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Adding ecosystem function to agent-based land use models

V. Yadav[a,*], **S.J. Del Grosso**[b], **W.J. Parton**[b], and **G.P. Malanson**[a]
[a]University of Iowa, USA
[b]Colorado State University, USA

Abstract

The objective of this paper is to examine issues in the inclusion of simulations of ecosystem functions in agent-based models of land use decision-making. The reasons for incorporating these simulations include local interests in land fertility and global interests in carbon sequestration. Biogeochemical models are needed in order to calculate such fluxes. The Century model is described with particular attention to the land use choices that it can encompass. When Century is applied to a land use problem the combinatorial choices lead to a potentially unmanageable number of simulation runs. Century is also parameter-intensive. Three ways of including Century output in agent-based models, ranging from separately calculated look-up tables to agents running Century within the simulation, are presented. The latter may be most efficient, but it moves the computing costs to where they are most problematic. Concern for computing costs should not be a roadblock.

Keywords

agent-based; carbon; century; ecosystem; simulation

1. Introduction

The feedbacks between land use, specifically the human choice aspects of use, and the biophysical environment, are important current research questions in the arena of global change (Riebsame, Meyer, and Turner II 1994; Geoghegan et al. 2001). Within the biophysical environment, the feedbacks with the ecological component have been a persistent area of interest (Raich and Schlesinger 1992; Lambin 1997; Malanson 2003; Kareiva, Watts, McDonald, and Boucher, 2007), although feedbacks with the atmosphere are a growing theme (recognizing that none of the components are really separable). Two general themes emerge from the ecological orientation of land use studies: community ecology, with associated population ecology and biodiversity aspects; and ecosystem

*Corresponding author. vineet-yadav@uiowa.edu.

ecology, with a focus on the fluxes of energy and matter, especially carbon, nutrients, and water. These are the same two themes, biodemography and biogeochemistry, that Hutchinson (1948) forecast to be the core of ecology in the second half of the twentieth century. They are the same themes that are repeated in concerns about the other major aspect of global change, climate change, and are related to additional problems identified as global environmental changes, e.g. invasive species, nutrient cycles, and the hydrological cycle (NRC 2000). Here we focus on biogeochemistry in ecosystem ecology.

We will introduce the dominant approach of ecosystem ecology, simulation, and a primary tool used, the Century model, and then discuss a case study in which the model is faced with real questions of problematic data and computation issues. The context is the potential to incorporate a biogeochemical model in order to determine feedbacks in a model of land use decision-making in the agent-based framework. Agent-based models (ABM) are now at the forefront of land use change projection (e.g. Lambin, Geist, and Lepers 2003; Malanson 2003; Parker and Meretsky 2004; Deadman, Robinson, Moran, and Brondizio 2004; Sengupta et al. 2005; Bennett and Tang 2006; Brown and Robinson 2006; Evans and Manson 2007). Such advances are discussed elsewhere in this issue. We assume that reality can be represented formally and approximated, in abstracted and simplified form, in a model, and further abstracted into a computer program: a simulation. The computer program should embody the states of factors or variables and their effects on each other. In biogeochemical simulations, the effects are included as exchanges of energy or matter among the states and thus these models are relatively mechanistic. They compute fluxes based on known relations established from detailed studies at lower hierarchical levels. These models essentially solve difference equations.

Important land use changes in the future will likely involve the expansion and intensification of agriculture, which will have a number of environmental consequences in biogeochemistry (Houghton, Hackler, and Lawrence 1999). Tilman et al. (2001) cited expansion of agriculture onto 10^9 ha and consequent loss of ecosystem function and of biodiversity. Predicting such changes must involve how the land responds to and maintains agricultural productivity (e.g. Oleson and Bindi 2002; Parry, Rosenzweig, Iglesias, Livermore, and Fischer 2004). Productivity depends on biogeochemistry, and simulating biogeochemistry is a core component of ecosystem ecology (Odum 1964). Different land uses alter the fluxes of energy, carbon, nutrients, and water both horizontally and vertically. These fluxes result in changes in the fertility of the land and thus directly affect plant productivity of different potential crops, indirectly affecting the choice of crops or more specific land use decisions on irrigation or fertilization.

Another area of feedback is through the atmosphere and climate change. While ecosystems interact with the atmosphere in other ways (e.g. through hydrology), the exchange of carbon between the two has attracted attention because of the role of CO_2 in global climate change. Research in global change has led to an understanding that sequestration of soil organic carbon (SOC) has the capacity to provide buffer periods of short duration during which mitigation strategies can be devised to reduce the overall impact of atmospheric carbon emissions (e.g. Yadav and Malanson 2007a). This realization has led to policy efforts focused on raising awareness among land managers regarding the environmental benefits of adoption of carbon conserving land uses and management schemes (e.g. Grandy and Robertson 2007). Although it is known which land uses will fix more carbon in plants and in soil, this information is more useful for land mangers if actual gains and losses can be established in connection with actual land uses in an area. In the context of an ABM, such knowledge of actual gains and losses will be useful if carbon is to be included as a factor that drives the objective optimization criteria used by land managers in deciding a particular land use. Quantifying these gains and losses requires combining a SOC model with an ABM model. The challenge is how to couple a system dynamics SOC model to an ABM model of land use so that the agents have a knowledge of SOC gains and losses associated with each land use choice.

Many models have been developed, and broad comparisons of models are a useful introduction to their relative strengths and weaknesses (e.g. Cramer et al. 1999; Adams, White, and Lenton 2004). The most widely used biogeochemical simulations are the Century series (e.g. Parton, Stewart, and Cole 1988; Parton et al. 1993; Parton, Gutmann, Williams, Easter, and Ojima 2005). Century has been used hundreds of times, beginning with an emphasis on Great Plains grasslands but now with wider applications. Alternatives exist. DNDC (DeNitrification-DeComposition; Li, Frolking, and Frolking 1992; Tonitto, David, Drinkwater, and Li 2007) and RothC (Coleman et al. 1997; Cerri et al. 2007) are competing agriculture models. FOREST-BGC (Running and Coughlan 1988) and its descendants (e.g. Running and Hunt 1963; Keane, Ryan, and Running 1996; Kang, Lee, Lee, and Running 2006) are also used broadly, although it was designed for forests.

2. Century model description

The Century model (Parton et al. 1987) is a generalized ecosystem model (Figure 1) that simulates plant production, nutrient cycling, and soil organic matter dynamics for grassland, savanna, forest, and agroecosystems. The Century model also includes simplified soil water and temperature models. The model runs using a monthly time step and the major driving variables include: soil texture, monthly average maximum and minimum air temperatures (2 m height), monthly precipitation, and detailed land cover and use data. It is designed to represent a single homogeneous land cover unit of unspecified extent. A daily time step version of the Century model (DayCent) has recently been developed in order to simulate the full greenhouse gas fluxes from managed and natural ecosystems. The DayCent model (Parton et al. 2001) includes a process-based nitrogen trace gas flux sub-model, and detailed soil water and temperature sub-models. The new model also simulates soil nitrification, denitrification, and NO_3 leaching using a daily time step. The DayCent model requires the same data sets to run the model, but also needs daily maximum and minimum air temperature and daily precipitation.

One of the major driving variables for ecosystem models is land use management. Numerous papers have shown that land use practices can greatly impact the carbon balance, nutrient cycling, trace gas fluxes, and plant production of natural and managed ecosystems (Paustian, Parton, and Persson 1992; Parton and Rasmussen 1994; Probert, Keating, Thompson, and Parton 1995; Paustian, Elliott, Peterson, and Killian 1996; Parton et al. 2001). Cultivation of forest and grassland systems generally results in a substantial (50–

70%) decrease in soil carbon levels, decreased plant production, and increased trace gas fluxes (Patwardham et al. 1995; Parton, Tappan, Ojima, and Tschakert 2004). Crop rotations, tillage practices (conventional, conservation and no-till affect soil disturbance; Hobbs 2007), and inorganic and organic fertilizer additions substantially modify ecosystem properties of agricultural systems, with high input agricultural systems having the potential to increase soil carbon levels and plant production, while low input systems reduce soil carbon levels and plant production (Parton et al. 2004). The major variables that drive ecosystem responses to land use management practices are the amount of plant material and nutrients added to ecosystems and the cultivation practices. Higher nutrient additions generally result in increased plant productivity which results in greater inputs of carbon to the soil (higher soil carbon levels) and larger nitrogen trace gas fluxes. Adding organic matter to the soil generally results in greater increases in soil carbon levels compared to inorganic nutrient inputs (Paustian et al. 1992; Parton and Rasmussen 1994). Tillage practices that reduce the disturbance of the soil (no-tillage and ecotillage) tend to increase soil carbon levels (Metherell et al. 1995), while intense tillage practices can substantially reduce soil organic matter levels. Incorporation of perennial crops in the crop rotations tends to increase soil carbon levels since they have larger inputs of carbon to the soil via root inputs, reduced disturbance of the soil, and reduced loss of nutrients (Parton et al. 2004). Forest management practices like clear cutting, thinning, and post-fire salvage logging and replanting activities can greatly impact forest plant production, nutrient cycling, and soil carbon levels (Sanford, Parton, Ojima, and Lodge 1991; Peng, Apps, Price, Nalder, and Halliwell 1998; Cerri et al. 2004).

The Century model has been used extensively to evaluate the impact of agricultural and forest management practices on grassland, forest, and savanna systems around the world (Sanford et al. 1991; Paustian et al. 1992; Gilmanov et al. 1997; Peng et al. 1998; Cerri et al. 2004; Del Grosso, Mosier, Parton, and Ojima 2005). The Century model was one of the first ecosystem models set up to represent the impact of diverse land use management practices on ecosystem dynamics (Metherall et al. 1994). The model simulates all of the major crops grown in temperate and tropical regions, nutrient and carbon additions via organic and inorganic sources, and different harvest, grazing, fire, and soil tillage practices for agroecosystems. The impact of fire, insect grazing, and forest management practices on savanna and forest ecosystems is also represented in the Century model. The model software includes a set of subroutines that simulate the most common agricultural and forest management practices and also allow the user to specify the actual land use of the research site. This paper will focus on how agricultural land management practices are implemented in the model, and how the Century model has been linked to agent-based agricultural land use models.

Users of the Century and DayCent models need to specify detailed land use and land management records for each month during the model simulation run. Figure 2 shows the type of agricultural land management data needed to run the model. For each year of the model simulation, the user needs to specify the month when the crop is planted and harvested, specific months when fertilizer is added, and when irrigation and soil cultivation occur. Figure 2 also shows how crop rotations need to be changed if a historical period is modeled (e.g. Parton et al. 2004).

The Century model has been used extensively to simulate the long-term ecosystem dynamics of many of the agricultural field stations around the world. The model has been used to simulate ecosystem dynamics for over 40 long-term experiment stations (Paustian et al. 1992, 1996; Parton and Rasmussen 1994; Probert et al. 1995; Kelly et al. 1997; Cerri et al. 2004; Chilcott, Dalal, Parton, Carter, and King 2007) in both tropical and temperate systems. These sites typically have extensive data sets on the cropping rotations, cultivation practices, organic and inorganic inputs, and harvest practices during the experimental periods. Some of these sites have detailed land use and crop yield data going back 150 years, while most of the sites have extensive data for the last 30–50 years. These detailed data sets can be used to test the ability of the Century model to simulate plant production, nutrient cycling, soil organic matter dynamics, and nutrient losses for the major global agroecosystems. The primary limitations of agricultural research station data sets are the lack of initial soil carbon and nitrogen, and also the lack of detailed knowledge about the historical land use practices before the experiments began. Initial soil carbon and nitrogen levels are commonly estimated by using long-term Century model runs to simulate the initial soil C and N levels given rough estimates of the land use practices prior to the start of the experiments (Parton and Rasmussen 1994). The Century model runs are used to simulate changes in plant production, soil C and N levels, and nutrient cycling during the experiments, and suggest other experiments that will improve our understanding about the factors which control soil C and N dynamics.

During the last 15 years, we have used the Century model to simulate the ecosystem dynamics of agroecosystems at regional (Burke, Lauenroth, Parton, and Cole 1994; Del Grosso, Ojima, Parton, Mosier, and Peterson 2002), national (Del Grosso et al. 2006), and global scales (Del Grosso et al., in press). These regional and global scale model simulations have been used to assess the impact of historical agricultural land management practices on crop yield, soil C and N levels, and nutrient losses, and also to project the future impact of climate change on sustainability of agricultural systems. The major problem with these regional model analyses is that the land use data is poorly known at the regional scale, with considerable uncertainty about the crop rotations, cultivation practices, and organic and inorganic nutrient inputs used in the agricultural systems. Agricultural census data typically contain crop yield data for the major crop grown during the last 100 years, but do not include information about crop rotations used to grow these crops, cultivation practices, and organic and inorganic nutrient inputs. We have more detailed data about changes in land use management practices during the last 40 years; however, our historical information prior to the last 100 years is considerably less detailed (Parton et al. 2004).

The Century model has recently been used to evaluate the impact of uncertainty in historical land use data on simulated current soil C and N levels, nutrient mineralization rates, and crop yields. The goal of the research was to determine the impact of uncertainty in the time when different land use practices were started on current ecosystem properties. Our operating assumption was that the uncertainty in our knowledge about when major land use changes had occurred over 100 years ago would have minimal impacts on the simulated current levels of soil C and N levels and nutrient mineralization rates. The results from Parton et al. (2004) suggest that cultivation of soil results in rapid decreases in soil C and N levels for 30–40 years, and that simulated current soil C and N levels and nutrient mineralization rates are relatively insensitive to assumptions about when cultivation starts as long as it starts more than 50 years ago. Results from dryland systems take longer to reach near stable soil C and N levels (50–70 years), while irrigated agricultural systems stabilize soil C and N levels after 30–40 years of operating as an irrigated system. Simulated current soil C and N levels and nutrientmineralization rates are quite sensitive to changes in management practices that occurred less than 20 years ago suggesting that we need to have a detailed characterization of current land use practices, but can afford to have less detailed land use data prior to 50 years ago.

Del Grosso et al. (2006) used the DayCent model to simulate regional patterns in N_2O emissions and total national N_2O emissions from agriculture in the US. Detailed land use data on crop rotations, harvested land area for the major crops, cultivation practices, and organic and inorganic fertilizer inputs are available for the last 20–40 years at the agricultural–economic regional level. The US is divided into 63 agricultural–economic regions based on common cropping practices as defined by McCarl, Chang, Atwood, and Nayda (1993). These detailed land use data sets were used to simulate regional patterns and total N_2O emissions for the US during the last 25 years. Observed land use data sets were less detailed prior to 1980 and were represented in the model by simulating the significant crop rotations for each region. The crop rotations changed as a function of time prior to 1980, with the level of detail about these crop rotations becoming more uncertain going backwards in time from 1980 to plow-out. Soils were assumed to be initially cultivated (plow-out) between 1600 and 1850, depending on agricultural–economic region. For most regions of the US, pre-1950 cropping was assumed to involve multi-year rotations that included corn, small grains, hay, and pasture. The exception to this pattern is the southeast US, where corn/cotton rotations were assumed to be the dominant practice. Prior to 1950, no inorganic amendments were simulated, but soils were assumed to be amended with manure. Beginning in 1950, synthetic fertilizer was included and amounts were based on limited data and extrapolation. Although land use for these simulations was at the agricultural–economic region level, daily weather was available at the county level. Consequently, the model was run at county level resolution and model results were combined with county-level crop area data from NASS to calculate county-level emissions.

The DayCent model has recently been used to assess the impact of different management practices on N_2O emissions from major non-rice cropping systems (corn, soy, and wheat) at the global scale (Del Grosso et al., in press). The goal was to determine what agricultural management practices are economically viable and have the potential to reduce N_2O fluxes. This type of global analysis has much more uncertainty compared to the US regional N_2O work (Del Grosso et al. 2006) since the driving climate data sets are only available at a coarse scale (2° × 2° lat/long cells), and historical land use data is only poorly known for most of the global agricultural systems. The approach used was to assume that current land use practices occurred during the last 100 years and that the major crops were grown as monocrops during that time period. Coarse estimates of fertilizer inputs, cultivation practices, and crop yields are available at the country level for most of the world and were used in this analysis. For countries with no fertilizer use data, nitrogen inputs were assumed to be equal to nitrogen removed from harvest based on FAO crop yield data. Manure additions were based on country-level animal number estimates. Manure N additions were assumed to be evenly distributed on all cropland simulated, while synthetic N additions were crop-dependent. The simulations included conventional tillage, and 75% of residue, along with grain, was removed during harvest operations. Within each 2° × 2° lat/long cell, crop area was identified from global vegetation maps based on satellite data, and only cells that had at least 5% cropland area were simulated. N_2O emissions were calculated for each 2° × 2° lat/long cell and summed to obtain country- and global-level emissions.

3. Application of Century in an agent-based context

We describe the issues that we faced in using Century to provide environmental information for an agent-based model (Yadav and Malanson 2007b). The agents are farmers in the Big Creek basin of southern Illinois in a 'Virtual Watershed' project (Lant et al. 2005; Sengupta et al. 2005). In addition to other factors, these agents use an index of environmental quality in which soil organic carbon calculated by Century is a component in their knowledge base for land use decisions. Alternatively, soil organic carbon could be monetized using information from a market such as the Chicago Climate Exchange (e.g. Victor, House, and Joy 2005). So the challenge is to compute soil organic carbon, which can be added to the farmers' knowledge base. Century was chosen to study dynamics of SOC associated with different spatial and temporal land use transformations because (a) it is a well proven soil organic matter (SOM) model, and (b) it has a facility to include soil erosion, which is one of the primary determinants of SOC dynamics in the study area (Yadav and Malanson 2007b; cf. Van Oost et al. 2007).

One of the first attempts at coupling an ABM model with biophysical simulation models was successfully carried out by Matthews (2006). In his integrated scheme (People and Landscape Model; PALM), decision-makers were household agents who made choices in favor of a particular land use/land cover (LULC) on the basis of their perception and self-knowledge, and by communicating with other household agents and exchanging messages with them. The impact of decisions made by household agents in PALM influenced water, nitrogen and carbon within homogeneous spatial units, the levels of which were simulated by the Decision Support for Agrotechnology Transfer (DSSAT) and Century models. In this modeling scheme the choice criteria for LULC employed by agents did not take into account the impact of their decisions on the flows of biophysical parameters like water and carbon. The methodology to integrate biophysical models within an ABM environment is significantly different if one considers the dynamics of these biophysical parameters. Here we discuss this type of coupling with regard to Century, but the same applies to all other biophysical models within the context of inclusive optimization criteria.

3.1 Restricted choice coupling

In the first case, which we call the 'restricted choice method', only the output from selected antecedent runs can be provided and an agent can scan through this output and decide which LULC/rotation sequence to choose with regard to its benign effects on SOC within the bounds of other optimization constraints. The Century model is run and the output stored in look-up tables for future use in the agent-based simulation. This type of coupling restricts an agent's choice to those LULC types for which effects on temporal SOC changes are pre-calculated. However, even for a limited number of crops and tillage practices the number of simulations to be performed to generate this output can become quite large. Changing soil types and temperature and precipitation regimes in different basins can further compound this problem because then these simulations have to be run for each different combination of soil type and climate scenario. Finally, except for long-term LULC, like forest, the number of simulations to be run becomes unmanageable as number of years following a projection of SOC levels increases, because the modeled SOC output changes through time due to changing initial conditions for any rotation period (Table 1).

To exemplify with three crops and three tillage choices there are a maximum of 729 rotations for a 3-year period (four of these 729 rotations are listed in Table 2), there are 9 management combinations, and any 3-year rotation in any order gives a total of 9^3 possibilities. To compute a complete array of choices for generating the SOC output for 3-year rotations for 6 years, we have to run 729^2 (531,441) simulations. Some of these choices would be unreasonable (and a challenge to identify a *priori*), but even if these choices are removed this table would remain large. For instance, in the Big Creek basin, after removing all the unreasonable choices, we were left with 160 unordered (because order does not matter in the final total calculated by Century with constant climate) rotation sequences comprising of 7 land uses and 3 tillage practices spread over 272 basins, and to account for all of these scenarios for a single 3-year period required 43,520 simulations. The actual number of crops to choose among and alternatives such as conservation reserve program and/or afforestation (Evans and Kelley 2004) could multiply this number beyond reason. To these choices we also need to add other land use selections required in Century, such as fertilizer types and amounts; in other places, decisions on irrigation would need to be added. Additional choices, such as whether or not the fields are grazed during the winter, are options. The timing of planting and harvesting, which on real farms can be a day-to-day choice depending on field conditions and the weather forecast, are also necessary inputs. We used only the most likely values for given crops. Next, we also need to include climate. Agents do not choose climate, but different agents could anticipate different climates. In our project we did not include a range of choices and only carried forward past interannual climatic variability or held it constant. Lastly, the characteristics of the field must be entered, with soil texture being most important, in our case determined from soil survey records for each of the 272 basins. The total number of choices that could be mapped out in a decision tree and the size of the look-up table in a restricted choice approach would not be very restricted!

While there is little difference in vertical SOC dynamics among many of the possible rotation sequences, we think that they differ enough in erosion to lead to important SOC dynamics across the landscape. Moreover, accounting of SOC transformations with each of these LULC is especially important in the present context as it impacts carbon budgeting and the implementation of a proper carbon crediting scheme for individuals involved in conservation management practices (Esuola and Weersink 2006).

3.2 Semi-integrated coupling

In the second case, a semi-autonomous coupling between Century and an ABM model could be attempted. In this case for any particular spatially explicit arrangement of an area like basins, soil and other initial required model parameter values can be previously defined and held constant. Rotation or LULC files can be provided for these spatial units and an agent can invoke the Century model to see the impact of his LULC choice on SOC levels. Due to bounded knowledge and optimization constraints it is unlikely that each single agent will run every LULC option possible for each field in order to understand the impact of its decision on SOC levels. Hence, only a limited number of Century simulations would be executed by an agent, but the decision tree that would need to be defined would still be large. Nevertheless, even with this limited number of simulations this type of coupling can become computationally intensive with a large number of agents and when more than one system dynamics model is integrated within an ABM environment. This type of coupling could be studied in the VirtualWatershed framework by putting Century into the hands of real farmers. This method is more akin to the integration used in PALM.

3.3 Fully integrated coupling

In the third case, i.e. a fully autonomous method, assisting agents, different from the LULC decision-making agents, are added in the ABM. The purpose of assisting agents is to help the LULC decision-making agent find, access, and use data and models. In some ABM environments both these roles can be combined and assigned to to the LULC decision-making agent, but for ease of modeling it is more straight-forward to keep these roles separate. This also aligns well with the idea of representing consultants, such as real USDA extension agents, as assisting agents that help LULC decision-makers choose land uses that increase SOC sequestration within a set of particular optimization constraints. A good example of how these assisting agents can work is provided by Sengupta and Bennett (2003). In their Distributed Intelligent Geographical Modeling Environment (DIGME), five different classes of agents were implemented which helped users find data for running models. Thus firstly, ‘model search and data search’ agents help users implement a spatial model and gather geographical data from network accessible repositories, after which ‘transformation agents’ convert the network accessible data into the format required by the model. Subsequently, ‘execution agents’ utilize both the model and data by executing the plan developed by the transformation agents. Lastly, ‘model agents’ facilitate the execution of the model and visualization of results. A similar strategy can also be devised to retrieve the data required by the Century model, which can be later used for the execution of the model and analysis of the results by the LULC decision-making agent. In this option only the actual choices made need to be simulated so the total computational requirements are relatively low, but they come at the point when they will slow any real-time use of the model by decision-makers.

The fact that this strategy can be devised does not mean that it will result in successful implementation of the Century or any other biophysical model. Problems arise because (a) running of any biophysical model requires estimation of model parameters from limited data, (b) in most circumstances initial model parameters are iteratively adjusted after running several simulations which is not easy within an ABM environment, and (c) at times a number of initial parameters are computed from running another model, which complicates any biophysical model in a fully integrated mode. To exemplify, in Century if the field estimates are not available then the values of soil texture, crop and tillage

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parameters have to be extracted from soil survey reports and other existing literature sources, symbiotic and non-symbiotic nitrogen fixation parameters have to iteratively adjusted by keeping into account annual net primary productivity, and erosion has to estimated from other models. All these hindrances can be removed if previously tested parameter values are provided with the model, but this is a large data and analytical effort in itself.

3.4 Coupling choices

To summarize, the choice of any of these three different methods of integrating biophysical models within an ABM environment will be governed by the objectives of the research. For short time periods and few land uses, the first strategy might be preferable, as it can be easily implemented. The semi-integrated method is suitable in situations where large numbers of land use options have to be provided to agents for longer time periods. The third method is the most difficult, but once implemented it can be used in other instances of ABM models that use the same biophysical models.

4. Conclusion

It is becoming increasingly likely that ecosystem function outcomes, such as carbon and nitrogen fluxes, will be included in agricultural land use decisions due to some combination of interests ranging from the local to the global, such as interests in maintaining soil fertility and sequestering carbon. The decision-makers will have some ability to judge such outcomes based on experience, guidance from others, policy, or even computer simulations – but all produce only partial knowledge. In some cases, such as for carbon markets, the demand for specificity in ecosystem function may be high, and then some representation of ecosystem function outcomes is needed in order to model land use change in a spatially explicit agent-based framework.Detailed biogeochemical simulations, such as the Century model discussed here, are the most effective way to calculate the ecosystem function, but these models require knowledge of a number of different parameters and are computationally intensive. Given the large number of options that a modeler is faced with, the combinatorial problem makes the computational requirements prohibitive. More work is needed on the human decision process so that the actual number of options is limited realistically. Lastly, the computational limitations found here are mostly in the organizing and managing of data for eventual use, which are as much a problem of human organizing ability as of computer storage, in the restricted choice and semi-integrated couplings. Moore’s Law (Moore 1965), which forecasts exponential rates of improvement in computing ability, would indicate that the limits of processing speed encountered in the fully integrated coupling should be less of an issue in the future.

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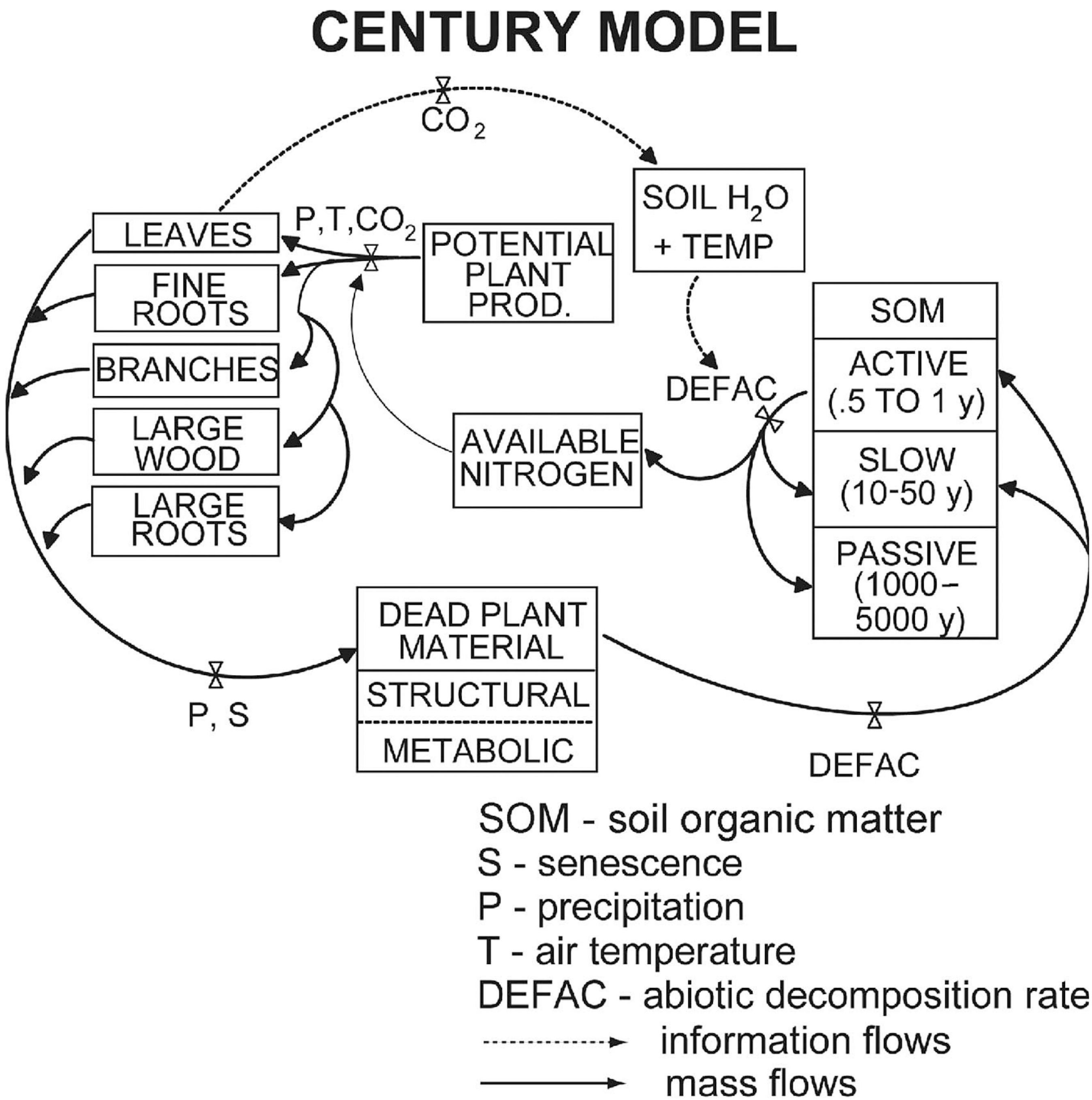

Figure 1.
General outline of the Century biogeochemical simulation

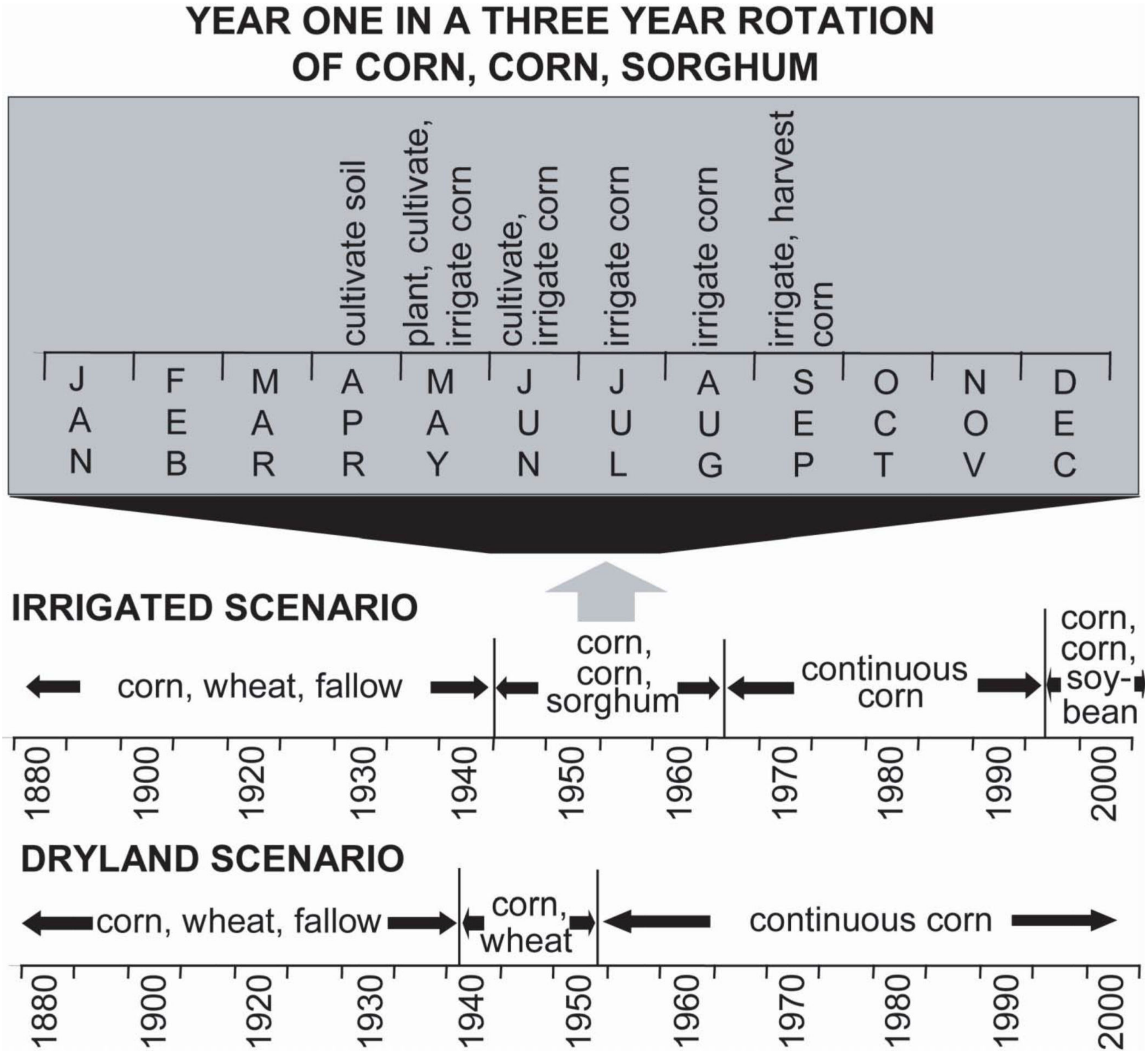

Figure 2.
The observed land use patterns for Hamilton, Nebraska used to drive the Century model from 1880 to 2000 by Parton et al. (2004).

Table 1

Example of annual and 3-year SOC change in the Big Creek watershed when repetitively applying a soybean/no-till, corn/no-till, soybean/no-till 3-year rotation. Because the change varies through time due to initial conditions we cannot use a single 3-year simulation result but must re-run the simulation for each rotation.

ID	Year	SOC in g C m^{-2}	Annual rate of SOC change	Three-year rate SOC change
Rotation-1	2006	2821.563		
Rotation-1	2007	3284.941	463.378	
Rotation-1	2008	2895.818	−389.123	
Rotation-1	2009	2996.638	100.82	175.075
Rotation-1	2010	3107.006	110.368	
Rotation-1	2011	2928.339	−178.667	
Rotation-1	2012	3020.881	92.542	24.243
Rotation-1	2013	3166.314	145.433	
Rotation-1	2014	2980.428	−185.886	
Rotation-1	2015	3071.773	91.345	50.892
Rotation-1	2016	3240.262	168.489	
Rotation-1	2017	3049.127	−191.135	
Rotation-1	2018	3135.453	86.326	−5.019
Rotation-1	2019	3314.312	178.859	
Rotation-1	2020	3116.223	−198.089	
Rotation-1	2021	3198.378	82.155	−4.171
Rotation-1	2022	3383.401	185.023	
Rotation-1	2023	3179.002	−204.399	
Rotation-1	2024	3257.93	78.928	−3.227
Rotation-1	2025	3446.954	189.024	
Rotation-1	2026	3239.724	−207.23	

Table 2

Examples of different crop rotations in the Big Creek watershed

Rotation No.	Year 1	Year 2	Year 3
1	Soybean – no till	Corn – no till	Soybean – no till
2	Soybean – no till	Corn – no till	Soybean – conservation tillage
3	Soybean – no till	Corn – no till	Soybean – conventional tillage
4	Soybean – no till	Corn – no till	Corn – no till