Landscape Ecology vol. 4 no. I pp 45-54 (1990)
SPE? Academic Publishing bv, The Hague

Regional modeling of grassland biogeochemistry using GIS

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Keywords: spatial modeling, grassland, biogeochemistry, scale dependent error

Abstract

We used an ecosystem model coupled to a Geographic Information System (GIS) to simulate spatial variability in storage and fluxes of C and N within grassland ecosystems. The GIS contained information on driving variables required to run the model. These were soil texture, monthly precipitation and monthly minimum and maximum temperatures. We overlayed polygon maps of the above variables to produce a driving variable map of our study region. The final map had 768 polygons’in 160 unique classes. The ecosystem model was run to a steady state for each class and NPP, soil organic matter (SOM), net N mineralization and trace gas emission were mapped back into the GIS for display. Variation in all of the above propertiees occurred within the region. NPP was primarily controlled by climate and patterns followed spatial variation in precipitation closely. Soil organic matter, in contrast, was controlled largely by soil texture within this climatic range. Error associated with aggregation within the study area showed that spatial averages over the study area could be used to drive simulations of NPP, which is linearly related to rainfall. More spatial detail had to be preserved for accurate simulation of SOM, which is nonlinearly related to texture. Mechanistic regional models form a valuable link between process studies and global models.

1. Introduction

Recently much attention has been focused on spatial patterns in ecosystem properties, at scales ranging from microtopographhc to global (Pastor *et al.* 1984; Schimel *et al.* 1985, 1988; Rosswall *et al.* 1988). In many studies, spatial variation is used as a tool for examining multiple controls over processes, such as the interactions of moisture, temperature, and texture in controlling soil organic matter turnover or net primary productivity (Burke *et al.* 1989; Sala *et al.* 1986; Schimel *et al.* 1985 and many others). Clearly, heterogeneity in soils, hydrology and vegetation will modulate the effects of global environmental change at landscape and regional scales (Pielke 1989; Schimel *et al.* in press). Regional data on CO, and trace gas fluxes must include knowledge of spatial variability for uncertainty analysis of global budgets (Schimel *et al.* 1988; Bowden 1986; Folorunzo and Ralston 1984;

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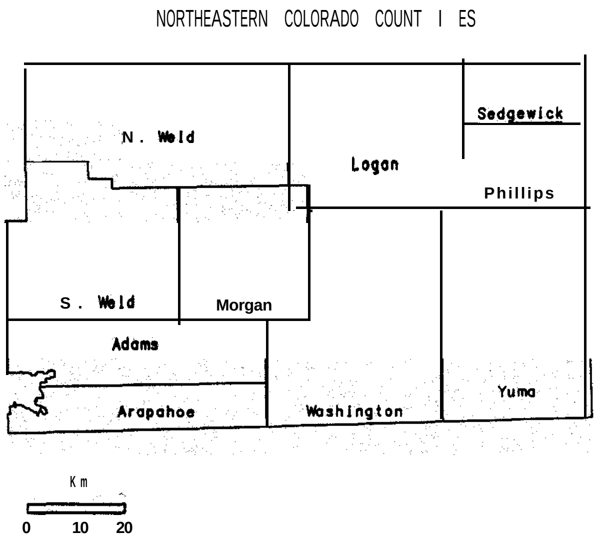

Fig. 1. Study area in northeastern Colorado used for the geo-referenced ecosystem simulation model. Boundaries denote counties, with Weld County split into two soil survey areas.

Bolin and Cook 1983). Process level, regional-scale models are an essential intermediate between understanding of plant and microbial processes and modeling of global biogeochemical cycles.

The linkage of ecosystem simulation models to geographic information systems provides technological support for analyzing spatial variability in ecosystem properties and processes. Major controlling variables over ecosystem processes have inherently different patterns and scales of variation. A geographic information system (GIS) is an appropriate tool to integrate databases as multiple layers of driving variables for modeling ecosystem processes. Across any region, interactions among driving variables are complex; simulation modeling is an important tool for analyzing such interactions. The combination of ecosystem simulation models and geographic information systems is a powerful tool for spatial integration of biogeochemical cycling-rates and storage.

This paper will address the application of an ecosystem simulation model, Century, to a geographic information system of driving variables for the prediction of ecosystem state variables and processes in U.S. Central Grasslands. Previous regional applications of Century have been limited to spatial variation of climate variables only, with no inclusion of the regional variation in soils or management (Parton *et al.* 1987, 1988; Schimmel et *al.* 1989; Cole et *al.* 1988). In this study, we conducted an analysis of the grasslands of eastern Colorado using both climate and soils databases.

2. Methods

The area we chose for analysis was the northeastern quarter of Colorado (Fig. 1), extending from latitude 39°35′ to 41 and longitude 102° to 105°1, and comprising 9 counties.

2.1. Century Ecosystem Model Description

Century (Fig. 2) was developed to simulate grassland systems, and has been described extensively in the literature (Parton *et al.* 1987, 1988). The model was designed to require a minimum number of site-specific inputs for modeling of ecosystem processes using monthly time steps for long time periods, hence the name Century. Processes represented include plant production, allocation of plant residue and major elements into several organic matter fractions, mineralization of those elements into inorganic form, and recycling into plant components. Atmospheric inputs and outputs are included in the model. Century has also been modified to include cropping practices with various levels of residue return (Cole *et al.* 1988) and grazing influences (Holland 1988).

Of particular relevance to this study are the inclusion of climate and soil texture as driving variables for production and decomposition in the model (Fig. 2). Required input variables are mean monthly maximum temperature, mean monthly minimum temperature, mean monthly precipitation, and soil sand content. Precipitation drives net primary production, which is constrained by nutrient availability. Precipitation and temperature are combined into a climatic decomposition parameter, controlling the rate of decomposition of plant residue and all fractions of soil organic matter. Conversion of

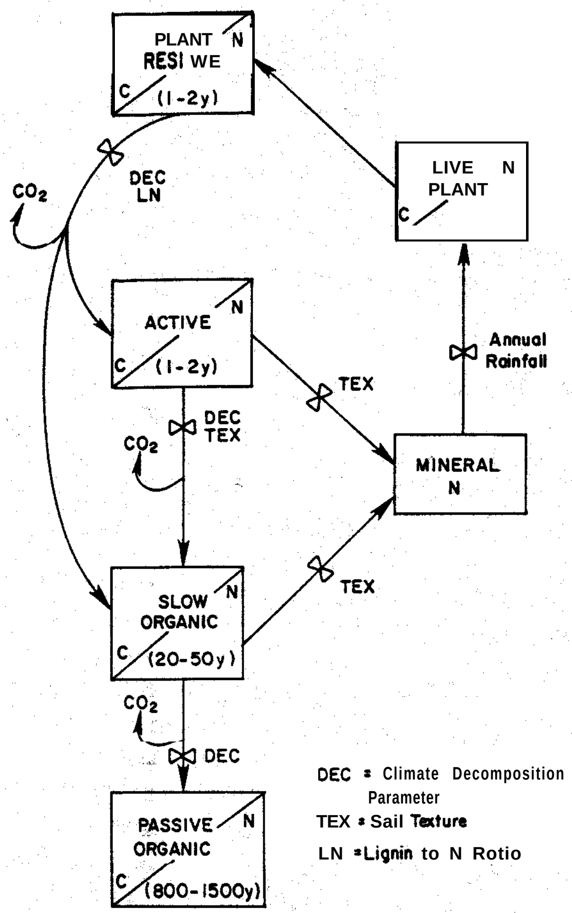

Fig. 2. General structure of the Century ecosystem model (Parton *et al.* 1987), reprinted from Schimel et *al.* (1989).

soil organic matter from active pools to intermediate pools is controlled by both the climatic decomposition factor and soil texture. As sand content decreases, a higher proportion of active soil organic matter is moved to the intermediate pool, simulating the effect of fine soil particles on physical and chemical protection of soil organic matter from decomposition (Jenkinson 1977; Sorenson 1981).

2.2. Database description

We compiled climate and soils databases from long term U.S. Weather Bureau records (U.S. Department of Commerce, 1964), and USDA Soil Conservation Service (SCS) soil surveys, respectively. The climate database consisted of 20 weather stations located within or adjacent to our study area, for which 'monthly precipitation and maximum and minimum temperature were available. The soils database was compiled using 1:250,000 soil maps for each soil survey area within our study area. Map unit delineations at this scale have a resolution of approximately 2.5 km^2. Each map unit represents several related soil series. General attributes of each soil series as well as the percent of map unit area occupied by each area are described in the soil survey text. Soil texture, organie matter and area data for each series were manually translated from the soil survey text and a weighted average texture was calculated. This procedure was repeated for map units of all soil survey areas.

2.3. Construction of the GZS

We used the ARC/INFO geographic information system for all data entry and analysis, running on VAX Station 3200 workstations. Weather station data were entered into INFO, registered by latitude and longitude. Data for each station included 36 variables; monthly data for maximum and minimum temperature and precipitation. Rather than create 36 maps for climate overlays, we created only two climate maps, one each for average annual precipitation and mean maximum temperature. We assumed that seasonality within a mean annual precipitation class or mean temperature zone was constant. Point data for mean maximum temperature (more variance than mean minimum temperature) were entered into ARC/INFO's TIN program, creating a Triagulated Irregular Network. The TIN was then contoured at an interval of 1 "C, a resolution we considered appropriate for the Century model. Monthly maximum and minimum values were then averaged within bands and the mean assigned to the contour band. The same procedure was followed for precipitation, using annual precipitation as a contouring variable, and averaging monthly data within each contour interval (2 cm intervals).

Generalized county soils maps were individually

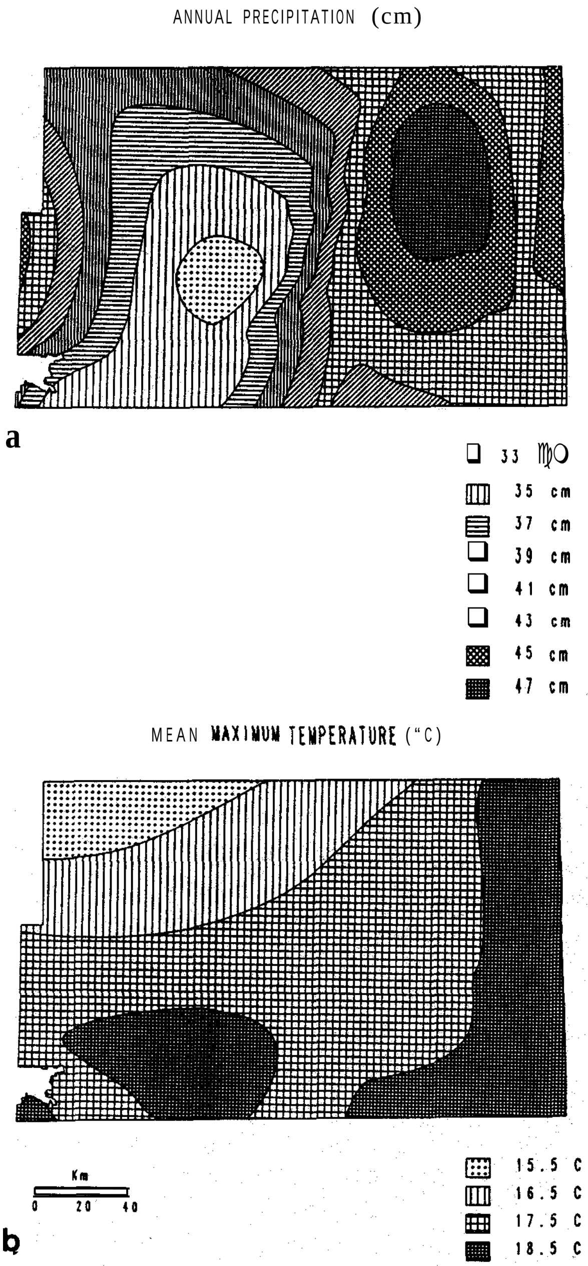

Fig. *3a,* b. Contour maps of annual precipitation and mean monthly maximum temperature, generated from 20 weather stations.

digitized and projected into the UTM (Univeral Transverse Mercator) coordinate system. Soil association names were registered with each polygon of each map, and soil texture classes registered with each association. Using the soil texture triangle (Soil Survey Staff 1982), we assigned a sand class (i.e., 0–20%, 20–40%, etc) to each soil texture. This class interval was appropriate given the sensitivity of relationships in the Century model. The 10 county maps (Weld County in two sections) were then edgematched, resulting in a composite map with 677 polygons (Fig. 4a). The ARC/INFO ‘dissolve’ subprogram was used to eliminate lines between polygons in the same sand class. The resulting soil texture map had 293 polygons (Fig. 4b).

2.4. Regional modeling

Three sets of driving variables were now mapped for our study area. We overlaid these three maps to produce a 768-polygon driving variable overlay map for the regional ecosystem simulation.

Rather than running simulations for each of the 768 polygons, we ran the model for each unique combination of driving variables *(i.e.,* 8 precipitation classes × 4 temperature classes x 5 soil texture classes = 160). The model was run to steady state (about 10,000 years) under moderate grazing. Output for soil organic carbon, annual aboveground net primary production, net N mineralization, and nitrogen oxide (dinitrogen, nitrous and nitric oxides, lumped) flux was then mapped to the appropriate polygons.

3. Results and discussion

3.1. Climate maps

Contoured annual precipitation, ranging from 33 to 47 cm, indicates two orographic effects on precipitation (Fig. 3a) in our area. Within 50 km of the western edge of the study area, precipitation increases in a westerly direction. This is due to increasing elevation and the effect of upslope flow on winter precipitation. A larger scale orographic effect is shown in the slow increase in precipitation with easterly direction, beginning in the middle of the study area and extending eastwards. Contoured mean maximum temperature, ranging from 15.5 to 18.5°C, shows a general increase in temperature in a southeasterly direction (Fig. 3b).

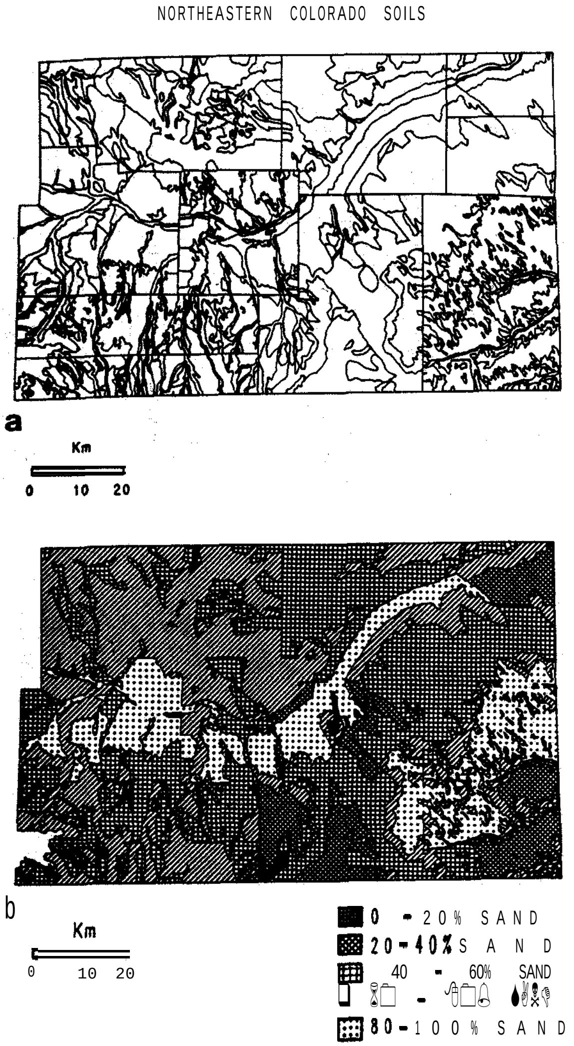

Fig. 4. (a) Composite map including all map units from generalized county soils maps in northeastern Colorado. (b) Final soil texture map produced from composite soils map, including 5 texture classes.

3.2. *Soil map*

The final soil texture map (Fig. 4b) illustrates the complexity of soils within this section of Colorado. Much of the area in the region is loamy uplands. The southwest corner of the study area is characterized by fine, linear fluvial features representing current drainages and paloechannels. Yuma County, located in the southeast corner of the study area, is characterized by patchy eoian features. These sand hills were formed during the late Holocene by northeasterly paleowinds that transported sands from the Platte River basin (Muhs 1985). The smallest patches represent the oldest, most resistant sand hills from an earlier period during the Holocene (Muhs 1985).

Several problems are evident for soils data in the composite texture map (Figs. 4a and b). First, several political boundaries were not dissolved between map units, because soils on either side were assigned to different texture classes. To some extent, these units represent a textural gradient that is imposed at a political boundary. A second error type can be seen in the lower left-hand corner where two county maps seem to be offset by about 2 km. Because we did not ground-truth the soils maps, it is difficult to tell which map border is correct. Both these problems and other boundary issues will be resolved with the advent of the new State General Soil Geographic Database (STATSGO) (Soil Conservation Service 1984) SCS soils maps, due to be released soon.

3.3. *Model output*

Simulated spatial patterns in ecosystem properties reflect the response of the model to input data as they vary across the region. Thus, patterns in output are the necessary result of spatial variation in input variables, and of the relationships built into the model.

Simulated aboveground net primary production (NPP) ranged from less than 165 to 210 g/m^2/year (Fig. 5a). These values overestimate total aboveground NPP estimated at the Central Plains Experimental Range (Sims and Singh 1978; Dodd and Lauenroth 1979; Schimel *et al.* 1985) (Table 1), and predicted by other models (Lauenroth 1979; Sala *et al.* 1979). This overestimation by the model occurs because precipitation data used for the polygon are higher than the actual site precipitation. Spatial patterns in simulated NPP correlate most closely with annual precipitation contours (Fig. 3a), with an effect of soil texture only in the 37-39 precipitation zone. It is well-established that in our area, net primary production is mainly limited by precipitation (Lauenroth, Dodd and Sims 1978; Sala *et al.*

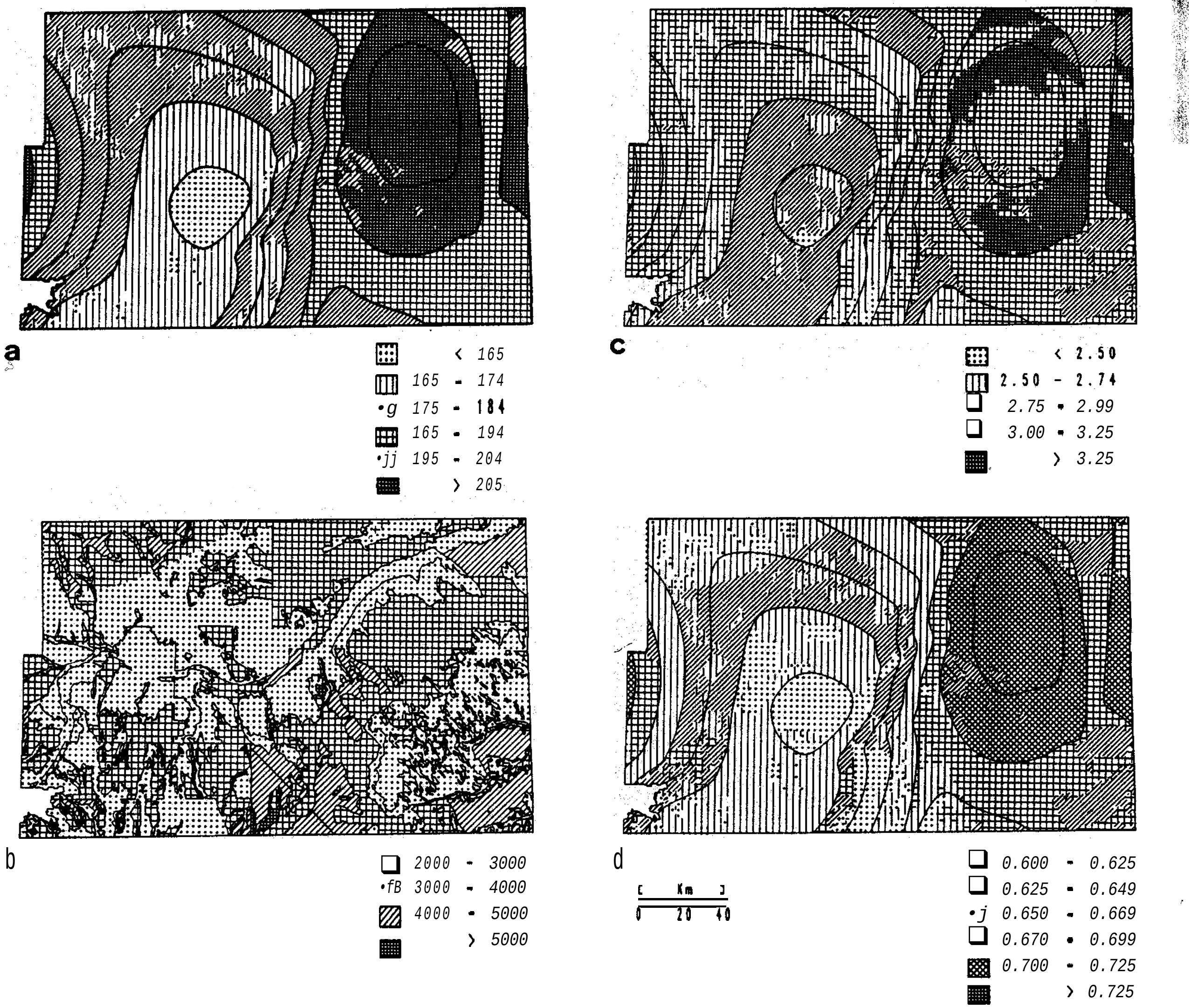

Fig. *5a, b, c,* d. Simulated output from the Century ecosystem model for net primary production, soil organic carbon, net annual N mineralization, and net annual N_2O production in northeastern Colorado. Lines overlaid represent annual precipitation contours (a, c, d) and soil texture classes (b).

Table 1. Soil biogeochemical properties measured at different landscape positions at the Central Plains Experimental Range (Parton et al. 1988; Schimel *et* al. 1985, and Lauenroth and Miechunas, unpubl. data).

Landscape	Soil organic carbon (to 20 cm)	Range of estimated annual aboveground net primary production		Net annual N mineralization	N_2O
		Grass	Total		
		(g m^2)			
Swale	3385	55-132	79-139	5.5	0.01
Midslope	1626	33-89	36-92	4.1	0.02
Ridgetop	1695	37-89	40-102	3.0	ND

Table 2. Regional estimates of biogeochemical properties and processes in northeastern Colorado. Estimates were made at 3 levels of resolution, association (n = 768, resolution = 2.5 km^2), county level (n = 10, resolution = 1500 km^2), and multi-county level (n = 1, resolution = 4000 km^2).

Properties	Mean (g/m^2)	Standard deviation	Total (g)
Net primary production			
- association level estimate	184	17	7.36×10^{12}
- county level estimate	186	12	7.44×10^{12}
- multi-county level estimate	184		7.36×10^{12}
Soil organic carbon			
- association level estimate	3135	761	1.25×10^{14}
- county level estimate	3273	575	1.31×10^{14}
- multi-county level estimate	2710	-	1.08×10^{14}
N_2O production			
- association level estimate	0.66	0.05	2.64×10^{10}
- county level estimate	0.67	0.05	2.67×10^{10}
- multi-county level estimate	0.64	-	2.55×10^{10}

1988), thus the model constrains NPP by precipitation (Parton et *al.* 1987), and simulated spatial NPP patterns correspond with precipitation pattern. In the 37-39 cm precipitation zone, areas with fine-textured soils were predicted to have lower net primary production, as a result of nutrient limitation through microbial competition for nutrients. The model simulated greater microbial biomass in these fine-textured soils (Schimel 1986), apparently competing with plant uptake for available nutrients.

Simulated soil organic carbon ranged from less than 2000 to greater than 5000 g/m^2 (to 20 cm depth) as previously documented (Schimel et *al.* 1985) (Table 1), with spatial patterns correlating closely with soil texture (Fig. 4b). With increasing sand content, the model predicts less stabilization of soil organic matter and hence more decomposition, and lower soil carbon pools. Yonker *et al.* (1988) and Burke *et al.* (1989) found similar results with data collected across landscape and regional gradients in soil texture. At the northwest edge of the study area, an effect of temperature is also evident, with higher soil carbon simulated due to slower decomposition. The lack of correspondence between precipitation and soil organic carbon suggests that, at this scale, soil organic carbon pools are relatively independent of net primary production, being primarily controlled by decomposition and SOM stabilization rates. This is an interesting contrast to the strong climatic dependency shown at regional (Jenny 1941) and global scales (Post et *al.* 1985).

Predicted patterns of net N mineralization are shown in Fig. 5c. N mineralization rates were simulated to range between 2.3 and 3.3 $g/m^2/yr$, corresponding best with rates estimated at ridgetop positions at the Central Plains Experimental Range (Table 1). Texture, precipitation, and temperature exerted influence over N mineralization (Parton *et al.* 1987), with higher rates of N mineralization under warmer and wetter conditions. Net N mineralization was predicted to be lower in fine-textured soils, indicating the influence of higher soil organic matter, greater microbial biomass, and higher turnover of nitrogen through the microbial biomass. Spatial patterns in net N mineralization were thus predicted to be quite complex, due to the modeled interactions among the three major driving variables included in this analysis.

Predicted oxidized nitrogen emission rates ranged from 0.56 g/m^2 to 0.73 g/m^2, and increased with temperature, moisture, and sand content (Fig. 5d). The range of N_2O predicted is high compared to estimates from the Central Plains Experimental Range (Parton et *al.* 1988; Schimel *et al.* 1988) (Table 1), however, the simulations include N that has been reduced to NO and N_2 as well as N_2O. These predicted rates are difficult to validate because of the problems associated with measuring NO and N_2 and will require further work.

3.4. Scale-dependence of results

Using the output from the georeferenced ecosystem simulation model, we examined the relationship between spatial scale of input and estimates of regional biogeochemical fluxes. To do this, we estimated regional output with three spatial scales of inputs, the soil association level (finest scale), county level, and multi-county level (Table 2). Association scale estimates were made by multiplying output from Century by the area of each polygon, and summing the polygons to produce the best regional estimate. We then obtained a single set of driving variables for each county, weighting the polygons in the driving variable overlay. For each county, then, we had an average precipitation class with its associated monthly inputs, an average temperature class, and an average soil texture class. A single model run could be associated with each county, the output multiplied by the area of the county, the counties summed, and a second regional estimate formulated. Finally, we performed the same procedure for the entire study area, calculating a weighted-by-area mean precipitation class, temperature class, and texture class. Output for this class of driving variables was multiplied by the whole area for a final regional estimate.

There were no differences among estimates of net primary production at the assocation, county, and multi-county level. The net primary production map indicated that NPP is most closely related to annual precipitation. In the model, annual precipitation is linearly related to NPP. Since we obtained an average precipitation for each county and the region using a linear weighting algorithm, and precipitation is linearly related to NPP, there were no nonlinear effects introduced.

The results of the exercise for soil organic carbon, however, indicated that the multi-county level estimate underestimated carbon by approximately 14%. The major control over SOM in this area was soil texture. The model has a nonlinear relationship (negative quadratic) between soil texture and total carbon. Thus, linear averaging of the input data (soil texture class) caused underestimation of the regional average. County level estimates were not subject to as much error as the multi-county level estimate; this was probably because the counties in the study area correlated fairly well with soil texture. Similar results were obtained for oxidized nitrogen gas production, although the underestimate in this case was small.

4. Conclusions

A critical decision in georeferenced modeling is the choice of spatial resolution. Processes such as organic matter stabilization or trace gas emission may have nonlinear relationships to driving variables. Small areas with high or low values for driving variables can have a disproportionate impact on the results. Such areas may be included by use of fine scale databases, or by nonlinear weighted averaging within polygons. Thus, resolution of databases should be a function of the relationship between driving and output variables, and of the scale of variation of the driving variable. In our study, climatic data could be aggregated to a coarse scale, while preserving reasonable estimates of NPP. More detail had to be preserved for soil texture, because of nonlinear relationships.' Fundamental limits are set by the scale at which the input data were collected.

The analysis of scale-dependant error is important for application of georeferenced models. First, we must know the error of regional estimates for inclusion in continental or global studies; this error is in part a function of the fundamental scale of the driving variable database. Second, we must know within-polygon error when using a polygon estimate to make inferences about a specific point within a cell. if the average texture of a polygon is loam, how much in error is the estimated SOM for a loamy sand contained within that polygon? The former concern is critical to use of regional models in global studies. The latter is critical when georeferenced models are applied in ecosystem management .

In the future, we will extend this analysis to cropland and incorporate management information into our georeferenced ecosystem simulation model. Data on management history and current practices such as rotation scheme, tillage intensity, and fertilization regime are critical to an accurate assessment of soil organic matter, NPP, and other ecosystem processes (Alway 1909; Russel 1929; Hilde and Metzger 1939; Haas et *al.* 1957; and many others). In addition, we hope to include satellite imagery as a means of sensing driving variables that have strong temporal variability. Remote sensing may also be especially useful in validating relative spatial and temporal variations in predictions of net primary production. Such a validation would allow us to identify areas in which our input data are inaccurate or incomplete.

5. Acknowledgements

The authors thank Mike Galvin for programming and system configuration, Beth Holland for modeling advice, and Paul Snook for graphic output. Wayne Larsen with the Soil Conservation Service provided information from the NSSAD system. We thank Merlyn Paulson for access to digitizing equipment. The Long Term Ecological Research Program (NSF Grant No. BSR-8612105) sponsored this work, and the Joint Facility for Regional Ecosystem Analysis (NSF Grant No. BBS-8714296) provided geographic information system software and hardware. The Great Plains Research Program (NSF Grant No. BSR-8605 191 and USDA support) supported Galvin for programming work. Thanks to K. Flach for critical review of the manuscript.

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