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An Object-Oriented Framework for Dynamic Ecosystem Modeling:

Application for Integrated Risk Assessment

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Abstract:

Ecological risk assessment requires the integration a wide range of data on anthropogenic processes, ecological processes, and on processes related to environmental fate and transport. It is a major challenge to assemble a simulation system that can successfully

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capture the dynamics of complex ecological systems, and an even more serious challenge to be able to adapt such a simulation to shifting and expanding analytical requirements and contexts. The Dynamic Information Architecture System (DIAS) is a flexible, extensible, object-based framework for developing and maintaining complex simulations. DIAS supports fully distributed simulations in which the real-world entities that make up ecological systems are represented as software "domain objects." The Integrated Dynamic Landscape Analysis and Modeling System (IDLAMS) provides a good example of how DIAS has been used to build a suite of models for the purpose of assessing the ecological impacts of military land use and land management practices. IDLAMS is a prototype conservation modeling suite that provides military environmental managers and decision-makers with a strategic, integrated, and adaptive approach to natural resources planning and ecosystem management. The IDLAMS prototype used Fort Riley, Kansas as a case study to demonstrate DIAS' capabilities to offer flexibility, interprocess dynamics, and reuse of code for ecosystem modeling and simulation. DIAS can also readily lend itself to other applications in ecological risk assessment. It has great potential for the integration of ecological models (associated with biological uptake and effects) with environmental fate and transport models. A DIAS ecological risk assessment application could be used to predict the magnitude and extent of ecological risks and evaluate remedy effectiveness in a timely manner. Furthermore, because DIAS offers the potential for cost-effectiveness through the reuse of computer code, either by reusing legacy technologies or through the development of reusable objects and modules.

Key words: integrated ecological risk assessment, ecological modeling, fate and transport modeling, object-oriented architecture, code reuse

Introduction

Ecological risk assessments are mandated regulatory activities at contaminated sites managed by federal agencies. These assessments must be specific enough to support defensible determinations of acceptable and unacceptable risks to ecological resources. In addition, the information developed through the risk assessment process plays an important role in the development and evaluation of remedial alternatives and in monitoring and evaluating ultimate remedy effectiveness and site restoration.

In contrast to human health risk assessments, ecological risk assessments typically deal with complex systems and must integrate many more physical, chemical, and ecological processes and relationships. Ecological systems can be characterized by the interplay of diverse natural and anthropogenic processes interacting across a range of spatial and temporal scales. Because of this greater complexity, the direct and indirect effects of contaminants (such as reduced population size, productivity, and altered community structure) vary greatly among the exposed ecological resources. In addition, impacts associated with remediation activities may further adversely affect ecological resources through direct habitat loss or reduction in habitat quality.

Ecological risk assessments typically must gather, integrate, and evaluate site-specific information regarding 1) environmental fate and transport of contaminants, 2) the modes of action of each contaminant under evaluation (effects information), 3) contaminant uptake by biota from the environment and subsequent movement through food webs, and 4) the responses of the ecological resources under evaluation to the contaminant exposure (EPA, 1997). These data may be obtained by a variety of methods, including direct sampling and measurement of biological and environmental parameters, laboratory toxicity studies to develop dose-response relationships, extensive literature reviews, and mathematical modeling (EPA, 1993; Campbell and Bartell, 1998), to estimate contaminant- and species-specific doses and responses.

In addition to the difficulties associated with trying to establish cause-and-effect relationships between environmental contaminants and ecological resources, the collection and evaluation of necessary data are typically conducted under regulatory-driven timelines and budget constraints that may preclude certain types of data-gathering activities. Thus, there is a need for an easy-to-use tool that can readily integrate environmental and ecological models into an ecological risk assessment role and can offer a time- and cost-effective way to evaluate ecological risks. Researchers have recognized the need for more integrated and comprehensive approaches to modeling and simulation that can assess several components of an ecological system simultaneously (Maxwell and Costanza, 1995; Berry et al., 1996; Bennett et al., 1996; Frysinger et al., 1996; Fedra, 1996; Zandbergen, 1998, and Bartell et al., 1999).

The modeling and simulation approach is a method for evaluating potential impacts of different environmental scenarios associated with complex ecological systems. For example, the Grand Canyon Ecosystem Model (GCM, available at http://www.usbr.gov/gces) is a simulation program that permits quantitative predictions of the effects of Glen Canyon Dam management choices on downstream resources through the application and integration of several physical, biological, and socioeconomic models. Such a modeling approach may represent an effective tool for providing rapid, scientifically-based evaluation of potential risks and of remedial alternatives to support risk management decisions.

The original Integrated Dynamic Landscape Analysis and Modeling System (IDLAMS) was designed and developed to integrate data, environmental models, land-use planning, and decision support technologies through a geographic information systems (GIS)-based framework (Li et al., 1998). Initially, IDLAMS relied heavily on GIS technology to act as the integrating framework for dynamic ecosystem modeling. GISs have been widely used to visualize, integrate, and analyze spatial data pertinent to evaluating changes in ecological systems (for example, see Minns and Moore, 1992; Akcakaya, 1996 (online); Band et al., 1996; DOE, 1996; Zandbergen, 1998). Many of these efforts have resulted in the creation of larger, more comprehensive models that employ model-to-model or model-to-GIS linkages (Band et al., 1996; Ortigosa et al., 2000).

The use of GIS software as the integration framework for many of the systems seems obvious because of the important role spatial dynamics has in evaluating complex ecological systems. Although these efforts have illustrated the potential of integrated modeling, they have created integration systems that are somewhat inflexible and that do not adequately reflect true inter-process dynamics. The development and subsequent use of IDLAMS showed that the GIS framework, although a powerful tool for spatial display and analysis, was not an appropriate integration tool. While a powerful tool for displaying and analyzing large data sets, it could not serve as the adaptive platform for integrating diverse models and simulations (Sydelko et al., 1999).

It is a major challenge to assemble a simulation system that can successfully capture the dynamics of complex ecological systems, and an even more serious challenge to be able to adapt such a simulation to shifting and expanding analytical requirements and contexts. For these reasons, IDLAMS researchers turned to the Dynamic Information Architecture System (DIAS) to take advantage of a flexible, dynamic, and modular object-oriented approach. This new framework, built within DIAS, is the object-oriented (OO)-IDLAMS; it provides environmental managers and decision-makers with a strategic, adaptive approach to integrated ecological risk assessment, environmental management, and integrated natural resources planning.

Object-oriented architecture for ecological modeling

For ecological modeling, the main components of a DIAS simulation are 1) software objects (entity objects) that represent real-world entities such as atmosphere, fish, or river, and 2) simulation models (related to environmental fate and transport and ecological processes and responses) or other applications that express the dynamic behaviors of the real-world entities (such as sediment transport, stream flow, and reproductive cycles). The DIAS infrastructure makes it feasible to build, manipulate, and simulate complex ecological systems in which multiple objects interact via multiple dynamic environmental and ecological processes.

The DIAS approach allows for a very user-friendly modeling and integration platform because it embraces and extends the key software engineering tenets of the Object Paradigm, namely encapsulation and inheritance. Encapsulation promotes a clean modular design in which the various entity objects manage their own state/attributes and dynamic behaviors. Inheritance allows for code re-use and extensibility, because the object subclasses can "inherit" attributes and behaviors from parent-object classes. Thus, the time and effort required to develop alternative simulations by swapping one model for another or adding new models to an existing simulation is substantially reduced.

Many traditional model integration architectures create model-to-model links (Figure 1). However, as the number of models in the simulation suite grows, this approach becomes more cumbersome and more difficult to successfully implement. In addition, when new models are added or one model is replaced by another, the inter-model links in the system often have to undergo major revision to permit integration of the new models. To address this difficulty, DIAS extends the Object Paradigm by abstraction of the objects' dynamic behaviors, separating the "WHAT" from the "HOW." DIAS object class definitions contain an abstract description of the various aspects of the object's behavior (the WHAT), but no implementation details (the HOW); these details are addressed by other DIAS models or applications.

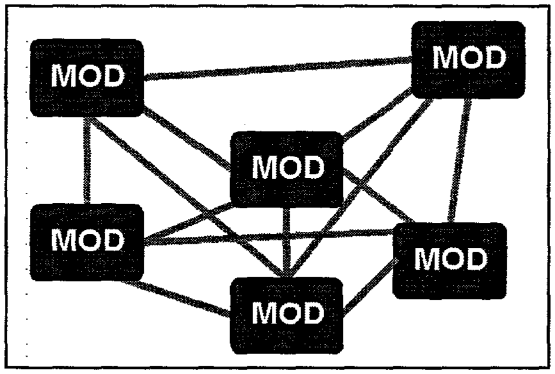

Figure 1. Traditional model-model interaction approach

To illustrate the principle of behavior abstraction, assume the model includes a Fish entity object behavior that results in the fish dying. This behavior is generically coded into the Fish object as “implement mortality.” This generic behavior “implement mortality” represents the “WHAT.” The implementation details for “HOW” the behavior “implement mortality” specifically occurs would depend on the external simulation process(es) of interest and included in the DIAS model suite. For example, depending on the objectives of the simulation, models that “implement mortality” may include population models, disease models, predator/prey models, or harvest models.

The DIAS approach allows models to be linked to appropriate domain objects “on the fly”, to meet the specific needs of a given simulation objective. This leads to even greater flexibility and extensibility of the simulation model. In DIAS, models communicate only with domain (entity) objects, never directly with each other (Figure 2).

From a software perspective, this makes it easy to add models, or swap alternative models in and out without major recoding.

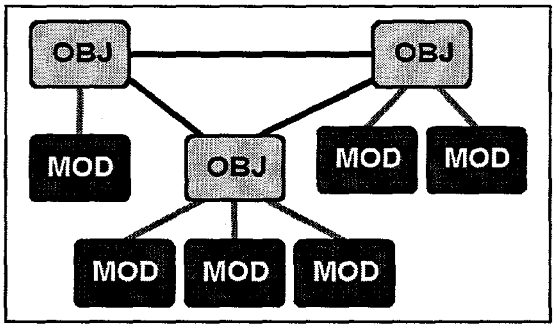

Figure 2. DIAS object-model interaction approach

In complex DIAS simulations, external models or applications participate in a simulation through a formalized registration process that "wraps" each model or application for use in DIAS. This "wrapping" procedure requires a formal registration procedure that enables the DIAS entity objects to implement external models to address behaviors. An important feature of DIAS is that the "wrapped" models and applications run in their native languages rather than requiring translation to a common or standard system language.

Thus, an environmental fate and transport model such as the QWASI model of chemical fate in lakes (Mackay, 1991), which simulates contaminant fate and transport in lakes, may easily interact with the Wisconsin Sea Grant Fish Bioenergetics II model (Hanson et al., 1997), which can be used to estimate contaminant bioaccumulation by fish. Using DIAS, these two models could be integrated to permit the user to predict contaminant uptake and concentration in fish under different contaminant-loading scenarios. For example, the QWASI model might implement a Lake object's behavior "update sediment PCB concentration" to estimate the PCB concentration in the lake sediments. The Bioenergetics model might then invoke an Individual Fish object's behavior "contaminant uptake" that would estimate contaminant uptake by fish feeding in the lake, and then in turn update the Individual Fish object's parameter "contaminant concentration" to provide a predicted contaminant concentration in the fish. A GIS application can also be added to the suite of models to provide for model integration of various spatially-explicit parameters such as the Sediment object's "extent" parameter, the Fish Population object's "distribution" parameter, and the Sediment object's "contaminant input locations" parameter. This GIS application can also be used to provide graphical displays of updated parameters such as "contaminant distributions" and "aquatic habitats with high bioaccumulation potential."

This ability to link external models and applications gives DIAS the ability to scale very well to increasingly complex problems. To adequately address the scientific domain of these new models, however, requires that intelligent domain (discipline) expertise be used in entity object design.

A major advantage of DIAS' object-model approach is that it includes the use of a dynamic entity object library that speeds application development. This object library contains entity objects that represent real-world entities, in both state and behavior, for a wide variety of subject domains. Each time a new application is developed using the DIAS framework, existing objects become more mature (new state and behavior are added) and new objects are added to the library. In this way, the library is continuously expanding, making future application development more efficient.

Another important feature of the DIAS framework is its ability to provide run-time feedback between models. Whereas users of the original IDLAMS were restricted by a static setup for simulation runs using a "hard-wired" sequencing of models and interactions, users of DIAS simulation applications have the freedom to choose various combinations of models and interactions for each new simulation run. Simulations are set up "on the fly," aided by an intelligent context-driven graphical user interface. The DIAS Simulation Analysis Frame is automatically populated with the appropriate objects once the user selects the desired combination of models to run for a given simulation, and the connections between models are established at run-time. The user need only indicate which combination of models should be included in the scenario, and this "context" drives simulation setup. An added benefit is the ability for users to track and visualize the simulation as it occurs and make changes to model parameters or model inputs during the course of a simulation. The following presents an example of the application of the DIAS framework and the OO-IDLAMS integration platform.

In addition to the DIAS components, the Framework for Addressing Cooperative Extended Transactions (FACET) software system can provide further powerful modeling and simulation functionality. FACET is a flexible architecture for implementing models of dynamic behavior of multiple individuals, or "agents." These agents can be human (individuals or organizations) or animal, and may exhibit any type of organized social behavior that can be logically articulated. FACET provides the ability to implement complex societal models, such as land management and use plans, independently from their associated natural process models. Interactions among agents in FACET are represented by "Course of Action" (COA) object-based models. Each COA contains a directed graph of individual actions, representing, for example, a specified procedure for land use, a standard policy for land management, or a known pattern of social behavior. Within DIAS, COAs are used to represent specific behaviors of entity objects.

OO-IDLAMS prototype

Study site description

The study area used for the OO-IDLAMS prototype is Fort Riley, Kansas, which is the same study area used in the original IDLAMS application (Li et al., 1998). Fort Riley lies on the western edge of the tall-grass prairie in the Flint Hills of eastern Kansas (Louis Berger & Associates, Inc., 1992). Fort Riley covers about 40,470 ha (100,000 acres), of which 29% is tall-grass prairie, 27% is abandoned cropland in various successional stages, 14% is tame pasture, 12% is woodlands (primarily bottomland), and 9% is shrubland. The remaining 18% consists of built-up areas. The tall-grass portion is probably one of the largest intact areas of tall-grass prairie remaining in North America today.

Land managers at Fort Riley have identified four goals for managing the natural resources of training areas. The main goal is to enhance the training mission. If vehicular and troop training causes too much damage, part of the facility might have to be closed for rehabilitation. If an area becomes too degraded, it also loses realism, which decreases the land's training value. On parts of the installation, open prairie provides minimal camouflage during maneuvers; increased forest cover would increase the value to the training mission. Simply planting trees in the middle of the grassland is not feasible because periodic fire would kill or damage the trees over time. A second goal is to enhance the condition of the vegetation as a conservation measure, so that the vegetation is as close to its potential natural climax as possible and is in stable and vigorous condition; reducing soil erosion is part of this goal. Third, the managers wish to enhance wildlife habitat. Several game species, including deer, elk, and prairie chickens, provide opportunities for hunting on parts of the installation, which helps to foster goodwill among off-base hunters. In addition, managers must be concerned with enhancing and protecting currently and potentially threatened and endangered plant and animal species. Finally, the fourth goal is for managers to determine the best allocation of their land management budget to the competing resource uses and needs on the installation.

Simulation implementation

The original IDLAMS integrates data, environmental models, land-use planning, and decision support technologies through a GIS-based framework. The system implemented for Fort Riley, Kansas, can model and predict changes in vegetation type that might result from fire, forest/shrub expansion, or secondary succession of grassland following training activity disturbances. It also has submodels for soil erosion prediction and wildlife habitat suitability analyses.

Environmental managers and decision-makers can use IDLAMS to:

- Simulate "what-if" scenarios for predicting future ecological conditions under a given land management plan;
- Incorporate trade-off analyses when comparing different land management alternatives; and
- Identify and resolve land-use issues and determine cost-effective solutions to long-term land stewardship problems.

Because the objective of the OO-IDLAMS prototype research was only to demonstrate the advantages of this new object-oriented architecture approach, not totally rebuild the old IDLAMS, the OO-IDLAMS prototype integrates only a subset of the original IDLAMS. Figure 3 illustrates OO-IDLAMS prototype conceptual design. Models in the new OO-IDLAMS include the Vegetation Dynamics Model and the Henslow's Sparrow Habitat Model (reimplemented as an external Environmental Systems Research Institute (ESRI®) application).

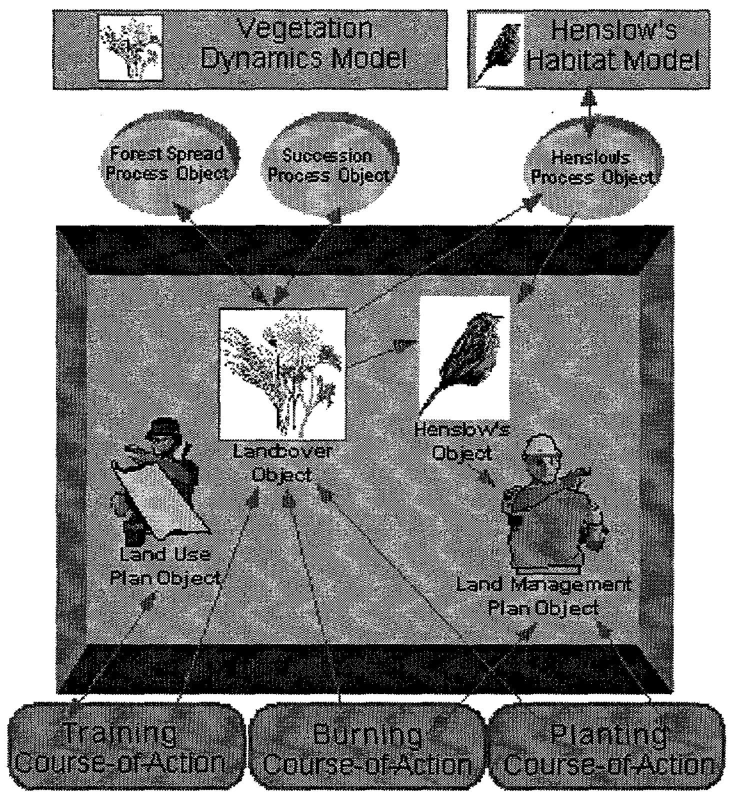

Figure 3. OO-IDLAMS Prototype conceptual design

In addition, to demonstrate improved modularity and flexibility of OO-IDLAMS and fully utilize the object-oriented capabilities of DIAS, the Military Training and Land Management components, previously coded within the original Vegetation Dynamics Model, were broken out into three COA objects. A DIAS COA object is essentially a flowchart of individual steps constituting a specific plan or action and is used in DIAS to model procedural or sequential processes. COAs are used to represent specific behaviors of entity objects. The three COAs used in OO-IDLAMS (Training, Burning, and Planting) represent the Fort Riley land use and land management plans (Figure 3). These plans are inherently procedural in nature and readily lend themselves to COA implementation. COAs are considered to be models within OO-IDLAMS. The natural succession processes remain part of the external Vegetation Dynamics Model and are registered with OO-IDLAMS as the external Vegetation Dynamics Model.

Figure 3 also illustrates the DIAS design principle in which models do not talk directly to one another but are only integrated through their relationships with the four entity objects (Landcover, Land Use Plan, Land Management Plan, Henslow's Sparrow). The OO-IDLAMS entity objects contain state variables (attributes) that represent the input/output parameters of the models within the simulation suite and encapsulate behavior implemented by the models in the suite.

OO-IDLAMS employs an object-oriented GIS module and provides real-time spatially oriented displays of an object's positions and/or parameters. This GIS module is designed to navigate within an OO-IDLAMS study area/frame to create, query, view, and manipulate objects. For each simulation implementation, model output parameters are generated at each time step of the simulation. The four parameters shown in Figure 4 are Landcover, Land Use Distribution, Planted Areas, and Henslow's Sparrow Habitat.

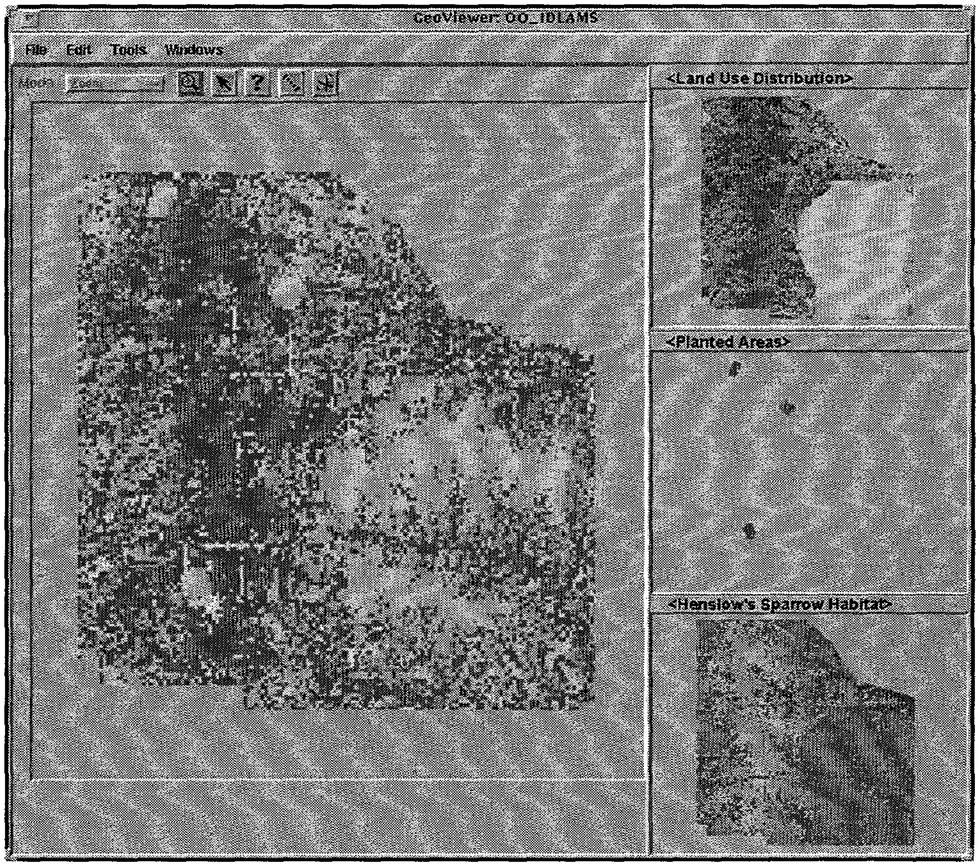

Figure 4. OO-IDLAMS GIS module provides real-time spatially oriented displays

Discussion

OO-IDLAMS demonstrates the flexibility of the DIAS object-model interaction approach. In the QWASI–Fish Bionergetics example, if the bioenergenics model needs to "ask" the Sediment object for the concentration of PCB, it will not know or care how that particular attribute is generated, whether by a fate and transport model or fed in through real-time monitoring data. It will simply look for and incorporate the requested parameter value (PCB concentration).

In the OO-IDLAMS prototype example, the behavior attached to the Landcover entity object “implement succession process” invokes the natural succession routine of the Vegetation Dynamics Model. Similarly, the behavior “implement forest spread process” invokes the forest spread routine of the Vegetation Dynamics Model. Both of these behaviors have corresponding simulations within the same model. However, if a different forest spread model is preferred, it can be added to the OO-IDLAMS simulation suite by simply setting the simulation context to invoke the new model instead of the existing Vegetation Dynamics Model. This illustrates a great advantage of the DIAS architecture, because when new models are added to the suite, existing links to other models remain unchanged. Thus, the time and effort required to assemble alternative simulations by swapping one model for another or adding new models to the simulation suite is substantially reduced. However, if the new model requires additional parameters or generates output that differs from the original model, the entity object will need to be edited to add new attributes or augment existing attributes to accommodate those changes.

In OO-IDLAMS the ability to implement complex societal models, such as land management and use plans, independently from their associated natural process models is accomplished through the use of COAs. It is important to have the capability to keep these models independent. While all processes of the Vegetation Dynamics Model impact vegetation, the nature of the vegetation change may differ dramatically among the different processes within the model. For example, natural succession is an ecologically driven process, while planting, burning, and training are management activities that result in man-made changes to the vegetation community. Isolating each process as a separate model allows for easier identification of important linkages and feedbacks among the different models. Furthermore, separating the management aspect of vegetation change from the ecological process is in keeping with the modular design approach and allows for greater flexibility in the creation of alternative simulation scenarios. Separating the management plans into distinct COA models provides the user with the ability to easily change management scenarios without affecting the natural succession processes (and the underlying model code).

The OO-IDLAMS prototype also illustrates the capability of DIAS to support run-time feedback between models. In the current modeling suite, feedback exists between the Henslow's Sparrow Habitat Model and the Planting COA (Figure 5). The Henslow's Sparrow Habitat Model assigns excellent habitat suitability to patches of preferred vegetation characteristics that are at least 65 ha in size. Planting native species next to a patch and therefore fulfilling the patch size requirement could greatly benefit the species. To accommodate this feedback loop, during every time-step the Planting COA will "ask" the Henslow's Sparrow object what the current state of its patches and additional hectares needed state variable is. This will invoke a process of the Henslow's Sparrow Habitat Model that creates patches of excellent habitat. The planting COA will check for adjacent damaged grassland areas that can be planted to fulfill the 65-ha requirement. If native species can be planted in such a way as to fulfill the requirement, the COA will plant to fulfill the 65-ha patch size requirement. Viewing the planted areas map after the simulation can be very helpful to a land manager interested in knowing where to plant native species in order to manage the Henslow's Sparrow.

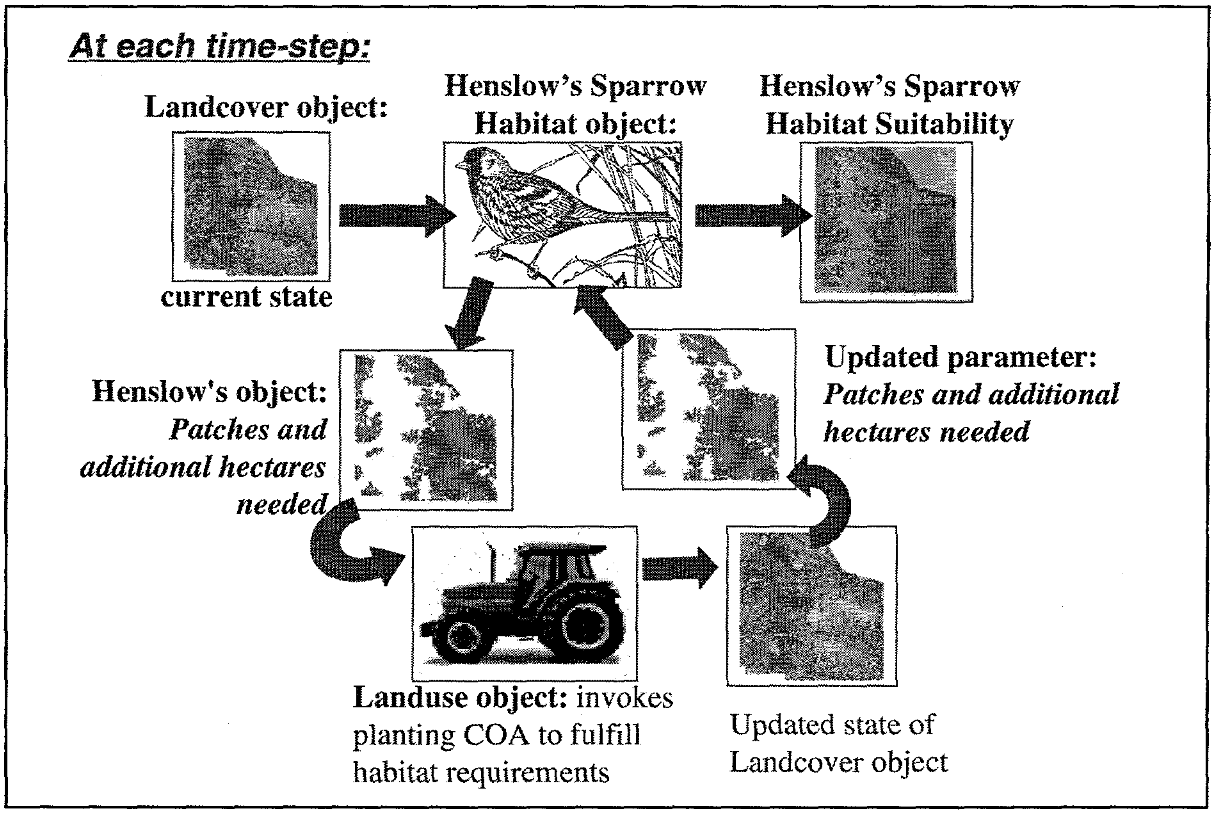

Figure 5. Illustration of the OO-IDLAMS run-time feedback between the Henslow's Sparrow Habitat Model and the Planting COA

Conclusion

The OO-IDLAMS prototype illustrates the advantages of the DIAS object-model approach to integrated dynamic simulation and modeling that can assist in evaluating a diverse array of environmental problems associated with land management. The DIAS architecture offers enhanced capabilities to:

- Allow for the integration of existing diverse models without extensive reworking, thus capitalizing on previous investments in already available models and applications;
- Encourage the development of object libraries that contain a large number of reusable objects to represent a wide variety of natural and artificial elements of the environment, and therefore reducing the long-term cost of redeveloping objects and technologies;
- Provide an integrated architecture that reflects the dynamics of living ecosystems, land uses, and land management practices;
- Support software applications that can operate at multiple spatial and temporal scales; and
- Incorporate new data, concepts, and technologies that will bring together the best available knowledge, science, and technology to address environmental problems in a scientifically defensible yet timely and cost-effective manner.

These DIAS capabilities would also greatly aid in addressing issues associated with ecological risk assessment and environmental restoration. For example, the DIAS architecture would aid ecological risk assessors by allowing them to rapidly and easily integrate a diverse set of dose and effects models together with contaminant fate and transport models and site-specific data to arrive at a risk estimate. While there are a variety of individual models currently available, difficulties in model integration typically limit the diversity of models employed by the risk assessors. Similarly, the DIAS architecture would permit a more rapid and comprehensive evaluation of remedial alternatives and restoration options by expediting the integration and use of diverse ecological and environmental models that might not have been considered for use because of integration issues. An integrated model would allow the risk assessor and risk manager to rapidly make predictions about remedy effectiveness with regards to risk reduction while at the same time providing predictions of implementation impacts and ecosystem recovery.

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Figure captions

Figure 1. Traditional model-model interaction approach

Figure 2. DIAS object-model interaction approach

Figure 3. OO-IDLAMS prototype conceptual design

Figure 4. OO-IDLAMS GIS module provides real-time spatially oriented displays

Figure 5. Illustration of the OO-IDLAMS run-time feedback between the Henslow's Sparrow Habitat Model and the Planting COA