An Advanced Object-Based Software Framework for Complex Ecosystem Modeling and Simulation*

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June, 2000

for

4th International Conference on Integrating GIS and Environmental Modeling
September 2-8, 2000
Banff, Canada

** Work supported under a military interdepartmental purchase request from the U.S. Department of Defense, U.S. Army, through U.S. Department of Energy contract W-31-109-Eng-38.

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4th International Conference on Integrating GIS and Environmental Modeling (GIS/EM4): Problems, Prospects and Research Needs. Banff, Alberta, Canada, September 2 - 8, 2000.

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GIS/EM4

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Abstract

Military land managers and decision makers face an ever increasing challenge to balance maximum flexibility for the mission with a diverse set of multiple land use, social, political, and economic goals. In addition, these goals encompass environmental requirements for maintaining ecosystem health and sustainability over the long term. Spatiotemporal modeling and simulation in support of adaptive ecosystem management can be best accomplished through a dynamic, integrated, and flexible approach that incorporates scientific and technological components into a comprehensive ecosystem modeling framework. The Integrated Dynamic Landscape Analysis and Modeling System (IDLAMS) integrates ecological models and decision support techniques through a geographic information system (GIS)-based backbone. Recently, an object-oriented (OO) architectural framework was developed for IDLAMS (OO-IDLAMS). This OO-IDLAMS Prototype was built upon and leverages from the Dynamic Information Architecture System (DIAS) developed by Argonne National Laboratory. DIAS is an object-based architectural framework that affords a more integrated, dynamic, and flexible approach to comprehensive ecosystem modeling than was possible with the GIS-based integration approach of the original IDLAMS. The flexibility, dynamics, and interoperability demonstrated through this case study of an object-oriented approach have the potential to provide key technology solutions for many of the military's multiple-use goals and needs for integrated natural resource planning and ecosystem management.

Keywords
Object-oriented architecture, military land management, integrated natural resource planning, adaptive ecosystem management, run-time model interoperability, code reuse, environmental decision-support.

Problem Statement

Military land managers and decision makers are recognizing the need for more strategic and adaptive approaches to integrated natural resources and ecosystem management. Decision makers face an ever increasing challenge to balance maximum flexibility for the mission with a multitude of other land use, social, political, and economic goals. In addition, these goals encompass environmental requirements for maintaining ecosystem health and sustainability over the long term. On-site and off-site environmental impacts, wildlife conservation issues, cultural resources concerns, and the need for training realism all dictate that natural resources be maintained and enhanced on these installations.

Background

GISs have been widely used to visualize, integrate, and analyze spatial data pertinent to evaluating changes in ecological systems (e.g., see Akcakaya 1996 (online); Fedra 1996; Frysinger et al. 1996; Zandbergen 1998; Ortigosa et al. 2000). The use of GIS software as a model integration framework seems obvious because of the important role of spatial dynamics in evaluating complex ecosystem processes. Although these efforts have illustrated the potential of integrated spatio-temporal modeling, they have created integration systems that are somewhat inflexible and that do not adequately reflect true interprocess dynamics.

In 1994, the Strategic Environmental Research and Development Program (SERDP) sponsored the development of the Integrated Dynamic Landscape Analysis and Modeling System (IDLAMS) to address the military's need for a model-integration framework (Li et al. 1998). IDLAMS is a prototype computer decision support system that integrates ecological models and decision support techniques and is based upon a GIS framework. The GIS-based approach used to develop the IDLAMS prototype will be discussed in this paper. 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. It is a major challenge assembling a simulation system that can successfully capture the dynamics of complex ecological systems, and a more daunting challenge is to adapt such a simulation to shifting and expanding analytical requirements and contexts.

To better meet the challenges of building a modular, flexible and adaptive model integration framework capable of simulating the dynamics of complex ecological systems, IDLAMS researchers turned to the Dynamic Information Architecture System (DIAS) (Christiansen 2000) to take advantage of a flexible and dynamic object-oriented (OO) approach. This new framework, built within DIAS, is the object-oriented (OO)-IDLAMS; it enables environmental managers and decision makers to use a strategic, adaptive approach to integrated ecological modeling, environmental management, and integrated natural resources planning. Other researchers have tried alternative integration approaches to modeling and simulation that can assess several components of an ecological system simultaneously (Maxwell and Costanza 1995; Bennett et al. 1996). These research efforts have also resulted in more modular and flexible approaches to model integration.

Approach

GIS-based model integration approach (IDLAMS)

IDLAMS is a prototype computer decision support system that integrates ecological models and decision analysis techniques and is based upon a GIS framework. IDLAMS predicts land conditions by simulating changes in military lands for given training intensities and land management practices. IDLAMS was developed as a multiagency partnership between the U.S. Department of Energy's (DOE's) Argonne National Laboratory (ANL) and the U.S. Army's Engineering Research and Development Center Construction Engineering Research Laboratories (ERDC-CERL).

The IDLAMS Prototype was developed by using Fort Riley's mission, and conservation goals, and objectives as a case study. Fort Riley lies on the western edge of the tall-grass prairie in the Flint Hills of eastern Kansas (Louis Berger & Associates, Inc. 1992). Land managers at Fort Riley have identified three major goals for managing the natural resources of training areas. The main goal is to enhance the training mission. A second goal is to maintain or enhance the condition of the vegetation; reducing soil erosion is part of this goal. Third, managers wish to maintain or enhance wildlife habitat, especially for currently and potentially threatened and endangered plant and animal species.

To accomplish the goals of the study, the IDLAMS team developed an approach that linked the required environmental and ecological models with a spatially derived GIS and goal-oriented optimization program entitled Scenario Evaluation Module. IDLAMS allows land managers to evaluate alternative land management strategies and to choose among them on the basis of values and objectives judged to be appropriate for their specific context. IDLAMS was designed to be easily operated by resource managers who are not specifically trained in environmental modeling.

Four major models were developed and integrated for the IDLAMS prototype (Figure 1): (1) a vegetation dynamics model, (2) a set of wildlife habitat suitability models, (3) an erosion model, and (4) a scenario evaluation module.

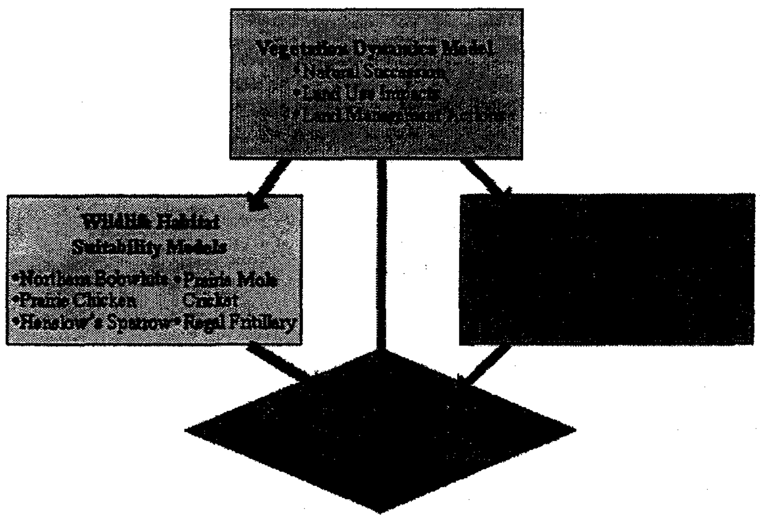

Figure 1 Fort Riley IDLAMS prototype system diagram.

Brief descriptions of these components and models follow.

Vegetation Dynamics Model

The Vegetation Dynamics Model is the core model for IDLAMS because the output from this model is the input for all other connected IDLAMS models (Figure 1). The Vegetation Dynamics model is a spatially explicit model that incorporates vegetation changes due to (1) natural succession, (2) land use impacts, and (3) land management actions.

Wildlife Models
These five submodels represent individual wildlife species and are based on U.S. Fish and Wildlife Service Habitat Suitability Indices (HSIs). Each submodel requires that

the user input either a vegetation/landcover map representing the current condition or a simulated landcover map generated by the Vegetation Dynamics Model. In some submodels, additional input maps may be required.

Erosion Model

IDLAMS currently integrates the Revised Universal Soil Loss Equation (RUSLE) to generate an erosion status map for each current condition or simulated vegetation/landcover map input by the user. RUSLE also requires other spatial data representing various factors affecting erosion.

Scenario Evaluation Module
IDLAMS uses a value-based decision-analysis process to link the ecological models with the management needs and user requirements of the resource manager. This module is then used to perform trade-off analyses for land management alternatives on the basis of the results from the spatially explicit modeling and to rank the alternatives according to how well they meet the specified objectives.

Object-oriented integration approach (OO-IDLAMS)

In 1998, SERDP sponsored an IDLAMS workshop to discuss lessons learned from the IDLAMS development and to identify future research priorities. Workshop participants represented the military user community, Army research laboratories, and other SERDP model developers. Some of the workshop's resultant goals for future research and enhancements to IDLAMS include the following:

1. More flexible and adaptive mechanisms for integrating disparate existing software applications;
2. Improved ability to reflect the dynamics of living ecosystems, land uses, and land management practices;
3. Capability to support software applications that can operate at multiple spatial and temporal scales; and
4. Reduction in the long-term cost of modeling technology by the use and reuse of existing data, models, and system components.

To accomplish these goals, a new SERDP-funded effort was undertaken by ANL and ERDC-CERL to evaluate a prototype of an object-oriented architecture approach to integration. This prototype is OO-IDLAMS. The flexibility, dynamics, and interoperability gained through an object-oriented approach have the potential to provide key technology solutions for addressing many of the military's goals and needs for integrated natural resource planning and ecosystem management.

OO-IDLAMS is built upon an object-oriented architecture called the DIAS. DIAS supports distributed, dynamic representation of interlinked environmental processes and behaviors at variable scales (spatial and temporal) of resolution and aggregation. A detailed discussion on DIAS can be found in Christiansen (2000).

For integrated environmental modeling, the main components of a DIAS simulation are (1) software objects (entity objects) that represent real-world entities such as atmosphere, fish, or groundwater; and (2) simulation models or other applications that express the dynamic behaviors of the real-world entities (e.g. surface exchange, reproductive cycles, and fate and transport). 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.

In 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.

Because the objective of the OO-IDLAMS prototype research was to demonstrate the advantages of this new object-oriented architecture approach rather than to totally rebuild the old IDLAMS, the OO-IDLAMS prototype integrates only a subset of the original IDLAMS. Figure 2 illustrates OO-IDLAMS prototype architecture. Models in the new OO-IDLAMS include the Vegetation Dynamics Model and the Henslow's Sparrow Habitat Model (an Environmental Systems Research Institute (ESRI®) application).

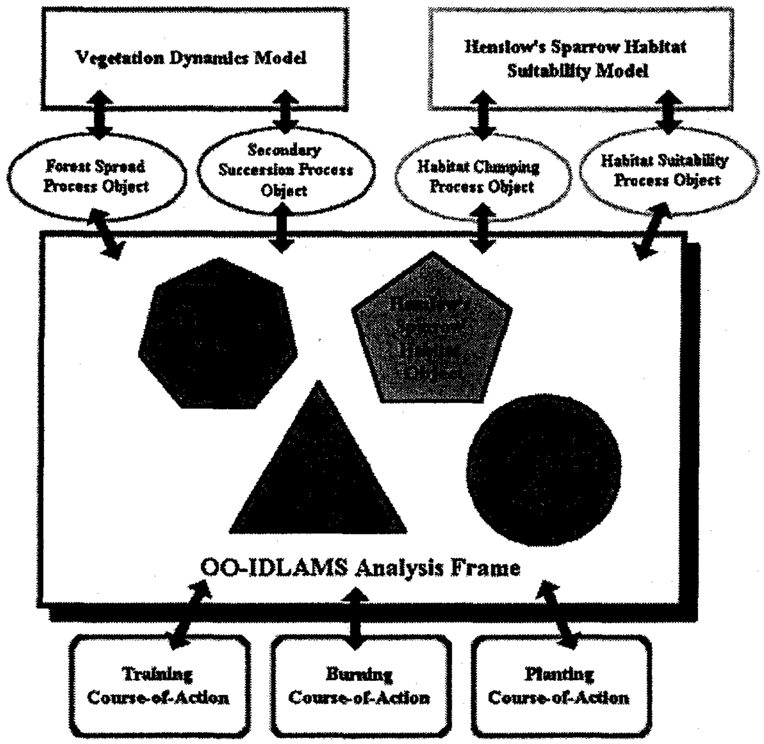

Figure 2 OO-IDLAMS prototype architecture diagram.

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.

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 Course of Action (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 (Dolph et al. 2000). COAs are used to represent specific behaviors of entity objects. The three COAs used in OO-IDLAMS (Training, Burning, and Planting) are relatively simple and represent the Fort Riley land use and land management plans (Figure 2). These plans are inherently procedural in nature and readily lend themselves to COA implementation.

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 3 are Landcover, Land Use Distribution, Planted Areas, and Henslow's Sparrow Habitat.

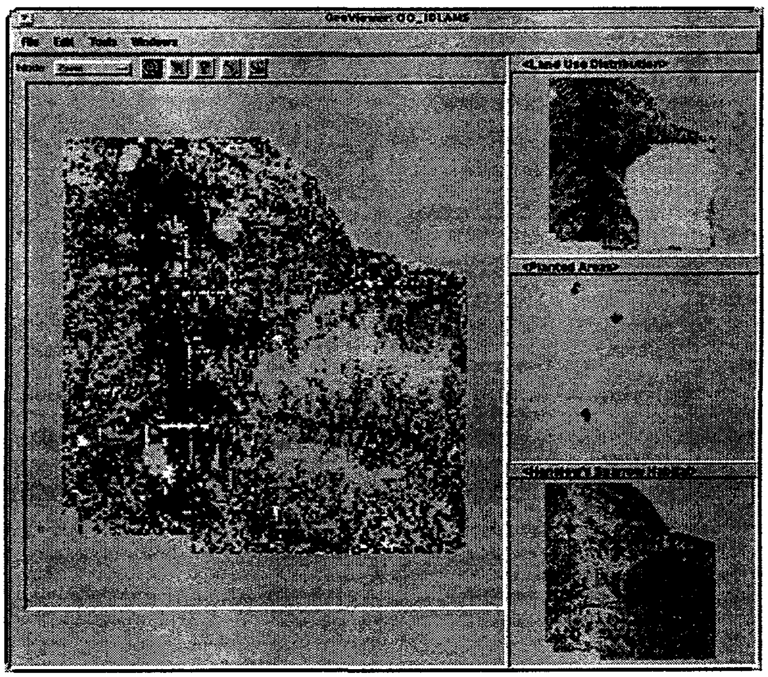

Figure 3 OO-IDLAMS GIS module provides real-time spatially oriented displays.

Discussion

OO-IDLAMS demonstrates the flexibility and dynamics of the DIAS architecture. 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 external 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. This feature illustrates an 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 by adding new models to the simulation suite are 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.

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 invoked by the Land Use Plan Object (Figure 4). 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 the current state of its *patches and additional hectares needed* attribute. 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.

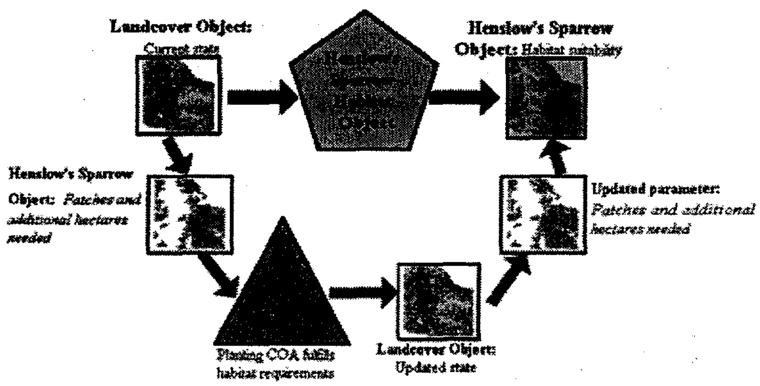

Figure 4 Illustration of run-time feedback between the Henslow's Sparrow Habitat Model and the Planting COA invoked by the Land Use Plan Object.

Conclusions

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. The DIAS architecture offers enhanced capabilities to:

1. Allow for the integration of existing diverse models without extensive reworking, thus capitalizing on previous investments in currently available models and applications;
2. 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 reduce the long-term cost of redeveloping objects and technologies;
3. Provide an integrated architecture that reflects the dynamics of living ecosystems, land uses, and land management practices;
4. Support software applications that can operate at multiple spatial and temporal scales; and
5. 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 manner.

The OO-IDLAMS Prototype represents a next generation technology as a more flexible, modular approach to the integration of models within a dynamic simulation for ecosystem modeling. The flexibility, dynamics, and interoperability demonstrated through this case study of an object-oriented approach have the potential to provide key technology solutions for many of the military's multiple-use goals and needs for integrated natural resource planning and ecosystem management.

Future Research Needs

Although DIAS provides an excellent framework for the integration of multiple models (even models at different spatial and temporal scales), it does not solve the more basic ecological and environmental research issues related to model integration. These issues include, but are not limited to (1) the ecological implications of multiple-scale modeling and simulation and (2) the impacts of data aggregation and disaggregations. However, DIAS can be used as a workbench from which to explore and investigate these issues. In addition, further development of the DIAS architecture should include the application of uncertainty analysis functionality to models within the DIAS suite and a multidisciplinary/multiagency approach to object design and development.

Acknowledgements

The original IDLAMS research was partially funded by Fort Riley, Kansas. The continued efforts on the IDLAMS application and the development of the OO-IDLAMS application were funded by the SERDP. Work supported under a military interdepartmental purchase request from the U.S. Department of Defense, U.S. Army, through U.S. Department of Energy contract W-31-109-Eng-38.

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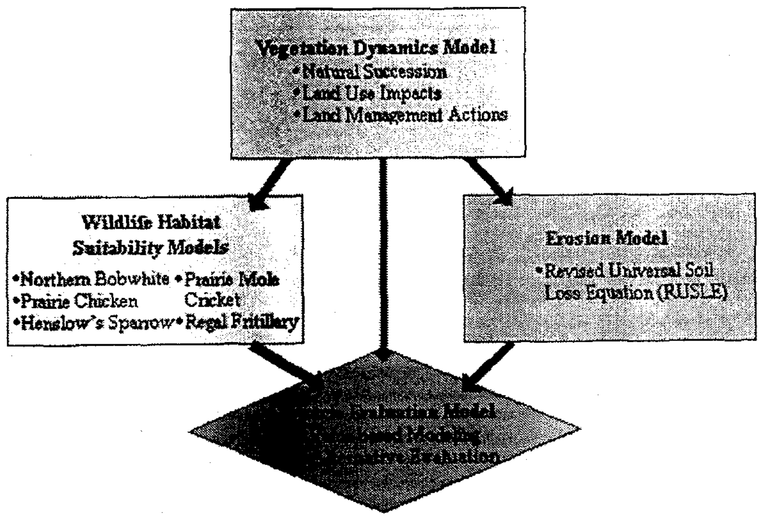
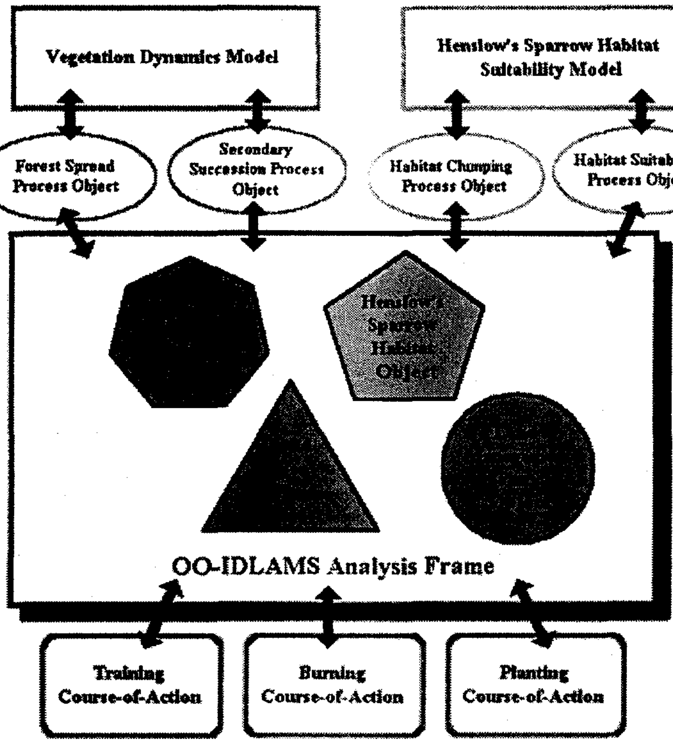
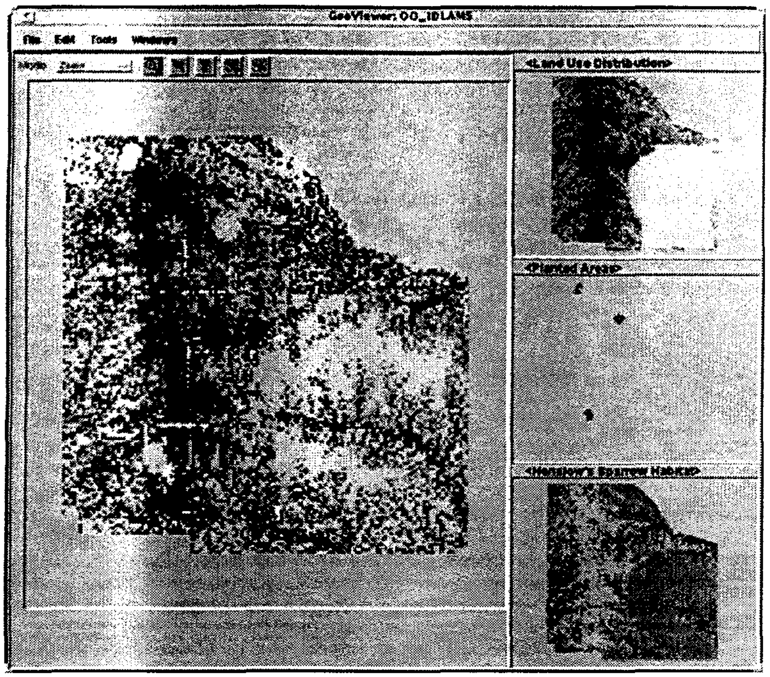

Vegetation Dynamics Model
•Natural Succession
•Land Use Impacts
•Land Management Actions
Wildlife Habitat
Suitability Models
•Northern Bobwhite
•Prairie Chicken
•Henslow's Sparrow
•Prairie Mole Cricket
•Regal Fritillary
Erosion Model
•Revised Universal Soil Loss Equation (RUSLE)


Vegetation Dynamics Model
Henslow's Sparrow Habitat Suitability Model
Forest Spread Process Object
Secondary Succession Process Object
Habitat Clumping Process Object
Habitat Suitability Process Object
Henslow's Sparrow Habitat Object
OO-IDLAMS Analysis Frame
Training Course-of-Action
Burning Course-of-Action
Planting Course-of-Action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File Edit Tools Windows
<Land Use Distribution>
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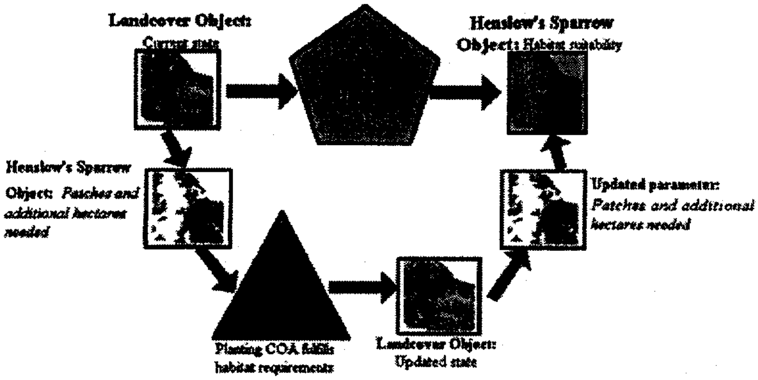
<Henslow's Sparrow Habitat>


Landcover Object:
Current state
Henslow's Sparrow
Object:
Henslow's Sparrow
Object: *Patches and additional hectares needed*
Updated parameter:
Patches and additional hectares needed
Planting COA fulfills habitat requirements
Landcover Object:
Updated state