The Land-Use Change Analysis System (LUCAS) for Evaluating Landscape Management Decisions*

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Abstract

Ecological dynamics in human-influenced landscapes are strongly affected by socioeconomic factors that influence land-use decision making. Incorporating these factors into a spatially-explicit landscape-change model requires integrating multidisciplinary data. In order to study the effects of land use on landscape structure in regions such as the Little Tennessee River basin in western North Carolina and the Olympic Peninsula of Washington state, we have developed the **L**and-**U**se **C**hange **A**nalysis **S**ystem or **LUCAS** for UNIX-based workstations. The map layers used by LUCAS are derived from remotely-sensed images, census and ownership maps, topographical maps, and outputs from econometric models. These map layers are stored, displayed, and analyzed using a public-domain Geographic Information System (GIS). Simulations using LUCAS generate new maps of land cover representing the amount of land-cover change so that issues such as biodiversity conservation, assessing the importance of landscape elements to meet conservation goals, and long-term landscape integrity can be addressed.

1 Introduction

Landscape pattern is a product of the interaction between ecological and socioeconomic processes. Understanding the function and structure of landscapes, primarily in terms of human impacts, requires integration of biological and socioeconomic knowledge. Natural resource managers, in particular, need this integration to effectively evaluate the social and environmental consequences of alternative management scenarios. The Man and the Biosphere (MAB) project where land use and its impacts are compared between the Olympic Peninsula and the Southeastern Appalachian Biosphere reserves [8], is a program

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whose mission is to address these issues.

This project integrates knowledge spanning many disciplines in order to evaluate land use and its impacts. Integration requires not only interpretation across disciplines, but also compatibility in the different forms of data acquired. Such forms include spatial and tabular databases, results of mathematical models, spatial analyses, and expert opinions. Unfortunately, conventional approaches of integrating and applying knowledge are not adequate to examine the complex and highly-variable ecological and socioeconomic issues that influence human land-use decision making and the impacts these have on landscapes [2].

Technologies are now available to facilitate the development of a multidisciplinary model for studying sustainability. Geographic information systems such as the Geographic Resources Analysis Support System[1] (GRASS) developed by the U.S. Army Construction Engineering Research Laboratories [12] can easily be used to represent and manipulate spatial data on workstations. In addition, adaptive management approaches provide a conceptual framework from which to evaluate alternative scenarios [7]. The Land-Use Change Analysis System (LUCAS) is a prototype computer application specifically designed to integrate ecological and socioeconomic information using GRASS for adaptive approaches to landscape management.

The motivating integration model for LUCAS is discussed in Section 1.1 followed by a brief discussion of the goals and objectives of LUCAS in Section 1.2. Section 2 details the socioeconomic model used in the current LUCAS prototype, and Section 3 reveals how C++ programming constructs are used to implement these models in LUCAS. The graphical user interface (GUI) which handles interactions between the LUCAS modules and the user, communications between system modules, and display of model outputs is discussed in Section 4. In Section 5, LUCAS is used to simulate selected scenarios of land-use management policies in the Little Tennessee River Basin (western NC) and the Hoh Watershed (Olympic Peninsula) in order to estimate projected changes in the landscape and associated impacts on selected species for 100 years (starting from year 1991). The

[1]Version 4.1 of GRASS was used for this project.

current state of LUCAS software development and availability are provided in Section 6.

1.1 Background on MAB Integrated Model

The Model discussed in [8] examines the impact of human activities on environmental and natural resource sustainability. The premise of the model is that landscape properties such as fragmentation, connectivity, spatial dynamics, and the degree of dominance of habitat types, are influenced by market processes, human institutions, landowner knowledge, and ecological processes. Therefore, modeling environmental sustainability of human-dominated landscapes will benefit from the integration of human and ecological processes.

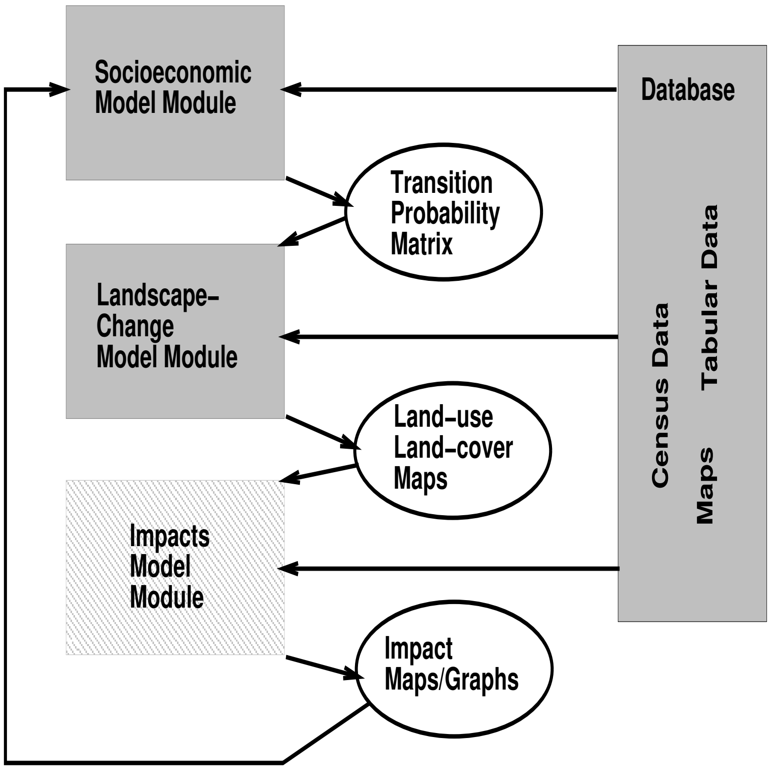


Fig. 1. *LUCAS modules of the Olympic Peninsula/Southeastern Appalachian Biosphere Integration Model.*

The structure adopted for LUCAS consists of three subject modules linked by a common database (see Figure 1). The first LUCAS module contains the socioeconomic models that are used to derive transition probabilities associated with changes in land cover. These probabilities are computed as a function of socioeconomic driving variables including, (1) transportation networks (access and transportation costs), (2) slope and elevation (indicators of land-use potential), (3) ownership (land holder characteristics), (4) land cover (vegetation), and (5) population density. Preliminary analysis of the Little Tennessee River Basin [5] revealed that land-cover change is most likely to occur on private land, near a paved road, on flat low elevation land, and close to the major urban center of the watershed (Franklin, NC). As demonstrated in [15], most of the transitions in land cover are forest coverting to grassy/brushy and unvegetated cover types. The construction of transition probability matrices that describe such changes in land cover are discussed in Section 2.

The landscape-change model resides in the second LUCAS module (see Figure 1). This module receives as its input the transition matrix produced in the socioeconomic models (Module 1), and accesses the same spatial database of driving variables. A single iteration of the landscape-change model produces a map of land cover that reflects socioeconomic motivations behind human land-use decision making (represented in the transition probability matrix).

The impact models defined in the third module of LUCAS (see Figure 1) utilize the land-cover maps produced by the landscape-change module to estimate impacts to selected environmental and resource-supply variables. These environmental variables include the amount and spatial arrangement of habitat for selected species and changes in water quality caused by human land use. Potential resource-supply variables include timber yields and real estate values. For simulations of land-cover change in the Little Tennessee River Basin, for example, output maps of the persistence of the animal and plant species in Table 1 can be generated by LUCAS.

1.2 Goals and Objectives

LUCAS is a computer-based application specifically designed to integrate current and forthcoming information for (1) providing a multidisciplinary modeling environment for addressing research questions concerning land use and its impacts, (2) applying adaptive management approaches in order to address management questions concerning landscape-impact assessment, and (3) designing a tool for workstations supporting the Unix[2] operating

[2]Unix is a trademark of AT&T Bell Laboratories.

Watershed	**Species**
Little Tennessee River Basin	Catawba Rhododendron Cranefly Orchid European Starling Mountain Dusky Salamander Northern Flying Squirrel Princess Tree Southeastern Shrew Wood Thrush
Olympic Peninsula: Hoh and Dungeness Watersheds	Cascade Oregon Grape Heather Vole Honeysuckle Horsetail Licorice Fern Mountain Alder Mountain Huckleberry Red Squirrel Twinflower

TABLE 1
Species' habitat impacts modeled by LUCAS.

system, X-Windows[3], and Motif[4] user libraries.

The immediate objectives of LUCAS are to (1) integrate the various components of the Olympic Peninsula/Southeastern Appalachian Biosphere Reserve Land-Use Model discussed in Section 1.1, and (2) to develop a graphical user interface (GUI) capable of extracting different forms of land-use data for the adaptive management approach.

2 Socioeconomic and Landscape Change Modeling

The integration of socioeconomic and ecological variables discussed in Section 1.1 is accomplished spatially through the use of gridded maps. Individual maps may represent a single data theme which describes physical landscape attributes (e.g., land cover, slope, soil type), spatial features (e.g., distance relationships, adjacency rules), the results of socioeconomic and ecological processes (e.g., changes in real estate values, species abundance, and erosion), and land-ownership characteristics (e.g., tract size, shape, and history).

[3] X11 Release 5 environment.
[4] Motif version 1.2.1 libraries.

2.1 Landscape Condition Label

Pixels (or grid cells) in each map are assigned to one of the discrete categories used to describe that data theme. Categories for a vegetation data theme, for example, are listed in Table 2. After overlaying the maps to form a composite map, the categories from each data layer in the composite map are represented as a string of characters called a *landscape condition label* [4]. Each character of this label reflects a category from one of the original maps. For example, the composite map label 2413 might designate a grid cell belonging (moving from right to left) to the third vegetation-cover category, the first aspect category, the fourth land-ownership class, and second range of elevation.

1	grassy/brushy
2	unvegetated
3	coniferous forest
4	deciduous forest

Table 2
Sample category values for vegetation in LUCAS.

2.2 Transition Probabilities

As mentioned in Section 1.1, transition probabilities govern changes in land cover by reflecting the economic, sociological, and ecological influences on landscape structure and function. These probabilities are derived empirically through a time series analysis of changes in land cover, while considering road networks, population density, and physical attributes of the landscape. Using multinomial logit models [13], the transition probabilities reflecting changes in the land cover of the Little Tennessee River Basin of western North Carolina can be structured as a matrix with individual rows in the matrix representing probabilities of transition from one land-cover category to any possible category for a given landscape condition [16] . During a LUCAS simulation, the landscape condition labels in the composite map are matched with equivalent landscape condition values in the transition probability matrix (TPM). The appropriate set of transition probabilities are applied and the resulting landscape category is assigned to the appropriate pixels in order to generate a new output map of land cover.

i	$\vec{x}_i$	Attribute
1	2	Privately Owned
2	1	Forest Cover
3	512	Elevation (meters above sea level)
4	30	Slope (degrees)
5	15	Population Density (1,000's per acre)
6	120	Distance to Nearest Road (meters)
7	1300	Distance to Nearest Town (meters)

FIG. 2. *Sample landscape condition label for a forested grid cell in the Little Tennessee River Basin.*

For example, the landscape condition label of a given forested (vegetation category 1) grid cell of the Little Tennessee River Basin which is privately-owned (ownership category 2), 512 meters above sea level (elevation), of 30 degree slope, 120 meters from the nearest road, 1,300 meters from the nearest town, and reflects a population density of 15,000/acre can be represented by the 7×1 attribute column vector $\vec{x}$ shown in Figure 2. The value of each $\vec{x}_i$ is used in a multinomial logit equation [13] (suitable for regression analyses of continuous and discrete independent variables) to generate the probability of transition to another vegetation cover class (unvegetated or grassy/brushy). Specifically, this probability is given by

$$Pr[i \rightarrow j] = \frac{\exp(\alpha_{i,j} + \vec{z}^T \vec{\beta}_{i,j})}{\sum_{k=1}^{n} \exp(\alpha_{i,j} + \vec{z}^T \vec{\beta}_{i,k})}, \tag{1}$$

where $\vec{z}$ is a 5×1 column vector composed of the last 5 elements (i.e., $\vec{x}_3, \ldots, \vec{x}_7$) of $\vec{x}$ from Figure 2, $\alpha_{i,j}$ is an estimated constant (intercept), n is the number of vegetation types (see Table 2), and $Pr[i \rightarrow j]$ is the probability of land cover at the privately-owned forested grid cell at time t having the same cover class $i = \vec{x}_2 = 1$ at time $t+1$ (i.e., $j = 1$) or changing to another cover class (i.e., $j = 2, 3$). Since each $\vec{\beta_{i,j}}$ (for $j = 1, 2, 3$) is a 5×1 column vector of estimated coefficients from [14], 3 probabilities of transition can be calculated using Equation (1) for $j = 1, 2, 3$. A random number is then chosen from a uniform distribution between 0 and 1. If the random number falls within an interval associated with a transition probability to a different land cover, the grid cell is changed; otherwise, the grid cell remains in its present land cover. For the grid cell whose landscape condition label is given by Figure 2, the probability of transition to grassy/brushy and unvegetated land covers is easily computed using the logit coefficients (β_j's) provided in Table 3. For this grid cell, the probability of transition to unvegetated land cover is $Pr[1 \to 2] = 0.99$ (i.e., very likely), and the probability of transition to grassy/brushy land cover is $Pr[1 \to 3] = 1.11 \times 10^{-16}$ (i.e., not very likely). These probabilities constitute 2 of the 3 elements of a single row of the 3×3 TPM for transitions from privately-owned forest in the Little Tennessee River Basin.

In general, the various sets of logit coefficients for transitions from each vegetation cover (j) with different ownership classes are estimated separately by maximizing their respective likelihood functions using a nonlinear optimization method [14] to match observed (historical) land cover changes. The *null transition* or probability of no land cover change ($Pr[1 \to 1]$ from above example) is simply determined by

$$Pr[j \to j] = 1 - \left(\sum_{k \neq j} Pr[j \to k] \right).$$

Current Forest Cover	Transition To	
Attribute	Grassy	Unvegetated
intercept (α)	-0.6193	40.785
elevation (β_1)	-0.00104	-0.0682
slope (β_2)	-0.0561	-0.0855
population (β_3)	0.00078	-0.0108
distance-roads (β_4)	-0.1038	0.25446
distance-town (β_5)	0.000632	-0.0176

TABLE 3

Logit coefficients for transitions from privately-owned forest in the Little Tennessee River Basin based on 1986–1991 historical land-cover transitions.

Within the LUCAS Socioeconomic Model module (see Figure 1), this process is then repeated for each grid cell (having public or private ownership) in order to produce a new map of land cover. The spatial pattern of land cover and any associated impacts (see Section 1.1) is analyzed at the end of each time step, and the simulation is continued for a specified duration of time.

2.3 Map Manipulation via GRASS

GRASS[5] was chosen to be the GIS because it is a public–domain package that is available on many workstation environments. The user may already have map layers in the GRASS format or can readily convert maps from other popular packages such as ARC/INFO[6] to a GRASS format. Since the output maps of LUCAS are also in a GRASS format, the user can take advantage of the rich utilities that GRASS has to offer for further analysis. GRASS also was easy to integrate into LUCAS because it offers a series of map manipulation libraries with all of their source code and a well–defined programming interface [12]. The use of GRASS as the source and sink of map manipulation in LUCAS is illustrated in Figure 3.

GRASS is not a perfect tool, however. As a non-commercial package, many bugs persist in the code. For example, the GRASS X-windows monitor often functions properly under SunOS 4.1.3, but not under Solaris 2.4. Some of the features of GRASS are not well documented, which made the availability of the source code invaluable. The environment works well for someone with knowledge of UNIX and programming, but would be rather challenging for an ecologist without such skills. In spite of its many foibles, GRASS is a useful environment in which to work and program.

3 Software Design

Creating an analytical tool which is both efficient and flexible can be a difficult task. Many decisions must be made along the way to satisfy the end user as well as the developer. Although the user is very concerned about the system interface and form of the output, the internal program structure is of little interest. The developer, on the other hand, must produce an efficient software package that is easily modified to adjust to the needs of diverse users. Some of the important considerations that went into the initial design of LUCAS are discussed in the following sections.

[5] GRASS version 4.1 update release 4.

[6] ARC/INFO is a registered trademark of ESRI, Environmental Systems Research Institute, Inc. 380 New York Street, Redlands, CA 92373.

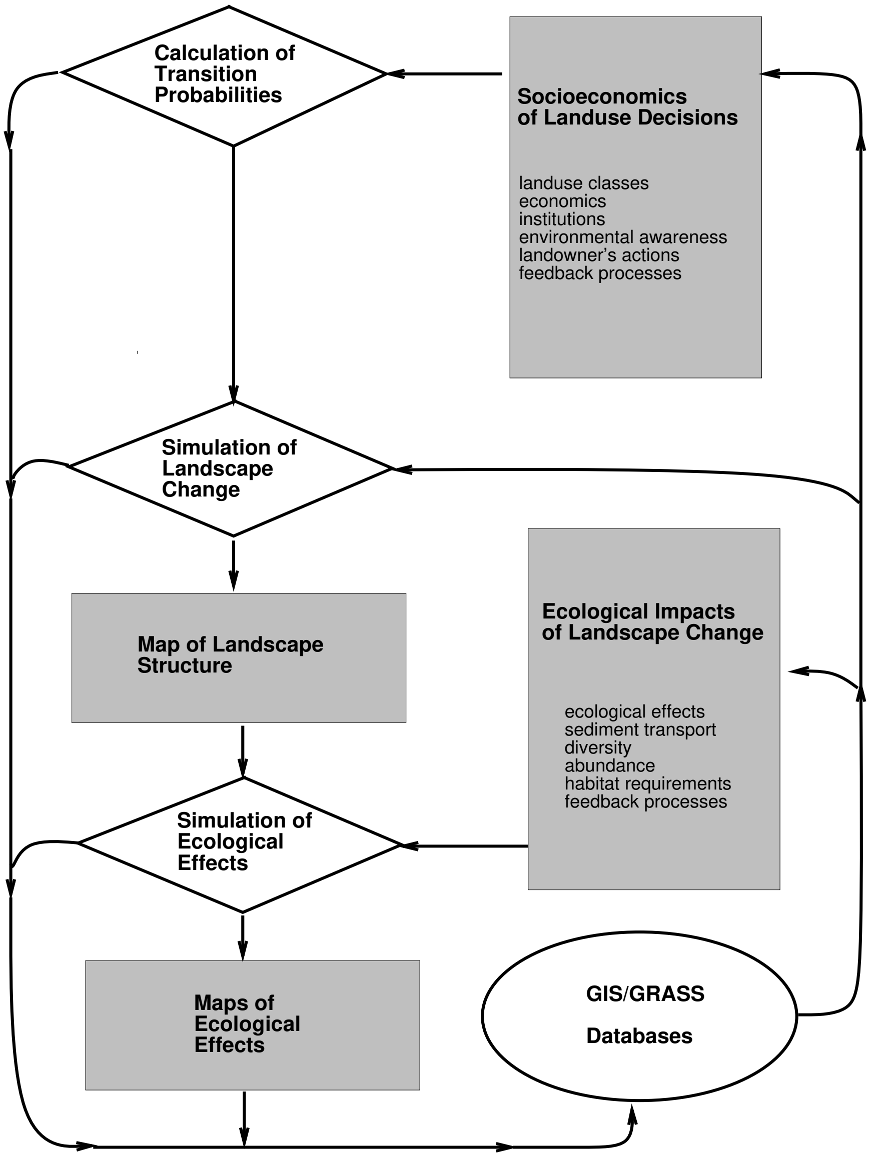


Fig. 3. *Use of GRASS (GIS) as the source and sink of map manipulations in LUCAS.*

3.1 Modularity and Implementation

The major modules of the LUCAS model are diagrammed in Figure 1. The Socioeconomic Model Module is handled by economists who use information in the common database to generate the mulitnomial logit coefficients necessary to calculate the transition probability matrix (TPM) entries. The other two modules, the Landscape Change Model and Impacts Model Modules, comprise the LUCAS program. LUCAS was designed to be a modular system, with the potential for additional ecological impact or socioeconomic modules to be added later. This need for modularity lead to the choice of C++ as the programming language. C++ is well suited to modularity because of its "object-oriented" view of data and methods.

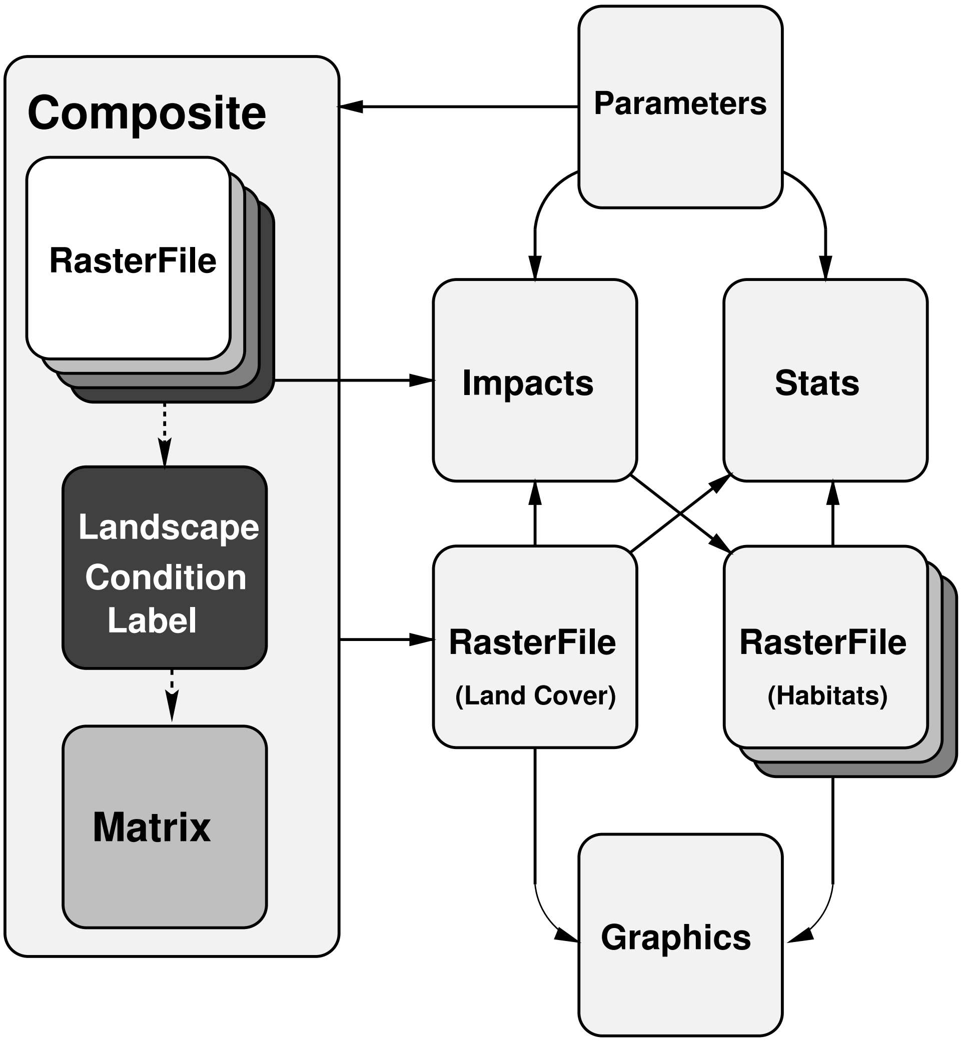


FIG. 4. *C++ Classes used in implementing LUCAS.*

The primary concern when designing these objects was flexibility and the ability to adapt existing code to different or additional land use analysis. As with any program, flexibility can adversely affect performance, so occasionally some flexibility had to be compromised.

Figure 4 shows the relationship among the C++ class objects used in the implementation of LUCAS. The **Composite**, **Matrix**, and **Stats** classes are the primary units in the Landscape Change Model Module. A user selects a particular scenario to be run via the GUI discussed in Section 4. This scenario corresponds to a file which specifies the logit coefficients and necessary map layers for the simulation. This scenario information is managed by the **Parameters** object which notifies other objects of the specifics of the current scenario.

The **Composite** class takes many **RasterFile** objects, input map layers corresponding to attributes in the landscape condition label (LCL), and creates a "composite" map. This virtual map is then traversed via **LandscapeConditionLabel** objects which create a LCL vector out of the various map layers. The **Matrix** class, also contained in the **Composite** class, manages the TPM and random number generator. Landscape change is accomplished by passing a **LandscapeConditionLabel** object to the Matrix object which calculates the transition probabilities for this particular LCL. A pseudorandom number is generated and the new land cover type for this grid cell is determined. A map of all of these grid cells comprises a new land cover output **RasterFile** object. This map is passed to the **Stats** object which calculates the statistics discussed in Section 3.3.

The Impacts Model Module is embodied by the **Impacts** class object. The new land cover **RasterFile** object, along with the other original map layer **RasterFile** objects, are used to produce new map layer objects corresponding to the impacts being analyzed. Currently only the habitat suitability of an area for certain species in Table 1 is studied.

The resulting land cover and habitat maps can be viewed via the GRASS monitor which is driven by the **Graphics** object.

3.2 Additional Design Considerations

In addition to modularity, memory and storage constraints were also of concern when designing LUCAS. The single largest performance bottleneck in LUCAS is disk I/O. Reading and writing each row of each map layer requires disk accesses, therefore as few accesses as possible were used. Internally GRASS uses run–length encoding (RLE) [10] to compress the raster maps, which takes advantage of repetitions of the same cover type in a map layer, which further saves on disk I/O. The routine which demands the most memory is the statistical patch identification algorithm which requires an entire map layer to be in memory. A patch is a group of contiguous grid cells with identical LCLs.

These potentially large maps made loading the entire composite map into memory unfeasible and necessitated a row–oriented approach to analyzing and manipulating the maps. Fortunately the underlying GRASS routines already dealt with maps in a row–oriented fashion, so working with the "composite" map and the resulting GRASS land-cover map was simplified.

Another issue was portability, as a parallel version of LUCAS running in a heterogeneous environment was planned (see Section 6). Fortunately, the strong type checking of C++ lends itself to more standard, portable code.

3.3 LUCAS Statistical Output

The output statistics generated by LUCAS are available in two formats: (1) a machine readable SAS statistical format file [11], and (2) a series of graphs[7] for various statistics collected each iteration that the user can select from the GUI. The SAS file, using whitespace delimited ASCII text, allows the user to import the results into a statistics program, graphics package, or spreadsheet, and perform additional analyses external to LUCAS. The graphs provide a visual representation of the changes in certain variables as the landscape changes. Statistics calculated by LUCAS for each land-cover type include:

• Area	• Proportion of land cover
• Amount of edge	• Amount of total edge
• Edge/Area ratio	• Standard deviation of patch size
• Mean patch size	• Size of largest patch
• Number of patches	• Mean patch shape (using a normalized shape index)
• A cumulative frequency distribution of patches by size	

Table 4
Statistics calculated for each landcover map.

4 Graphical User Interface

Early users of LUCAS are expected to be experts in landscape management. Explicit knowledge of the integration of socioeconomic and ecological variables (see Section 2) using the software design discussed in the previous section is not required by users such as ecologists, economists, sociologists, or forestry personnel. To accommodate the needs of

[7] These graphs of resulting statistics are displayed using the public–domain program `xgraph`.

such experts, a graphical user interface (GUI) was developed for LUCAS. A GUI is the best way to provide an intuitive interface for an application which integrates interdisciplinary data of different scales and type. One of the most challenging aspects of designing an intuitive interface for LUCAS was to first understand the needs of landscape management, and then to develop the interface with these requirements in mind.

4.1 LUCAS Computing Environment

A majority of the LUCAS modules were developed on UNIX-based workstations (e.g., Sun SPARCstation 10) running X Windows (X11 Release 5) with the OSF/Motif library toolkit (version 1.2.1). It is expected that most LUCAS end-users will have such a UNIX-based system available. OSF/Motif provides a standard for user interface behavior which allows users of other *Motif, Microsoft Windows*, and *Presentation Manager* applications to use Motif-compliant applications without the need to learn a new graphical user interface. The OSF/Motif run-time libraries are available on most platforms, including HP, DEC, IBM, SUN, and Silicon Graphics. This availability was an important factor in our selection of OSF/Motif for the LUCAS GUI development. In order to develop an application which is not only portable to various hardware platforms, but which also provides a familiar *look and feel* to windowing system users, the principles in the OSF/Motif Style Guide were applied to the LUCAS GUI where appropriate.

The OSF/Motif library is a toolkit which contains a pre-defined set of components called *widgets*. A widget consists of a complex data structure (an object) and a set of procedures (methods). Widgets are organized into classes which are groups of widgets with similar characteristics. Each widget class has a set of associated resources and actions. A resource is an attribute of a widget class such as foreground color, background color, or font. An action is triggered in response to the occurrence of certain types of events. Widget classes are organized into a hierarchy whereby a widget class inherits resources from its superclass. All resources are inherited by a subclass from its superclass so that the inheritance of resources extends all the way back to the root widget class in the inheritance hierarchy.

Since the Sun SPARCstation 10 does not come pre-configured with OSF/Motif, the IXI

Motif developers kit and run-time libraries were purchased and installed for LUCAS GUI development. The IXI Motif software provides a standard implementation of OSF/Motif for Sun workstations running the SunOS operating system.

4.2 User Interface Language (UIL)

In order to make the LUCAS interface more easily maintainable, the proprietary Motif User Interface Language (UIL) was used to define the widgets used in the interface. Originally, the interface was written solely in C [9] which became too cumbersome and complex to easily alter the look and feel of the interface. UIL is a high-level, almost script-like language which is rapidly compiled into a binary format. All of the widget callback and support routines must be written in C and linked to the UIL code. An additional `.uid` file must be present in the directory with the executable to use the UIL-compiled code. UIL does not allow as much flexibility as raw C code, but it also does not require as much programming to create and maintain a simple interface such as the one used in LUCAS.

4.3 Running a Simulation

To run a landscape change simulation on a watershed area, the user first chooses the dependent variable whose change is to be simulated in the modeling software. Although the LUCAS GUI has a choice of three dependent variables (land cover, land use, and ownership boundaries), the current software only works with a land-cover dependent variable. Any of the other two choices for dependent variable in the LUCAS GUI will result in a warning message being posted to the user.

The user then chooses the watershed, directory of maps (mapset), and beginning map year to run the landscape change simulation on. The landscape change scenario is chosen from a list of possible scenarios which comprise pre-defined rules for generating transition probabilities reflective of certain changes in land use. Since the landscape change can be based on either a pixel or a patch based model, the user must specify whether change is determined by individual pixels or clusters of pixels having the same landscape condition label.

The number of replicates, number of timesteps, and number of maps to save are chosen

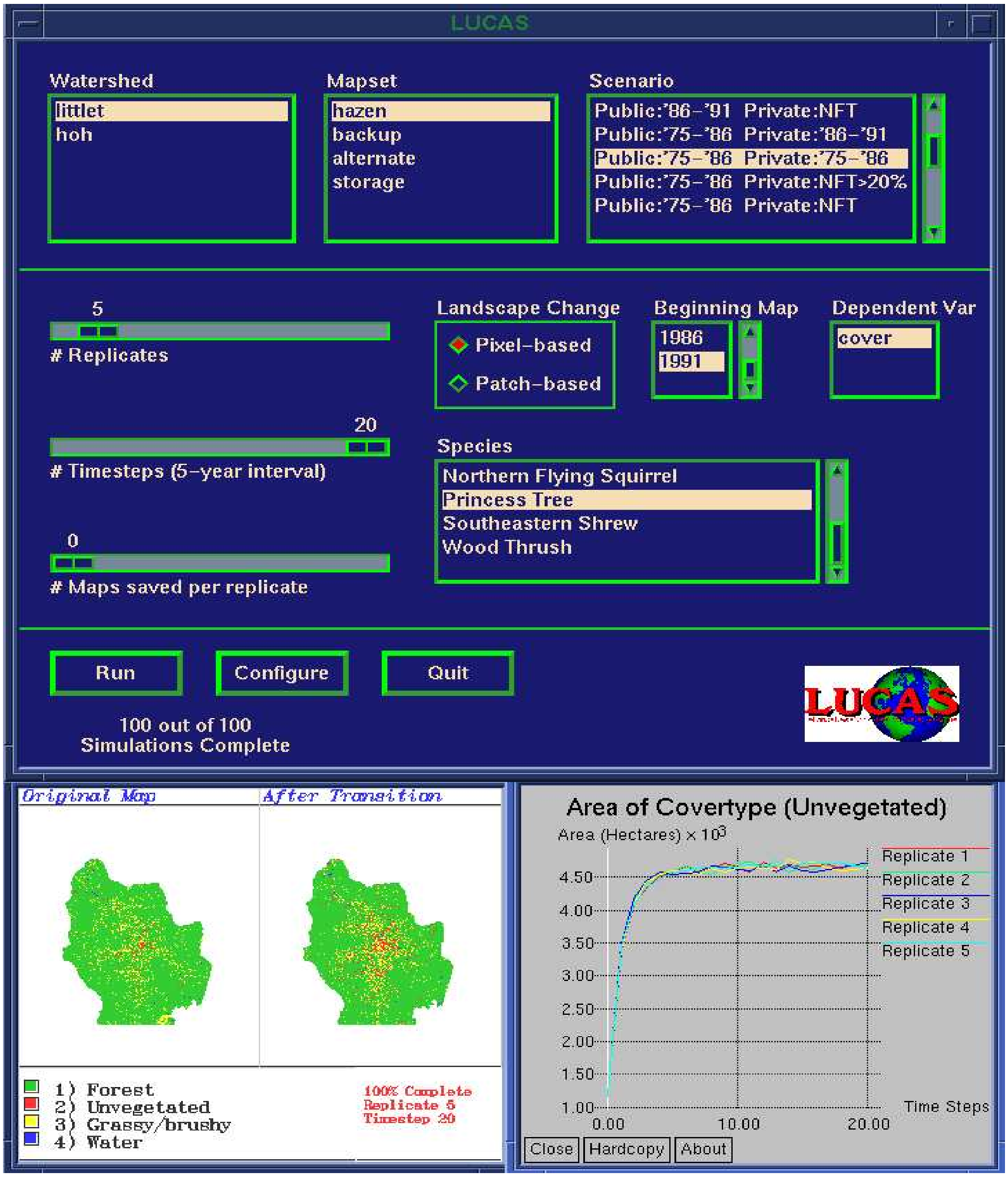


FIG. 5. *LUCAS graphical user interface with sample beginning and ending land-cover maps for a simulation run along with graph of output summary statistics.*

from a group of slide bars on the lefthand side of the LUCAS GUI (see Figure 5). The number of replicates multiplied by the number of timesteps gives the total number of maps that will be generated. If the user does not indicate that generated maps should be saved, then no maps from the intermediate timesteps will be saved.

As noted in Section 1.1, the user can select one or more species impact modules interfaced with LUCAS. The landscape map at each timestep is evaluated for the amount of suitable habitat for the particular species that the user is interested in.

To initiate all LUCAS simulations, the user presses the Run button located at the bottom of the LUCAS GUI. At this point, the landscape change modeling program is invoked and the user interface is inactive. When the simulations are complete, a menu is realized which allows the user to display graphs of statistics generated during the landscape change simulations. A sample display of the current LUCAS graphical user interface along with output maps and graphs of summary statistics is shown in Figure 5.

5 Sample Scenarios

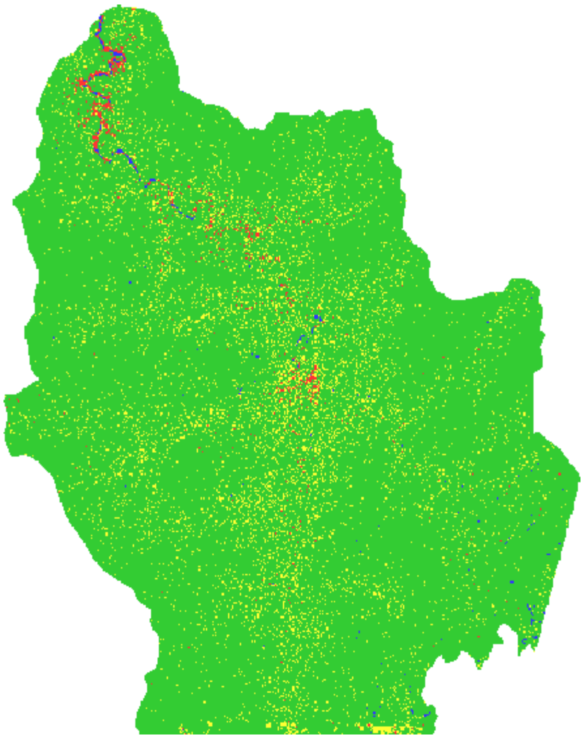
In this section, we demonstrate the use of LUCAS to simulate land-cover change and its impact on the habitat of species in the Little Tennessee River basin and the Hoh Watershed of the Olympic Peninsula.

5.1 Little Tennessee River Basin

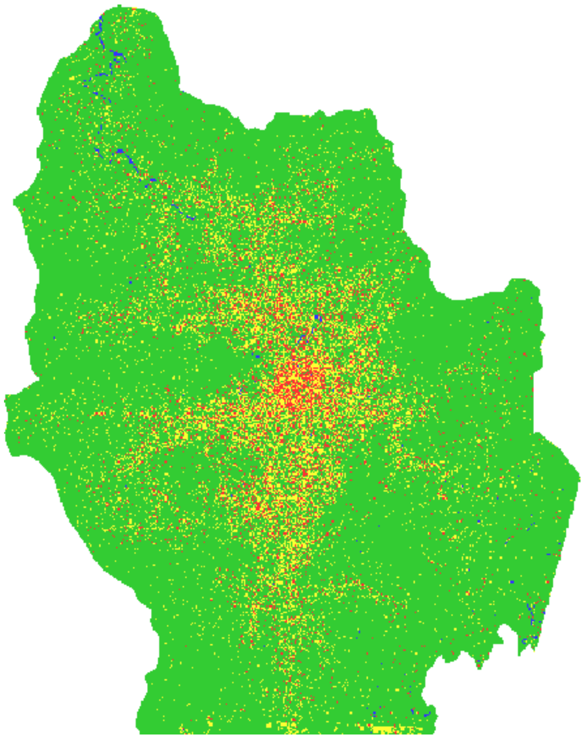
LUCAS has recently been used [14] to assess the influence of land ownership on land-cover change in the Little Tennessee River Basin of western North Carolina. Transition probabilities for 100 year simulations of land-cover change have been generated [16] using historical data from two periods: 1975–1986, and 1986–1991. As discussed in Section 2, these probabilities can reflect transitions between discrete land-cover types with respect to certain socioeconomic and ecological variables. In this particular simulation, the land-cover types are

- forest,
- unvegetated, and
- grassy/brushy.

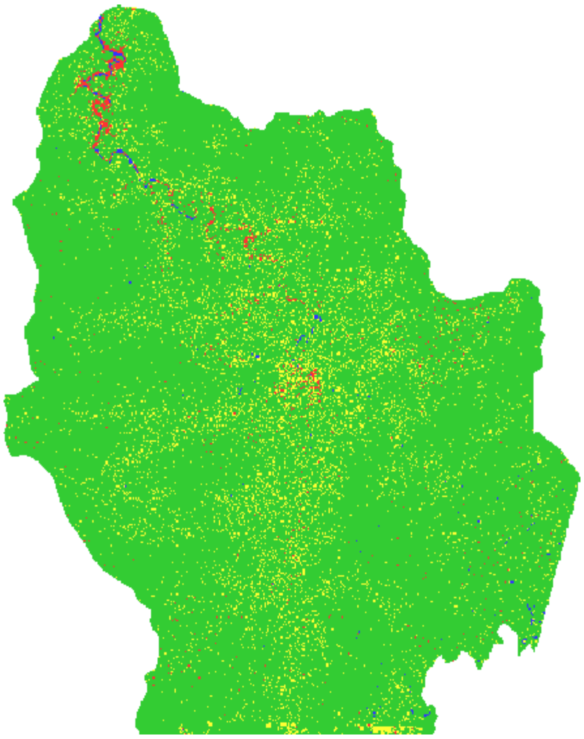
while the physical landscape attributes (independent variables) are



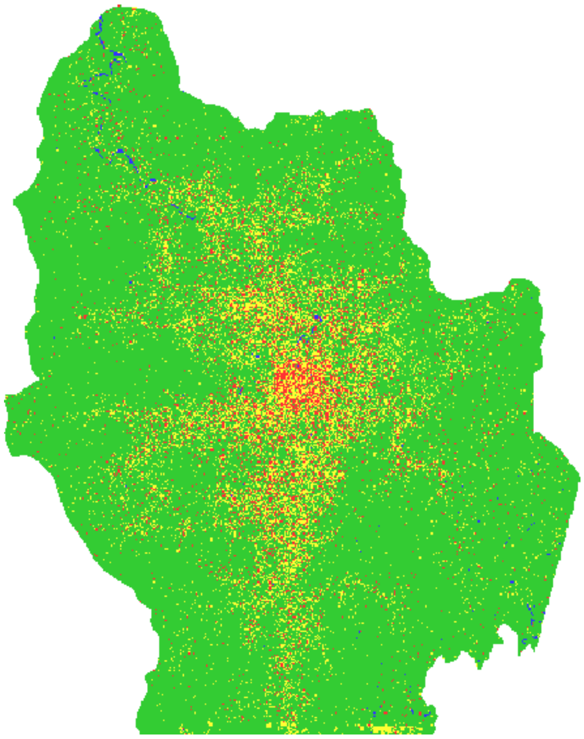
(a) Scenario 1: Public and Private HTP 1986–1991



(b) Scenario 2: Public HTP 1975–1986, Private HTP 1986–1991



(c) Scenario 3: Public HTP 1986–1991, Private HTP 1975–1986



(d) Scenario 4: Public and Private HTP 1975–1986

Fig. 6. *LUCAS output maps of Little Tennessee River Basin.*

- elevation,
- slope,
- population density,
- distance to roads, and
- distance to town (Franklin, NC).

Transition probability matrices (TPM's) are then generated for each time period and initial land-cover for both public and private land ownership. Hence, $12 = 3\times2\times2$ TPM's are generated by the Socioeconomic Model Module (see Figure 1) in LUCAS. Figures 6(a) through 6(d) show the LUCAS output maps (only one of five replicates shown) from 100-year simulations (beginning with the year 1991) of land-cover change for the Little Tennessee River Basin. In these figures, green denotes forest land, yellow denotes grassy/brushy cover, red denotes unvegetated area, and blue denotes water. Scenarios of land-cover change based on Historical Transition Probabilities (HTP's) [16] for public and private lands are listed in Table 5.

	Ownership Type	
	Public	Private
Scenario 1	1986–1991	1986–1991
Scenario 2	1986–1991	1975–1986
Scenario 3	1975–1986	1986–1991
Scenario 4	1975–1986	1975–1986

TABLE 5

Scenarios of land-cover change for Little Tennessee River Basin according to historical transition probabilities.

As discussed in [14], the importance of shifts in land-cover-change dynamics is illustrated by the differences between Figures 6(a) and 6(d). The greatest change in the landscape was observed when the empirically observed 1975-1986 transition probabilities, which were greater than the 1986-1991 transition probabilities, were applied across lands under both ownership types (Scenario 4, Figure 6(d)). Forest cover exhibited the greatest decline and fragmentation when transition probabilities for the period 1975-1986 are applied to both public and private lands. The least change in the landscape is observed when the 1986-1991 rates of transition were applied across lands under both ownership types (Scenario 1, Figure 6(a)). In this scenario, landscape patterns remained relatively stable through time, as indicated by the proportion of forest (see Table 7 in the Appendix for agreements in proportion of land cover between simulated and actual landscapes).

5.2 Impacts and Multiple Domains

LUCAS can also be used to assess the impact of land cover change on certain ecological variables as outlined in Section1.1. Currently only the impact on species' habitat is modeled. Figure 7 shows the GRASS monitor which appears before and after a simulation of Scenario 4 from Table 5, displaying both the changes in land cover and in the habitat region for the *European Starling.*

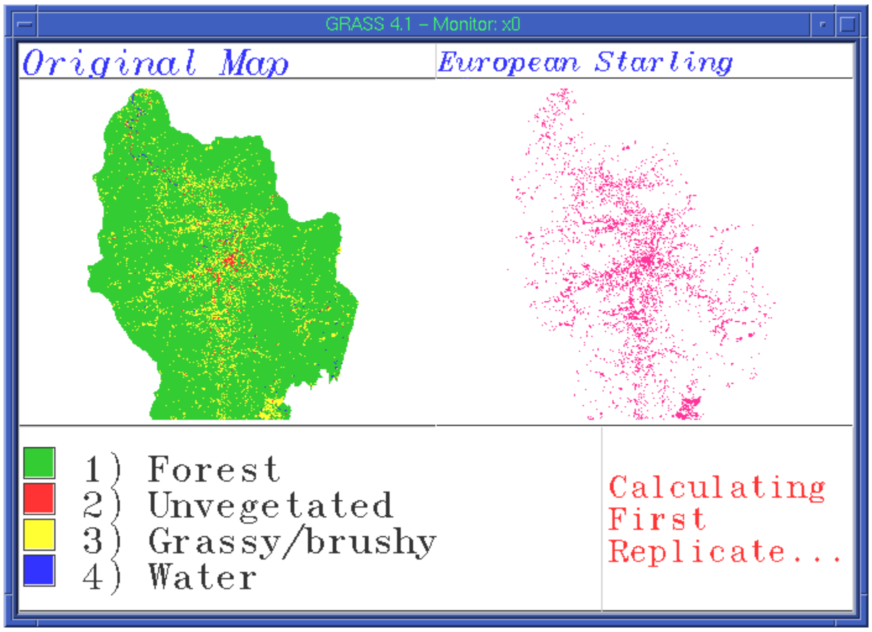
Although most of the scenarios mentioned earlier are for the Little Tennessee River Basin, other domains are also supported. Figure 8 shows the same scenario run on the Hoh Watershed on the Olympic Peninsula with impacts on the habitat of the *Red Squirrel.* Notice that different impacts are available in different watersheds (Table 1).

6 Summary and Future Work

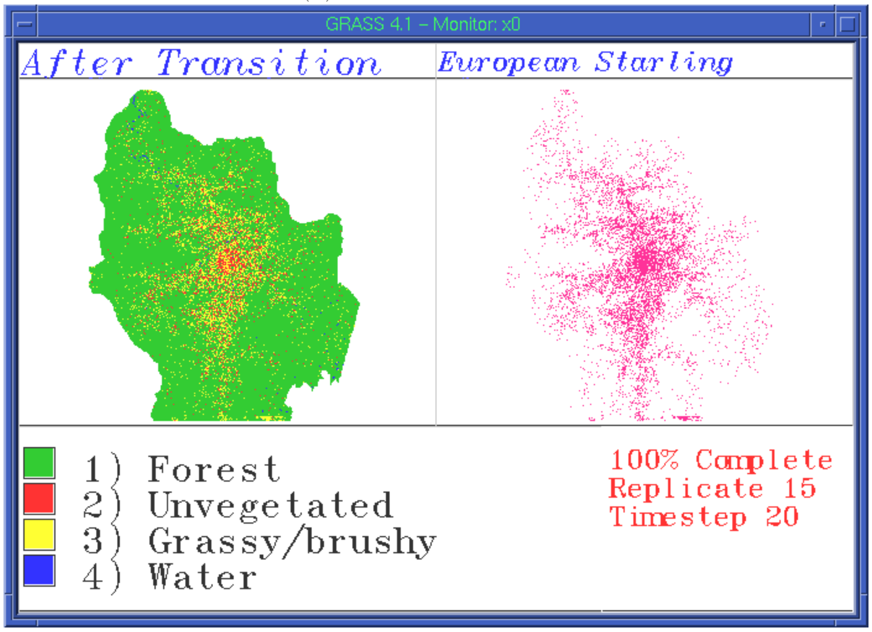
In the Southeastern Appalachians and Olympic Peninsula, efforts are being directed toward managing the landscape. Such efforts clearly benefit from advances in remote sensing technology and GIS. While improvements in remotely-sensed data have increased our ability to interpret changes in land cover, geographic information systems such as GRASS have simplified the integration of spatial information across disciplines. LUCAS can bring these recent developments into practice by providing a flexible and interactive computing environment for landscape management studies. Future LUCAS-based impact studies for the Little Tennessee River basin and Olympic Peninsula, for example, will address changes in timber output, water quality, and erosion.

Because each sample scenario from Section 5 required slightly more than three quarters of an hour of elapsed wall-clock time for 15 replicates (see Table 6) on a 70 MHz SPARCstation 5 Model 70 with 32 Mb of memory, another version of LUCAS has been implemented using PVM [3] on a heterogeneous network of high-performance workstations [6]. The relative speedup speedup[8] of the the distributed version (including start up) over

[8] Due to communication and initialization overhead, the speedup is not the ideal value of 16.



(a) Before Simulation

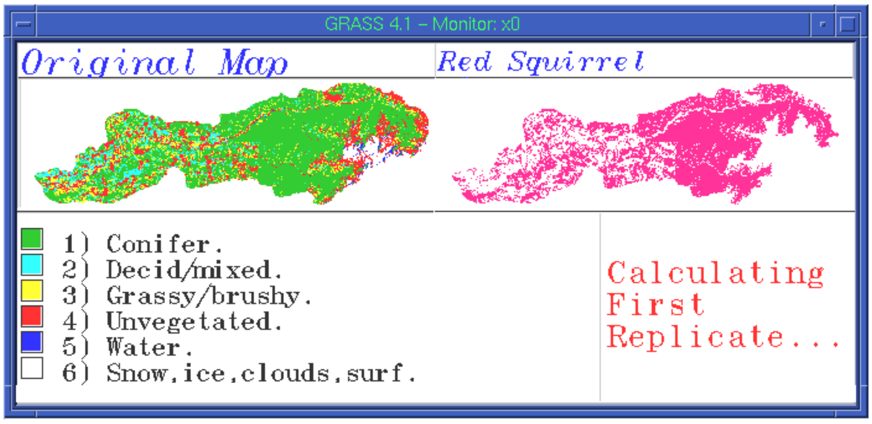


(b) After Simulation

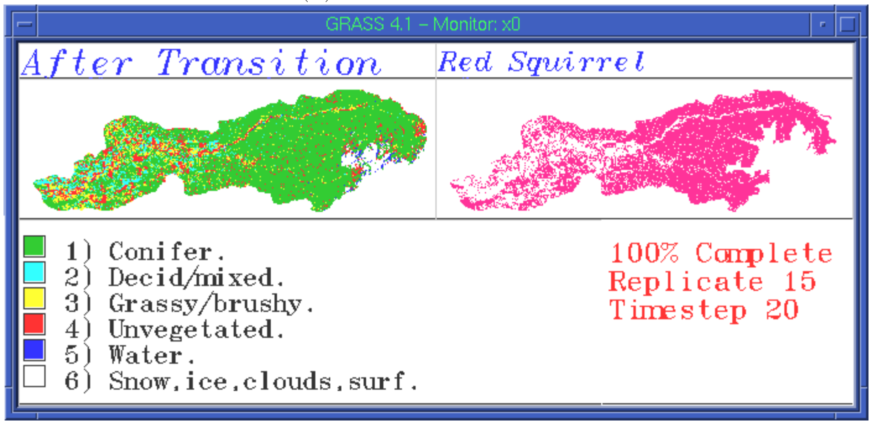
Fig. 7. *GRASS Monitor: Little Tennessee River Basin.*

the serial version tested was 10.49. The use of parallel algorithms [1] for computing map statistics on machines such as the Thinking Machines CM-5 could also be exploited.

Additional information can be obtained by e-mailing to `lucas-info@cs.utk.edu` which will automatically reply with a brief message. For more complete information, the LUCAS World Wide Web page at URL `http://www.cs.utk.edu/~lucas` is available. Images of



(a) Before Simulation



(b) After Simulation

FIG. 8. *GRASS Monitor: Hoh Watershed on the Olympic Peninsula.*

Time Steps	**Replicates**	**Number of Machines**	**Approximate Time (min)**
20	1	1	3:07
20	15	1	46:10
20	15	16	3:30 (plus 0:55 start up)

TABLE 6
Wall-clock execution times of LUCAS on a SPARCstation 5.

the GUI, sample simulations and literature regarding LUCAS can all be found at this site.

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Appendix

For validation of the LUCAS output maps for simulating land-cover change in the Little Tennessee River basin, Scenarios 4 and 1 from Table 5 can be applied in succession (beginning with the year 1975) for three (5-year) time steps, i.e., Scenario 4 (1975–1986) for two time steps and Scenario 1 (1986–1991) for the final time step. The LUCAS-generated land-cover maps for each time step can then be compared with corresponding land-cover maps available from the GRASS database (see Section 2.3). Table 7 illustrates the excellent agreement in the land-cover proportions between the actual and LUCAS-generated maps. The land-cover proportions shown for LUCAS reflect the mean over 10 replicates, and the initial 1975 land-cover map for the LUCAS simulation was taken from the GRASS database (i.e., no differences the for initial year). For the year 1986, the LUCAS-generated map from the second time step or year 1985 (two 5-year time steps) is compared with the available 1986 (not 1985) land-cover map from the GRASS database. Similarly, the actual 1991 land-cover map from GRASS is compared with the 1990 (final time step) land-cover map generated by LUCAS.

	1975		1980		1986		1991	
Land Cover	Actual	LUCAS	Actual	LUCAS	Actual	LUCAS	Actual	LUCAS
Forest	0.89	0.89	0.88	0.88	0.85	0.87	0.89	0.88
Grassy/Brushy	0.01	0.01	0.04	0.04	0.03	0.04	0.01	0.02
Unvegetated	0.10	0.10	0.08	0.08	0.12	0.09	0.10	0.10

Table 7

Proportions of land covers for simulated and actual landscapes in the Little Tennessee River basin.