

Applying a complex, general ecosystem model (EDYS) in large-scale land management

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Abstract

A critical need in the management of public and non-urban private lands in the United States and elsewhere is assessing the efficacy of different management alternatives under different environmental and land use scenarios. One type of tool that would be extremely valuable is large-scale ecological simulation models designed to project effects of alternative climatic, usage, and management scenarios on ecological resources. A modeling challenge in this type of application is to link mechanistic simulations of small-scale ‘ecosystem’ processes to large-scale ‘landscape’ processes to provide more realistic and exhaustive projections of effects and ramifications of management alternatives. The Ecological DYNAMICS Simulation model (EDYS) is a general ecosystem simulation model that mechanistically implements relevant processes in ecosystem dynamics, including: climatic inputs, soil water and nutrient dynamics, plant uptake and growth by species, herbivory, fire, contaminants, physical disturbance, and management activities. In the EDYS model, ecological processes simulated in plot-level ecosystem cells are scaled up to the landscape level using a grid-based representation of the spatial extent of that ecosystem across the landscape. A significant practical challenge in applying complex ecological models is compilation of appropriate input data from a wide-variety of print and on-line media. A semi-automated database is currently under development, which will compile, organize, and format data sets to facilitate future EDYS applications. Another challenge is linking different types of models, each of which is specialized to simulate particular aspects of ecosystem and landscape dynamics. As so many different types of organizations are presently involved in model development and resource management, ownership of models and datasets will increasingly become an issue in their distribution and use among different types of land managers. © 2002 Published by Elsevier Science B.V.

Keywords: Ecosystem model; Landscape model; Ecosystem management

1. Introduction

There are extensive areas of public lands in the US and the rest of the world with multiple

land uses, management objectives, and regulatory constraints on management options. These include state and national parks, forest service lands, rangelands, and wildlife refuges, and numerous large military installations. There are also designated management areas such as watersheds that include both public and private land.

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A critical need in the management of these lands is assessing the efficacy of different management alternatives under different environmental and land use scenarios. Technological tools widely used at present include remotely sensed imagery and geographic information systems. Simulation models associated with these technologies are usually empirically based—spatial data at fixed start and end dates with state transitions in between. Since such tools are retrospective, they can only be used to project past dynamics into the future.

One type of tool that would be extremely valuable is large-scale ecological simulation models designed specifically to project effects of alternative climatic, usage, and management scenarios on ecological resources. If these models mechanistically simulate well-understood ecological processes, then we can be much more confident about the validity of their projections.

However, it has become evident to ecologists and land managers that different ecological processes operate at different spatial and temporal scales (Levin, 1992). Many disturbances and stressors of interest in land management operate at small scales, including herbivory, timber harvest, trails and roads, endangered species dynamics, erosion, and successional recovery. Other processes such as fires, climate, invasion of exotic species, and habitat change for migratory species clearly operate at large spatial scales. Although these processes operate at different spatial and temporal scales, they are often tightly linked, in accord with the tenets of hierarchy theory (e.g. O'Neill et al., 1986). For example, initiation and propagation of natural fires is highly dependent on roads as fire breaks, fuel loads left after grazing and logging, and successional status of the community. The modeling (and management) challenge is to link mechanistic simulations of small-scale 'ecosystem' processes to large-scale 'landscape' processes to provide more realistic and comprehensive projections of effects and ramifications of management alternatives.

We have been working for several years on a general ecosystem model for terrestrial systems, the Ecological Dynamics Systems model (EDYS) (Childress et al., 1999a,b). In this model, we implement a general small-scale ecosystem model,

focusing on the plant community and below-ground processes, then extrapolate the small-scale dynamics to the landscape level to link them to processes operating at larger scales. Our specific objective is to provide a tool for projecting large and small-scale ecological dynamics resulting from different disturbance, stressor, and management scenarios for a wide variety of ecosystem and landscape types. A detailed description of the overall modeling approach, program structure, and data structures is presented elsewhere (downloadable text: Childress et al., 1999b).

In this paper, we will describe our approach in linking small-and large-scale processes in a single model. Development of complex models of this type is not the end of the story in providing a useful tool to land managers, however. We will also describe other practical challenges in applying complex models in a management context, including issues of adequate data inputs, linking with other models, and ownership of the model systems. These challenges are quite different from those for models developed in the course of basic ecological research.

2. Ecological dynamics simulation model

The EDYS is a general ecosystem simulation model that mechanistically implements most of the relevant processes in ecosystem dynamics. The model links a number of modules (climatic inputs, soil water and nutrient dynamics, plant uptake and growth by species, herbivory, fire, contaminants, physical disturbance, and management activities), each operating at appropriate spatial and temporal scale, to project ecosystem dynamics under a variety of specified climatic, disturbance, and management scenarios.

EDYS has as its basic computational unit a simulation of ecological dynamics in small representative areas called plots. The approach here is a mechanistic representation of small-scale ecological dynamics within a relatively homogenous subunit of the ecosystem. This is essentially a systems model with flows of material between a number of compartments (Fig. 1). The plot-level dynamics focus on below ground processes and

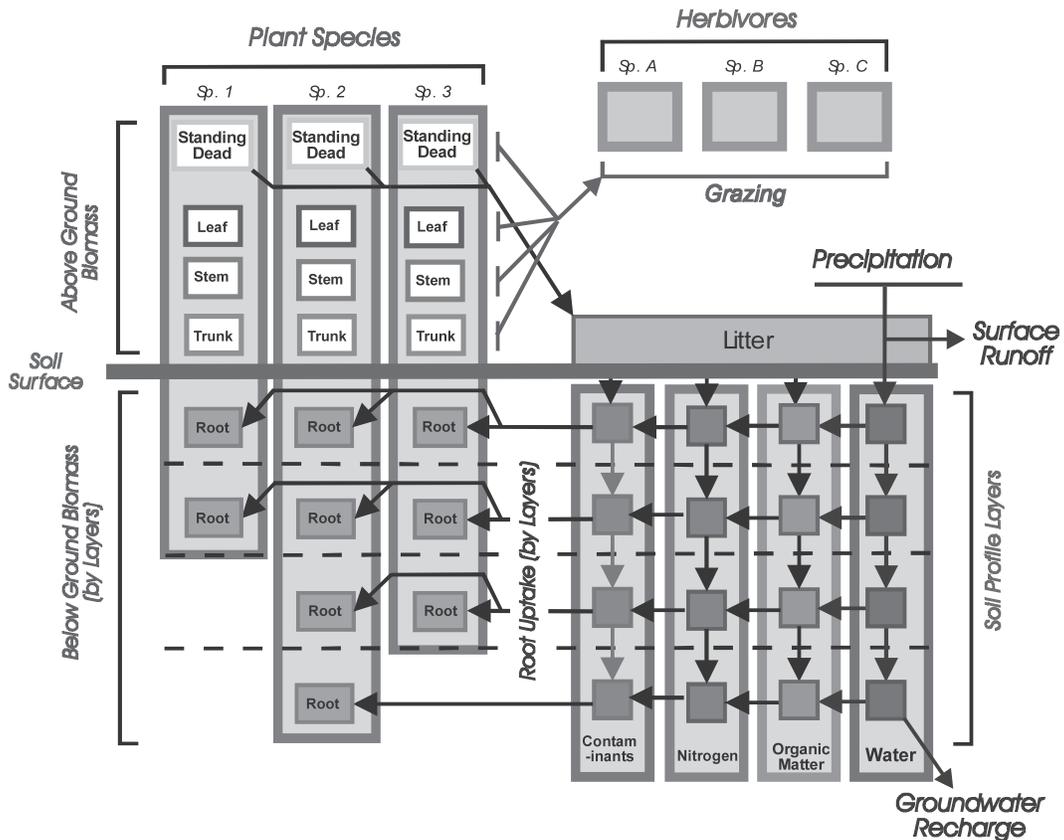


Fig. 1. Plot-level dynamics in the EDYS model.

plant dynamics. There is an explicit representation of the soil profile, including water, nutrient, and contaminant content and transport between horizons in the profile. Each plant species is represented as a biomass broken down into different components (roots, trunk, stems, leaves, seeds, and standing dead material). Plants competitively take up water, nutrients, and contaminants from the soil profile based on root architecture, and grow and allocate production to different components over time. Litter and organic matter within the soil profile decompose over time to complete the loop of materials in the ecosystem.

Within-plot hydrology is a primary driver of ecosystem dynamics in the model (Fig. 2). The hydrological module simulates precipitation, infiltration, mobilization of material in the litter and soil profile, evaporation, uptake by plants,

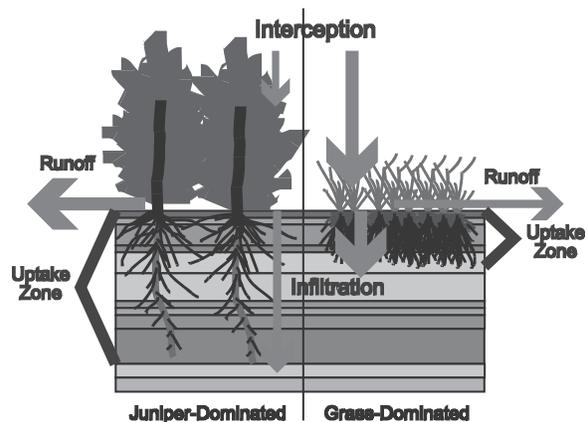


Fig. 2. Plot-level hydrological processes in the EDYS model.

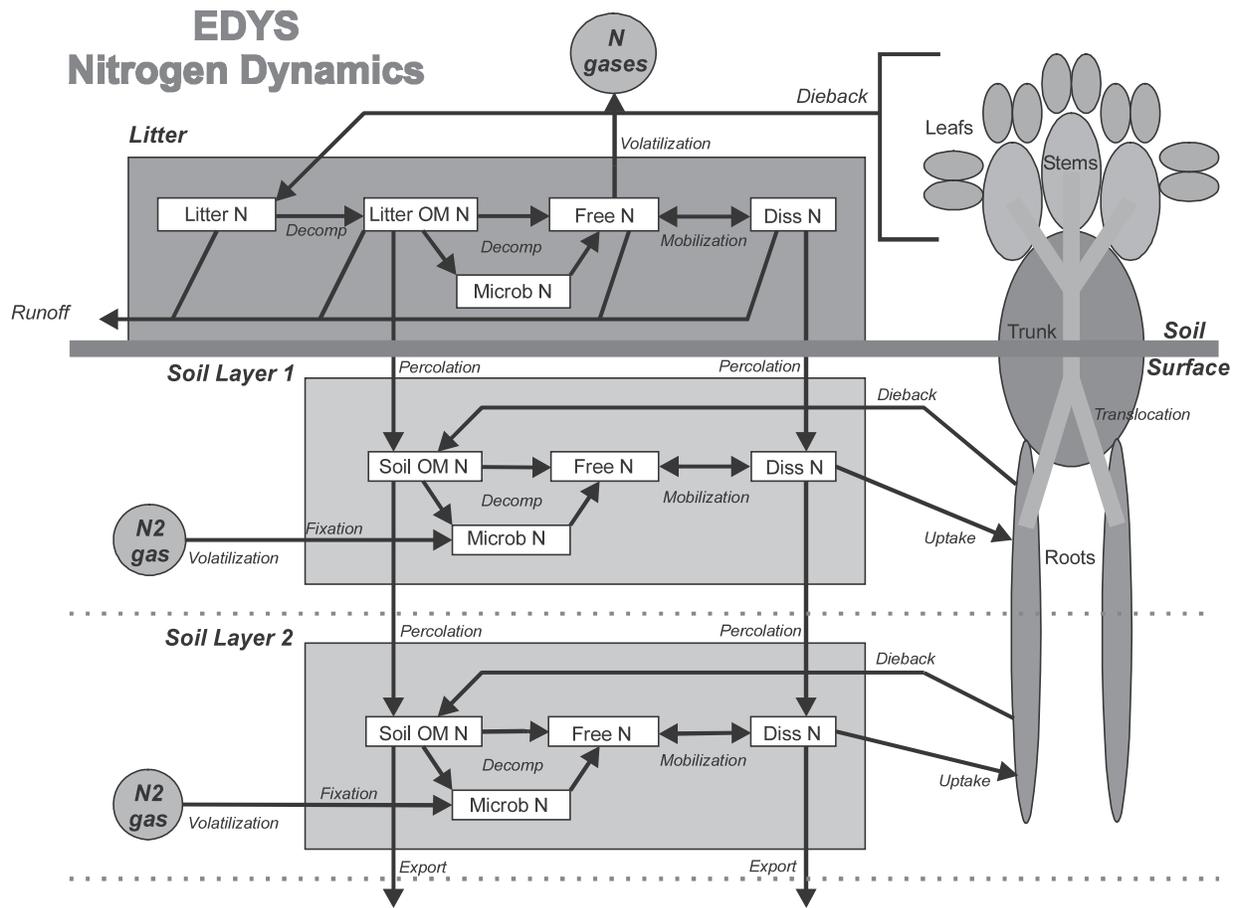


Fig. 3. Plot-level nitrogen dynamics in the EDYS model.

deep export out of the system, and surface runoff out of the plot. Several applications of the EDYS model to date have specifically focused on evaluating effects of vegetation on surface and subsurface water quantity and quality. Nitrogen is another key component in the model, and is an important factor in driving successional dynamics (Fig. 3). Contaminants are treated in an analogous manner to nitrogen, except that they may have detrimental effects on plants rather than nutritional. EDYS implements a detailed accounting system for compiling and recording pools, transfers, and cycling of these key materials at regular intervals. Because of this level of detail in material cycling in the ecosystem, EDYS is useful for addressing issues of contaminant fate

and effects, acid rain and other nutrient inputs, and carbon sequestration.

A key advantage of mechanistic representation of ecosystem processes is that disturbances and stresses are mechanistically represented, rather than projected from correlative, empirical, or abstract functions. For example, herbivory is implemented as the loss of plant biomass by species and components according to total forage demand and preferences specific to each herbivore. The effects of fire are similarly represented in fine detail: the biomass proportions of different above-ground components of different plant species lost to the burn depend on availability at that time of year, moisture content, total fuel loads, and fire intensity.

All processes simulated in the EDYS plot-level dynamics are expressed as units per square meter rather than units per plot. This means that plot size can be easily modified for different applications without requiring unit changes throughout

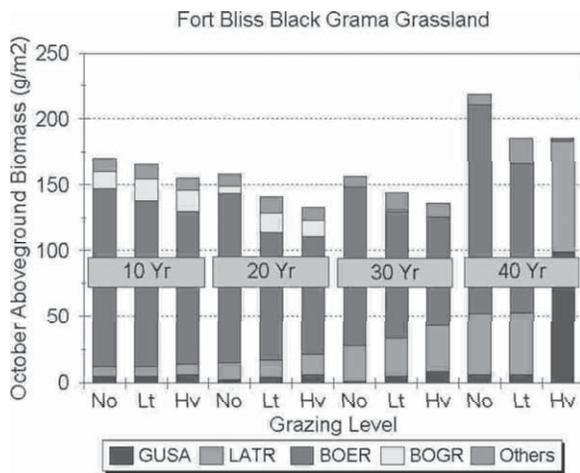


Fig. 4. Plant biomass projections in an EDYS application for a Chihuahuan grassland in New Mexico.

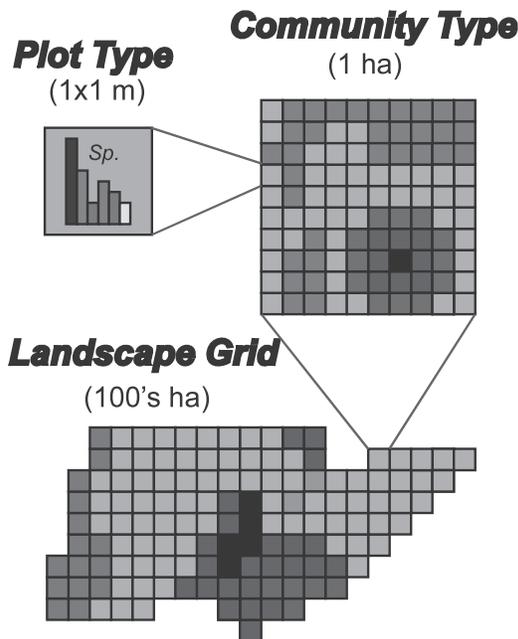


Fig. 5. Grid-based linkages of plot, community, and landscape-level dynamics in the EDYS model.

the model code. To date, plot sizes in different applications have ranged from 1 m² (slope revegetation assessment) to 40 acres (surface and groundwater production in a large watershed).

EDYS has been applied in several ecosystems to examine only plot-level ecosystem dynamics under several management scenarios. An interesting example was an examination of effects of different fire, grazing, and climatic regimes on community structure in a Chihuahuan Desert grassland community at Fort Bliss in southern New Mexico (Fig. 4). Forty-year simulations were conducted under different combinations of drought, average, and wet precipitation regimes, under low, moderate, and high-intensity grazing regimes, and with and without suppression of natural range fires. The simulated results indicated that only under conditions of drought, high-intensity grazing, and total fire suppression was there a collapse of the community from a grama grassland (BOER, *Bouteloua eriopoda*; BOGR, *Bouteloua gracilis*) to one dominated by creosotebush (LATR, *Larrea tridentata*) and snakeweed (GUSA, *Gutierrezia sarothrae*). Further, this collapse finally occurred only after 37 years of these sustained stresses.

3. Linking processes at multiple spatial scales

Because some ecological processes such as natural fire regimes, climatic regimes, and migrations of large herbivores operate at large spatial scales, it is important that models used in land management incorporate representations of large-scale systems such as landscapes. For example, management of watersheds requires consideration of the physical layout of elevations and channels as well as all the different ecosystem types that occur within it. In addition, management units may not closely correspond to any physical or ecological boundaries, but instead reflect political or ownership boundaries, or specific management units such as pastures or military training areas.

In the EDYS model, small-scale processes at the plot level are scaled up to the landscape level using a grid-based representation of the 'Landscape' (Fig. 5). Each cell in the landscape-level

grid is assigned a general ecosystem or 'Community Type' (e.g. ponderosa pine forest or little bluestem grassland), so that the spatial extent of each ecosystem type is explicitly represented. Plots in the EDYS model are further subdivisions of the community-level cells. 'Plot Types' represent variations of the community or ecosystem type, allowing EDYS to thereby represent spatial heterogeneity within the community type. Plot-level dynamics are essentially systems models of plant biomasses ('Species'), soil profiles, hydrology, and nutrients and contaminants.

EDYS does not conduct separate simulations of each cell across the landscape because for even small landscapes the computations would be intractable for so many cells. Instead, a series of representative plot types are simulated, and the results then applied to each cell in which each plot type occurs within the community-level grid. For example, in one application of the EDYS model for a training area at the US Air Force Academy in Colorado, nine different variations of the dominant ponderosa pine ecosystem were identified and plotted on the landscape grid representing the entire area. These variations reflected different age of the tree stands, variation in the soil profile, and different aspect and elevation. In the EDYS simulations, each variation was assigned a plot type, and each plot type independently simulated.

Plot type dynamics are an important element in the EDYS simulations because cells within the community-level grid may change plot type because of disturbance or management activities. For example, a burn through a cell would result in considerable loss of biomass, which should be reflected in the simulated dynamics within that spatial area. To accommodate this change, EDYS would create an entirely new plot type for this cell and other burned cells of the initial plot type, simulate the effects of the burn (i.e. remove the appropriate amount of biomasses), and maintain this plot type during the remainder of the simulation as another variation within that community type. Other undisturbed cells with the same initial plot type would not be affected, and simulations for this plot type would continue as before. If the simulation proceeded long enough for the disturbed plot type to have sufficiently recovered so

that the biomasses and soil profiles were indistinguishable from the undisturbed type, then EDYS would merge the plot types together again. In this manner, EDYS accommodates changes in vegetation and soil profile from any type of disturbance or management activity in any part of the managed landscape.

Landscape-level dynamics are also an important focus in EDYS. For example, surface runoff of precipitation is simulated as a cell-by-cell transfer of water and suspended sediments down-slope. Spread of fire is simulated as a stochastic cell-by-cell percolation of burns across the landscape, with the probability of the fire in each cell determined by the fuel load and moisture content in the cell, the number of adjacent burning cells, the intensity of the burn in adjacent cells, and direction of slope from adjacent burning cells. Use of different cells and communities by animals (e.g. grazers) is dependent on both the habitat quality of each cell as well as the spatial arrangement of plot types. Finally, management units across the landscape are areas in which uniform management practices are applied (e.g. pastures, brush clearing, prescribed burns). These units often have spatial boundaries (e.g. ownership boundaries) that have little correspondence to ecosystem spatial patterns, but nonetheless determine spatial distribution of land use (e.g. grazing) and disturbance (training and recreation).

EDYS has been applied in a wide variety of land management situations to address a number of management issues. Some examples include:

- Assessing potential impacts of different training regimes on vegetation, surface water runoff, and endangered species habitats: US Air Force Academy in Colorado; Fort Bliss in New Mexico; and Fort Hood in Texas.
- Assessing effects of invasion of woody plants (junipers) on surface water runoff and groundwater recharge: Clover Creek Watershed, Utah and Abo Arroyo Watershed, New Mexico.
- Assessing impacts of expanding wild elk herds on private winter grazing pasture and on threatened grouse habitat: Burns Hole Basin, Colorado.
- Assessing effectiveness of revegetation plans on stabilizing bare slopes: mine sites in Indonesia.

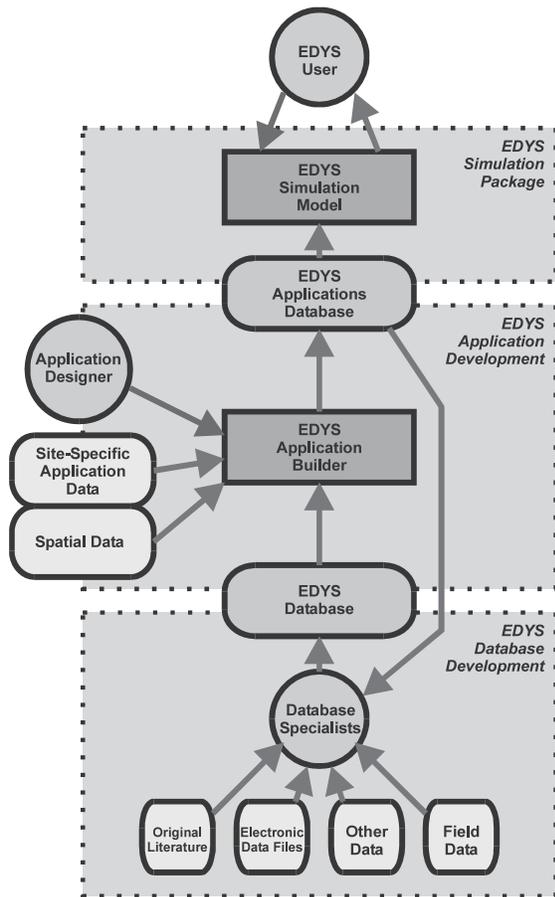


Fig. 6. System design for application of the EDYS model.

- Assessing effectiveness of revegetation plans on lowering water infiltration through mine tailings piles: mine sites in Montana, Nevada, and Indonesia.

4. Managing data requirements: the EDYS database

A significant practical challenge in applying complex ecological models such as EDYS is compilation of appropriate input data. All the processes implemented in the simulations must have appropriate initial values as well as parameters, usually for each plant species, each animal species, and each soil profile. The old programmer's

maxim 'Garbage In—Garbage Out' is particularly relevant here because of the tight linkages between all components and processes in the simulated ecosystem: the total projections are only as good as the weakest input data. Clearly, adequately parameterizing complex ecosystem models is a major challenge for management applications.

When computer simulations of ecological systems began in earnest in the 1960s, one of the biggest problems was lack of data about basic ecological processes. Now there are voluminous data available on all sorts of ecological processes from ecological systems around the world, which can be gleaned for use in model development and parameterization. Finding, categorizing, and archiving these data clearly require a major investment in time and resources, and recognition of this need was the primary impetus for establishment of the US National Biological Information Infrastructure. Other government entities such as the US National Weather Service (climatic data), US Geological Survey (digital elevation maps), and US Natural Resource Conservation Service (soil maps) are now increasingly making their data archives available in electronic format for Internet download in the National Spatial Data Infrastructure. However, even when available, identified, and compiled, appropriate data must still be organized in a format appropriate for loading into ecological models.

Data inputs are an explicit component of the overall EDYS system design (Fig. 6). Each EDYS application requires assembling all the maps and parameters required for simulating dynamics of each ecosystem in the application landscape (Site-Specific Application Data and Spatial Data, performed by the Application Designer). An important criterion in developing algorithms for simulating the variety of ecological processes in the model was to incorporate computations that utilized inputs and parameters for which conventional data are widely available. For example, most of the soil profile attributes are data which can be found in Soil Survey documents available for almost every county in the United States. These standardized data sources (Original Literature, Electronic Data Files, Other Data, Field

Data) are compiled in an ongoing effort by Database Specialists into the EDYS database for use in any application.

Essentially all of the data utilized in EDYS simulations are loaded from data files at the beginning of each simulation run. In general, data for each plant species, each community type, and each landscape are loaded from separate files according to the specifications for the particular application. For example, data loaded for each plant species include:

- Initial biomass and nutrient and contaminant content.
- Aboveground and belowground architecture.
- Nutrient and water requirements and use efficiencies.
- Seasonal maximum growth rates.
- Seasonal energy allocation matrices.
- Seasonal nutrient translocation matrices.
- Fire, herbivore, drought, and contaminant damage matrices.
- Seasonal constraints and triggers for all processes.

Data structures in the model include variables for storing intermediate results and computational parameters for all the processes associated with plant dynamics.

Data sets utilized in all EDYS applications to date are organized in a consistent format for easy re-use in different applications using the same community types, plant species, and soil horizons (Fig. 6, feedback arrow from EDYS Applications Database to Database Specialists). A semi-automated EDYS database system is currently under development (Fig. 7) to organize all the data compiled and formatted for all EDYS applications to date, and to facilitate rapid prototyping of future EDYS applications. It is anticipated that the database will prove to be as valuable to land managers as the EDYS model.

5. Linking with other models

No single model adequately simulates all biological and physical aspects of any ecosystem. It has been recognized for some time that to make projections of all these aspects requires linking multiple types of models (Botkin et al., 1979; Peters, 1991). Cross-disciplinary issues such as effects of vegetation cover on watershed production of surface water would be best addressed by linking models that specialize in particular areas.

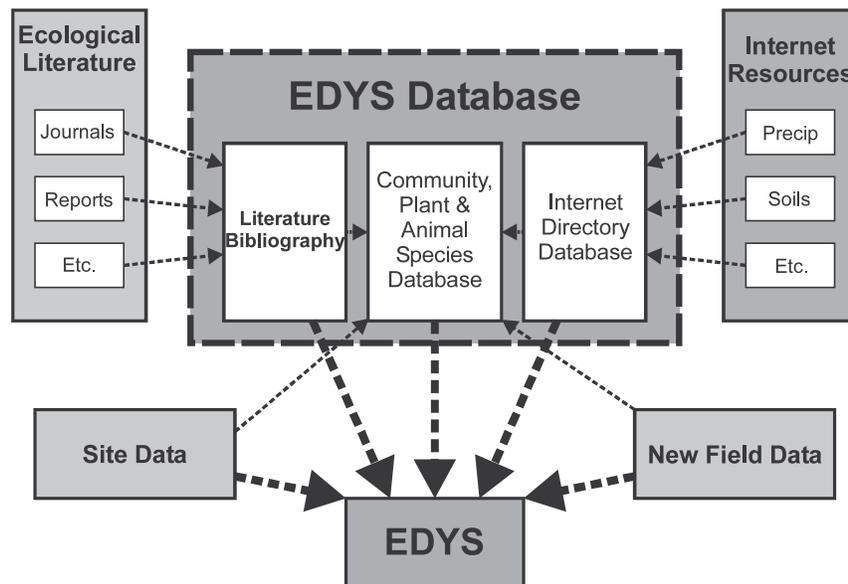


Fig. 7. System design for the EDYS database.

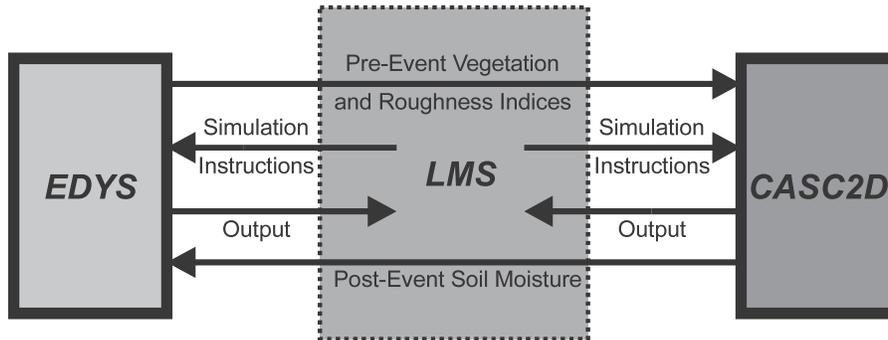


Fig. 8. Design for linking EDYS and CASC2D in the US Army Land Management System.

For example, EDYS simulates within-plot vertical movement of water and surface runoff for landscapes, but it is not as proficient in these areas as any number of existing rainfall-runoff models, especially for sediment transport and channel flow. Run-time linking of simultaneously executing models would be particularly attractive because each model could then update conditions for key variables and even digital maps during its run for access by other models during their runs. Of course, deriving specifications for data storage and exchanges and coordinating execution timing for the different models would be a major effort.

This is the objective of a special modeling initiative underway with the US Army Corps of Engineers called the Land Management System (LMS). This system will remotely link and coordinate a number of models and databases together via real-time Internet linkages (Goran et al., 1999). The different models and databases would be independently maintained and updated by the original developers at designated server sites. The LMS could then be used by any computer with an Internet hookup to remotely access, coordinate, and control simulation runs of different models simultaneously. Although a fully functional LMS will not be available for some time, some preliminary tests have been conducted in linking EDYS with the CASC2D hydrological model under development at the University of Connecticut (Fred L. Ogden). These tests involved using an early version of the LMS coordination software to designate short-term runs of each model, transfer output files from each to the other during breaks

in the run, and provide visual graphics and maps of results at different time steps (Fig. 8). Additional models of interest to the US Army for this system include those for simulating climate, air quality, and training activities.

It has become widely recognized that adequate management of natural resources must also take into consideration social and economic issues (Costanza, 1991). There would be considerable benefit in linking ecological and physical models with appropriate economic, social, and demographic models. However, meeting this need will require development of procedures for specifying model attributes, data needs, inputs and outputs, and implementation requirements for models from widely disparate disciplines. In addition, spatial and temporal scales for the processes simulated in these models will have to be carefully specified and evaluated. Multiple temporal and spatial scales implemented in complex ecosystem models such as EDYS may facilitate linking processes at whatever scales might occur among the models from disparate disciplines.

6. Ownership of models and data inputs

The challenge for linking various models leads to a final critical issue for application of complex models in management situations: ownership of models and data. EDYS is a proprietary model owned by its developers, even though most of the cost of development has been from project support from US Army Corps of Engineers. The

Corps and many other US federal agencies now frequently support such development projects in return for what amounts to a license to apply the products within their mission and jurisdiction. This arrangement is much like a site license for conventional software such as word processors and spreadsheets. Because so many organization types are presently involved in model development and resource management, the variety of arrangements for supporting development, designating ownership, transfer of ownership, licensing, specifications, deliverables, and maintenance will likely proliferate in the future.

Traditionally, ecological models have been freely distributed among all interested parties as part of the public domain, primarily because their support has come from government sources. Increasingly, models are developed and used by professional entities involved in environmental management, so ownership considerations necessarily include a profit motive. However, there are other issues related to ownership of models and supporting data, which are not financial:

- Control of the source and executable code and data files, especially during development. It is important to keep a consistent focus on the objectives and requirements during model development. This can be difficult when there are multiple funding sources and changing staff on the development team. This can also be difficult in the development of complex models in which a number of modules must be correctly linked. Therefore, ownership becomes a key issue in who designates and ensures objectives during and after development and testing.
- Maintenance and revisions. Error-correction and revisions are difficult to manage in complex models because, as in real ecological systems, a single change can have ramifications throughout the code. The developers have most of the experience in dealing with the model, and it is reasonable that they would be most proficient at model maintenance and managing revisions. It is also useful to have a single entity performing maintenance and revisions to control proliferation of different versions.
- Data requirements. As noted earlier, complex models have complex data requirements. Designating data requirements, developing QA/QC procedures for ensuring appropriate data are used, and building databases of parameters greatly facilitates model application. It is important to maintain data requirements along with maintaining the code and revisions to make sure that inputs are complete, appropriate, and in the correct format for the corresponding versions.
- Control of applications. EDYS is an example of a general ecosystem model specifically designed to be applicable for a wide variety of ecosystem types. While this ensures that the model can be applied in a wide variety of management situations, this does not ensure that it can be applied in any situation, nor that another model would not be more appropriate or cost-effective. Specific applications usually require some modifications of the main model to accommodate specific user needs. For example, a wide variety of management activities have been used in natural resource management (e.g., prescribed burns, chemical controls, seeding and planting, and fertilizing), and each of these must be carefully implemented in the model code to make sure that all ecological effects of the activities are quantitatively and qualitatively correct. Another example is alteration of the EDYS user interface to offer only reasonable and realistic scenarios and alternatives for simulation runs in a particular management application.
- Availability and distribution. There are now a variety of media for distributing and implementing computer code and data. In the LMS system mentioned above, the models would be executed remotely via the Internet. Other approaches would be to have executable code, databases, and documentation available for download, or to distribute them on CD-ROM. Decisions on how models should be distributed must also take into consideration technical skills and capabilities of potential users, means for distribution of revisions and upgrades, and media in which different types of data inputs are available.

7. Projections versus predictions

Another important issue in the interpretation of results from management models is distinguishing model projections from model predictions. Most people with little first-hand modeling experience believe that the value of models is to predict the future, that is, to make unequivocal predictions about conditions in the future. This is unfortunately not the case for most models relevant to natural resource management for two reasons.

First of all, models encapsulate a specific suite of assumptions about how the world works. These assumptions can be relatively good or bad, but for any model the suite is necessarily incomplete. Models do not capture all the components and processes of any system, and any model is a simplified abstraction of the real world. Therefore, the outputs from any model are logical projections of the assumptions and data in the model, and not necessarily of the real world.

Secondly, most of the driving forces in ecological models are beyond our capacity to predict into the future. These most obviously include climatic inputs such as temperature and precipitation regimes. Since we cannot accurately predict the weather, we certainly cannot predict ecological dynamics, which are dependent on the weather. Instead, we can derive a series of likely climatic scenarios based on historical weather patterns, put these scenarios into separate simulation runs, and from these project what we think the ecological dynamics would be given each scenario.

It is important that model users understand that the appropriate use of management models is to project the future given explicit assumptions about our understanding of how the system works, given specific scenarios for the driving variables, and given specific management alternatives they wish to consider, including no-action alternatives.

8. Conclusions

There are very complicated environmental issues involved in natural resource management which have to be managed one way or another.

At this time there is no substantive theory about building ecological models (Peters, 1991), much less models useful as management tools, and still less so for complex ecosystem and landscape models. We need to continually learn how to build these tools, how to apply them usefully, how to interpret what they tell us, and especially how to explain these tools and their limitations and interpretations to decision-makers. This is very simply learning by doing, very much in the framework of Adaptive Management (Walters, 1986). But it would be terribly unfair to ask of decision-makers that they consider all the relevant issues involved in managing natural resources without providing them tools that let them project and evaluate all ramifications of the decisions we ask them to make.

Acknowledgements

We are pleased to acknowledge financial support during development and application of the EDYS model in a series of grants and projects from the US Army Corps of Engineers, Construction Engineering Research Laboratory, Champaign, IL (PoC: Dr David L. Price), and the USDA Natural Resource Conservation Service, South Central Water Management Center, Little Rock, Arkansas (PoC: Dr Terry Atwood).

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