 1990s census of the land use boundaries, and 1 mile (1.6 km) concentric circles surrounding the city of Madelia. Example values are presented in parentheses.

Field	Description
AREA	Polygon area in m^2 (1,127.64550420000).
PERIMETER	Polygon perimeter m (280.32763887900).
DISTANCE	Distance in m (40,225.00000000000).
ALFCGSGJ	Ratio of net energy from alfalfa to net energy from corn grain and stover = ALFNETMENT/CGSNETMET (0.639).
ALFCGGJ	Ratio of net energy from alfalfa to net energy from corn grain = ALFNETMENT/CGNETMET (0.997).
ALFSBGJ	Ratio of net energy from alfalfa to net energy from soybean grain = ALFNETMENT/SBNETMET (2.559).
ALFCGSMD	Ratio of alfalfa energy output delivered per value energy input to corn grain and stover energy output delivered per value energy input (1.537).
ALFCGMD	Ratio of alfalfa energy output delivered per value energy input to corn grain energy output delivered per value energy input (1.896).
ALFSBMD	Ratio of alfalfa energy output delivered per value energy input to soybean grain and energy output delivered per value energy input (2.677).

Madelia_base_shapefiles

Layer	Description
madelhwy2 (route: coverage)	Major roads and highways within the Madelia fuelshed.
madeliabfcty.shp	Minnesota county boundaries within the Madelia fuelshed.
madeliabfwat.shp	Eight-digit HUC boundaries within the Madelia fuelshed.

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