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Linking Disciplines across Space and Time: Useful Concepts and Approaches for Land-Cover Change Studies

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This chapter develops concepts and approaches in which contrasting disciplines, and more specifically the fields of remote sensing, geographic information systems (GIS), and institutional analysis, can be appropriately integrated to advance our understanding of the human dimensions of land-cover change. While we have specifically applied these approaches to study how humans influence forest cover, they also may help direct the study of terrestrial vegetation change in general. We first discuss the dimensions of space, time, and human decision making and then examine how different aspects of the human-related land-cover change processes that affect woody plants vary across these dimensions. Finally, from this examination we present several simple graphical diagrams that help illustrate these complex relationships and thereby clarify the concepts presented here for readers who are unfamiliar with these approaches. These diagrams also can help researchers and students effectively display diverse datasets together and plan more robust strategies for land-cover change studies.

Dimensions of Space and Time: Maps and Timelines

Common understandings shared across disciplines help advance interdisciplinary land-cover change research programs, especially those that attempt to link the social and physical sciences. Yet the diverse vocabularies, contrasting research methods, and diverse datasets used by different disciplines can hinder the development of commonalities. Since most of the phenomenology of land-cover change is thought to exist within the four dimensions of space and time, perhaps we can help bridge our disciplinary differences by exploiting this fundamental connection. Any two analyses, regardless of disciplinary focus, have at least these four dimensions in common. Thus, this approach may help facilitate the development of a common set of

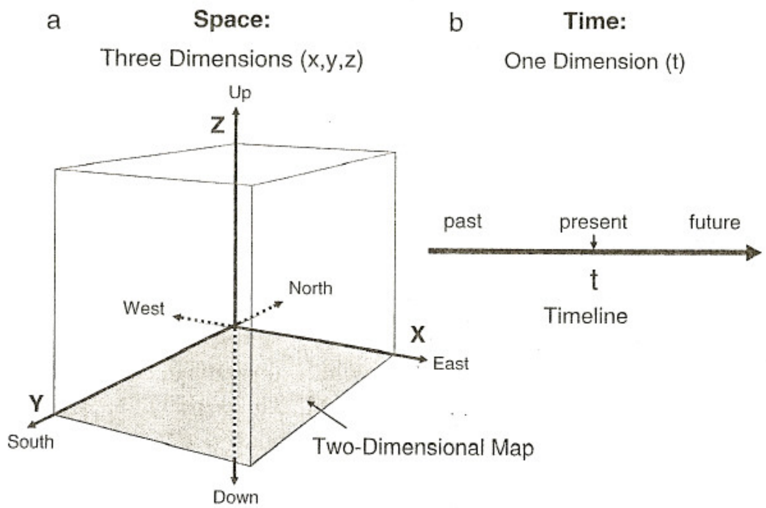

Figure 3.1
(*a*) Space can be depicted by three perpendicular axes: x, y, and z. The surface of Earth is often simplified in maps by using only the x and y axes, and is conventionally positioned such that north is to the top of the map. (*b*) Time can be depicted as a single axis (*t*) laid horizontally with the future positioned to the right.

basic nomenclature and conventions about how land-cover change processes manifest themselves across space and time.

The four dimensions of space and time in which land-cover change processes exist are depicted in figure 3.1. Three perpendicular dimensions are often used to define volumetric space, commonly known as the x, y, and z axes. One can, at least theoretically, travel forward and backward along all three of these spatial dimensions. Depiction of Earth's surface often uses only two dimensions because variability in the z-direction (elevation or height) is usually small relative to the other two dimensions. Thus, a "map," shown in *a* of figure 3.1, usually depicts variability in the x and y dimensions, although variability along the z-dimension is sometimes added as contours on topographic maps or as differential coloring of elevation of cells in a digital elevation model (DEM). Typically, the x and y axes are oriented such that the direction of geographic north is toward the top of the map.

Time, in contrast, varies only along one dimension, and, unlike travel along the three dimensions of space, one can travel in only one direction through time (into the future), since travel into the past is not possible. All states of land cover and the

changes that affect them can be positioned along a timeline based on when in the sequence of time they occur (*b* in figure 3.1). Typically, timelines are drawn horizontally such that positions to the left are older than (occur before) those to the right. Thus, the map and the timeline together comprise two fundamental, graphical diagrams through which we can display measures of land-cover change. A third important, though less common, graphic will also be introduced later in the chapter.

In several major disciplines, emphasis is placed on one dimension over another. History, for example, traditionally places more emphasis on time (the temporal aspects under study) and less on spatial aspects. Geography, more than most other disciplines, emphasizes the spatial dimensions over the temporal one. Other disciplines, such as geology and ecology, contain more of a mix of both dimensions. Certain social sciences (e.g., political science, sociology, and anthropology) traditionally emphasize space or time when needed. For example, political scientists do, at times, undertake research that emphasizes the temporal aspects in longitudinal studies. Geographic studies within political science are less prevalent, although they are becoming more common as the technologies of GIS are applied more readily (see chapter 7). The emerging interdisciplinary field of land-cover change research, however, emphasizes all four dimensions of space and time. Both spatial and temporal variability are at the core of this important field.

With the diverse vocabularies of separate disciplines, it is no wonder that land-cover change processes can appear extremely complicated. Aggravating this is a sense of urgency often felt by researchers, students, policy makers, and land managers because of the inherent complexity in understanding land-cover change processes, and the feeling that our understanding lags severely behind the processes involved. Land-cover change specialists also may feel like they are caught up in a race—simply put, a race between land-cover change itself and our collective ability to document past and current land-cover change episodes and understand the human-environment relationships behind them. If our collective monitoring and understanding of land-cover change continues to lag severely behind those changes, how can humanity mitigate any negative consequences of land-cover change and try to prevent avoidable future problems? While individual examples of sustainable use of forests, for example, are plentiful in both developing and developed countries, the study of land-cover change currently would profit from strategies to apply the lessons of these individual positive examples over a greater area. Also, many local studies are currently unrelated to broader spatial and temporal trends, so the relevance of these studies is questioned (especially by policy makers) even though they contain a wealth of detailed information. Remote sensing combined with directed multidisciplinary field studies may offer one strategy to "catch up" with land-cover change.

Regardless of how one chooses a geographic area of interest, the land-cover change community faces a tremendous challenge related to discerning the relationship between information generated over a wide range of spatial extents and temporal durations. Inherent in many land-cover change studies is the goal of relating detailed studies of a small area, such as those at the plot, site, or landscape level (see the section on spatial patterns of change in this chapter for our definitions of these) to those conducted over larger spatial extents at the regional, continental, and global levels. One crucial puzzle we face is how to take advantage of the wealth of detailed work by individual researchers of different disciplines studying in contrasting geographic areas and relate the information from each of these cases to larger areas.

How can this synthesis be accomplished? What strategies can we use to help integrate all the varying analytical "lenses" used by scholars from a variety of social and physical science disciplines? Is it possible to build a geographic "quilt" of individual case studies such that it ultimately spans a large geographic area? Can we make individual case studies more comparable and compatible with each other such that we can identify significant trends manifest across all cases? While each land-cover researcher moves forward in his or her individual research endeavors, the broader land-cover change community as a collective group would probably benefit by generating a library of compatible studies (e.g., see chapter 13). Studies that are well documented with respect to their spatial and temporal dimensions can inform and build on one another. Specific articulation of the spatial and temporal parameters in each land-cover change study would significantly ease case-to-case integration and compatibility. While this proposition is simple, it is a collective-action problem, yet it may yield synergistic results that are critical for land-cover change research to progress. Moreover, diverse spatial and temporal perspectives will help the student and researcher understand how contrasting processes relate to each other and will help place a given case study in a broader context.

Human Decision Making

We propose a framework to aid in assessing land-cover change based on three critical attributes for categorizing and relating processes of human-environment dynamics. We stated earlier that space and time provide a common setting in which all biophysical processes operate. In addition, we can emphasize the important human

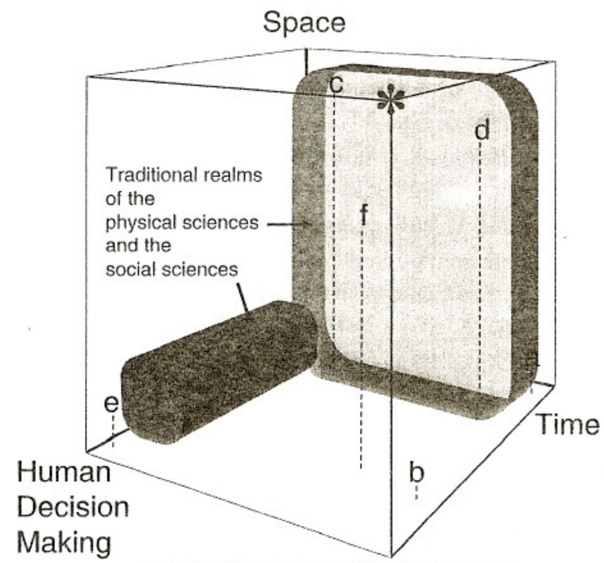

Figure 3.2
A three-dimensional framework, using space, time, and human decision making, can be used to distinguish the traditional realms of the natural and social sciences and different types of land-cover change studies.

aspects of land-cover change, a central theme throughout this book. When land-cover change processes incorporate human activities (NRC 1998), human decision making also becomes important. We can visualize this in figure 3.2 using three axes: space, time, and human decision making (Agarwal et al. 2002; Grove et al. 2002). This figure links together three important attributes in land-cover change research. The traditional, contrasting realms of the natural and social sciences also can be depicted in this framework, as well as categories of research or individual studies.

A robust understanding of land-cover change requires a multidisciplinary approach including an understanding of both biophysical phenomena, generally in the realm of the natural sciences, and phenomena involving human decision making, generally in the realm of the social sciences. Specific contrasting types of studies important to land-cover change research also can be seen in this figure: time-series studies and dynamic models with no human component (*a*); dynamic studies with human decision making explicitly incorporated (*b*); most traditional GIS studies (*c*);

GIS studies with an explicit temporal component and models such as those using cellular automata (*d*); econometric and game-theoretic studies (*e*); and recent multidisciplinary, dynamic, spatially explicit studies and models such as those using agent-based approaches (*f*). The space-vs.-time plane of the framework depicts strictly biogeophysical phenomena, traditionally the realm of the natural sciences, while phenomena mainly involving human choice and institutions, generally in the realm of the social sciences, are depicted near the human decision-making axis. The asterisk in figure 3.2 marks the ultimate goal of land-cover change research—a synthesis incorporating spatial, temporal, and human dimensions.

Scale: A Problematic Word

Both social and ecological processes can operate at different spatial extents and temporal durations (Allen and Hoekstra 1992; Ehleringer and Field 1993). Finding significant variance between study findings is in part hindered by a lack of a clear articulation of measures used in various studies and the lack of a vocabulary that crosses disciplinary boundaries (E. Moran 1984b, 1990). A glossary of terminology would facilitate communication of this information across disciplines.

The word "scale" is often heard in the context of land-cover change. Unfortunately, as described in Agarwal et al. (2002) and M. Turner et al. (2001), "scale" is often a confusing term in land-cover change research because it has conflicting meaning across disciplines. Notably, geography and the other social sciences, core disciplines in land-cover change studies, often use "scale" to infer opposite meanings. Geographers define "scale" as the ratio of length of a unit distance (scale bar) on a paper map to the length of that same unit distance on the ground (Greenhood 1964). Thus, a large-scale map usually shows more detail but covers less area (e.g., a paper map of a small town, produced at a 1:10,000 scale—the ratio between a given distance measured on the map [1] and the same distance measured on the ground [10,000] using the same ruler), while a small-scale map usually shows less detail but covers more area (e.g., a paper map of the entire United States, produced at a 1:6,000,000 scale). To the geographer the scale bar itself is what is large or small. Unfortunately, most other social scientists give opposite meanings to the terms large-scale and small-scale. For example, in these disciplines, a large-scale study generally means it covers a large spatial extent, and a small-scale study is a more detailed study covering a small area. Used in this way, the word "scale" can generally be dropped completely with little change in the meaning of the sentence.

To clarify this confusion, Agarwal et al. (2002) propose two other terms that carry more intuitive meaning—"fine-scale" and "broad-scale"—and, interestingly, M. Turner et al. (2001) independently proposed similar terms. In this book, we have made the decision to use other more specific and clearly defined terms in place of "scale" whenever possible and if they are available. For example, by substituting spatial extent, spatial resolution, temporal duration, or temporal interval (all defined in detail later in the chapter) in place of "scale," we feel multidisciplinary communication is strengthened.

Terms that describe the spatial and temporal characteristics of land-cover features or processes are critical for land-cover change research, yet these adjectives often have conflicting or ambiguous meanings. For example, terms like "long" and "short" can describe both distance and time, while space can refer to an area or a volume. Overcoming incongruent and ambiguous language presents an important challenge as land-cover change studies strive to link disciplinary studies of human-environment relationships.

Spatial Patterns of Change

Fortunately, we already have many words that are widely used across all disciplines and differentiate various temporal durations: day, week, month, year, decade, century, and millennium. However, different terminologies have been developed and employed in various disciplines to help communicate differences in spatial extents. After numerous sessions of trying to come to a common understanding among our affiliated anthropologists, geographers, political scientists, forest ecologists, demographers, historians, and others at our research center, we settled on several terms depicting various levels of spatial extent: globe, continent, region, location, landscape, site, and plot. Figure 3.3 illustrates how processes that affect forests can vary at different levels of spatial extent.

We use "globe" (in the context of land-cover change) to mean the terrestrial surface of Earth (about 150×10^6 km^2). "Continent" is at first glance also rather self-explanatory, referring to the seven great land masses on Earth (which range in area from 10×10^6 to 50×10^6 km^2). While this may be clear at present (though, on closer examination, the Europe/Asia division seems rather arbitrary and politically motivated), it is important to remember that plate tectonics has moved and rearranged the continents through past ages. A "region" is a subdivision of a continent, though it may comprise islands in one area of ocean (ranging from 100,000 to

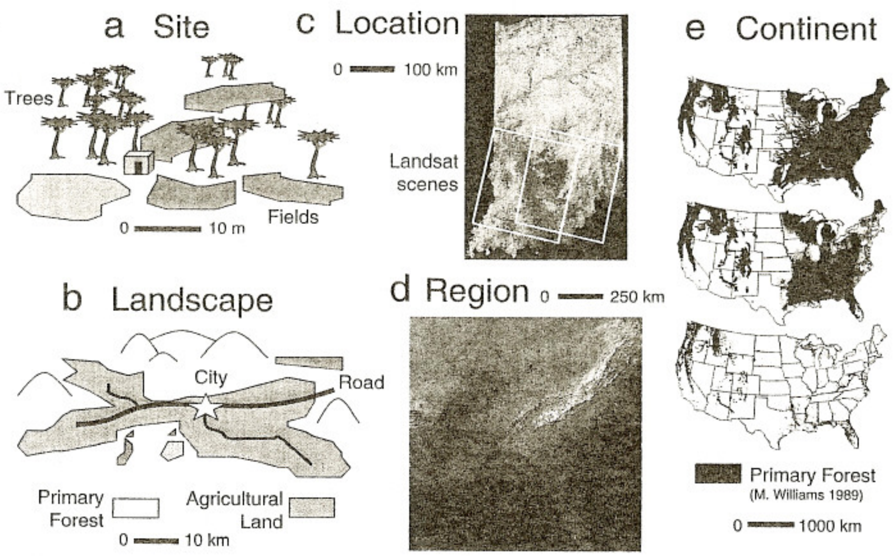

Figure 3.3
Anthropogenic land-cover change processes vary at different levels of spatial extent. Different factors influence land-cover change at different levels (see text for a more detailed explanation). (*e* from M. Williams 1989.)

10×10^6 km^2). A region may encompass one or multiple countries, or only a fraction of a country in the case of larger ones, such as the Midwest of the United States containing Ohio, Indiana, Illinois, Michigan, and so on. Alternatively, we can consider a region to be multiple countries, such as the region comprising the countries of Central America. The term "location" is defined in more detail in chapter 6, but we use it to designate the area captured within a time series of Landsat satellite images (from 15,000 to 30,000 km^2). The term "landscape" designates a fraction of a location and it can range from 100 to 10,000 km^2. We use the term "site" to describe a relatively small geographic extent (from 10 to 10,000 hectares) within which ecological and social fieldwork might be conducted by an individual or team of researchers. Therefore, a site is a local area that can be traversed on foot. Sites have been historically important to land-cover change research because it is at this spatial extent that household interviews and community surveys are conducted and at which institutional analysis usually takes place. Moreover, sites are particularly important as we strive to connect theory and empirical data on individual and community decision making to broader measures of space, time, and human decision

making. Plots are the smallest level of spatial extent (from a fraction of a square meter to 10,000 m^2) and are usually used in the context of the direct measurement of vegetation in the field (see chapter 5). Plots, sites, landscapes, and locations are the levels at which land-cover change studies tend to collect field-based data relevant to forests and how they change.

A difficult problem facing researchers of land-cover change is that human-induced forest change processes (e.g., deforestation) exhibit different dynamic patterns, or "space-time footprints," at different levels of analysis (see figure 3.3). It is apparent that one simply cannot add up, or aggregate, observations of changes at the site level and generate those observed patterns at larger extents, such as at regional and continental levels. We can illustrate this with a simple example. Let us assume we observe at a particular site a large old-growth tree being cut in a single day, thereby clearing an area of about 100 m^2 (*a* in figure 3.3). At first glance, a simple linear extrapolation may suggest that to clear primary forest from a continent, an area of about 1×10^{12} m^2, it would take more than 27 million years, an obviously fanciful estimate. History shows that the eastern United States (see *e* in figure 3.3) was almost completely cleared of primary forest in a period of around 300 years (M. Williams 1989). One obvious problem uncovered by this example is that the deforestation of the eastern United States was a complex process. It started in the early seventeenth century as several hundred colonists using medieval technologies cleared fields near Boston and Jamestown, two of the earliest colonies. By 1800, hundreds of thousands of colonists were clearing forest, and firewood supplied virtually all of the country's energy needs. In the late 1890s, the last large expanses of old-growth forest were being cleared from the Midwest for agricultural use and export wood products. Today, few, if any, of the last remaining small patches of primary forest (now accounting for less than 0.01 percent of the original area) are experiencing clearing (M. Davis 1996).

Diverse patterns of forest change are apparent across a wide range of spatial extents (see figure 3.3). Therefore, it is important that researchers clearly articulate the spatial extent of their respective studies so this diversity can be identified and any trends documented. At the site level, patterns of forests and fields (*a* in figure 3.3) may be affected by household economics, available family labor and technologies, land tenure, local institutions, cultural practices, ethnic backgrounds, and microclimates. At the site level (in an open-access situation), for example, optimal foraging theory would predict that certain tree species used for important products would be diminished in areas closer to households and along trails than in less accessible areas (Schweik 2000). At broader spatial extents at the landscape level (*b* in figure 3.3), land-cover change patterns may be a function of topography, proximity to city and road, city population, urban demand, and the institutional landscape (county/district institutional differences). At the location level, topographic relief, urbanization, population density, transportation infrastructure, and county institutional differences may play a role (*c* in figure 3.3, based on Indiana Gap data; see also chapter 6).

A regional spatial analysis may exhibit forest and deforestation patterns that are the result of factors such as topographic relief, regional climate, soils, population density, state institutional differences, and broader intrastate political differences (*d* in figure 3.3, a shaded relief image of topography from the Satellite Radar Topography Mission data [http://www2.jpl.nasa.gov/srtm/p_status.htm]). A continental analysis may highlight patterns in forest cover that are the result of broader spatial and temporal physical and human processes such as climate, historical human migrations and technological development, as well as state, national, and global institutions (*e* in figure 3.3).

Institutional Landscapes

Elinor Ostrom and others define "institutions" as the rules that humans follow, or the "rules-in-use," and as the mechanisms established to monitor and enforce those rules (E. Ostrom 1990; E. Ostrom et al. 1994; Schweik et al. 1997). Institutions can be formally designated by national, state, or local legislation, such as environmental statutes, but also can exist in a variety of other forms, such as the standard operating procedures of an organization, or informal social norms established by communities of people. Institutions, like the forests they govern, frequently carry spatial and temporal attributes and often change shape and composition over time. Schweik (1998) refers to these spatial and temporal distributions as "institutional landscapes."

Institutions are human-crafted mechanisms designed to alter human behavioral response in a given physical and social setting. Humans use rule configurations and monitoring and sanctioning mechanisms in an attempt to change their behavior. The incentive structure that institutions create raises the costs of undertaking certain actions while reducing the cost of other actions. Effectively enforced institutions can be just as important an influence on how humans impact land-cover change as biophysical factors, such as topographic attributes, or portions of the built environment (e.g., transportation infrastructure). Institutions, therefore, can be an important factor determining forest patterns across all the levels presented in figure 3.3.

Institutional landscapes vary with spatial extent and temporal duration. At the broader spatial levels of the location, region, or continent, international treaties are often negotiated (with varying degrees of success) with the goal of placing restrictions on the actions of organizations (e.g., companies and government agencies) associated with one or more countries. More common are the broad national laws that may place requirements or limitations on the actions of organizations or individuals. Similarly, environmental laws which affect forests are often created at other levels of governance, such as state or city zoning ordinances. Similarly, less formal institutions can be created, and these often have spatial attributes. Organizations, such as the U.S. Department of Agriculture Forest Service, sometimes create standard operating procedures that designate how and where operational-level actions may take place, for example, restricting forest cutting within certain distances of riparian areas. At the site or landscape level, social norms within communities may establish less formal (unwritten) rules for private property or communal ownership through which activities are required, permitted, or prohibited. Institutions also have a temporal dimension. A particular rule may be long-lived or, alternatively, may depend on political cycles and exist for only a brief period of time. For example, Schweik (1998) describes three different institutional configurations that governed the Hoosier National Forest between 1985 and 1992.

Temporal Patterns of Change

Human-induced land-cover changes can be portrayed on a timeline. Figure 3.4 shows two episodes of forest change in Indiana: (1) the progressive elimination of the primary forests from the state by colonists during the nineteenth century and (2) the regrowth of secondary forests during the twentieth century on less than a quarter of the state's area. Both episodes probably followed some type of logistic, or S-shaped curve. The figure shows that deforestation rates probably have varied widely, starting slowly, progressing to a maximum in the 1860s, and then slowing as the last remnants of primary forest were cleared in the early years of the twentieth century. Surveyed in the early 1800s, Indiana was 87 percent forested (the remainder of the state was covered with wetlands and prairie; see *b* in plate 4) before settlement by colonists, yet by 1870 and 1900 primary forest covered 30 percent and 6.5 percent of the state, respectively. The initial deforestation was largely the result

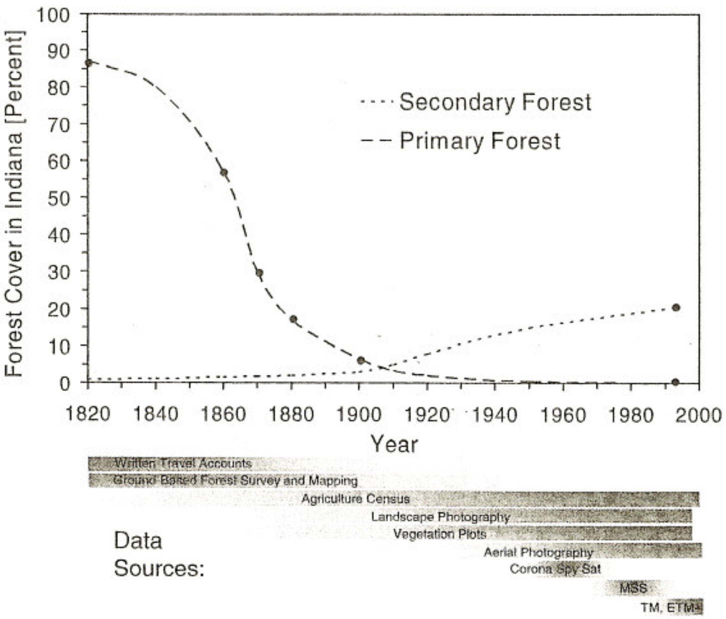

Figure 3.4
A timeline showing two distinct episodes of land-cover change affecting Indiana's forests. MSS, TM, and ETM+, Landsat Multispectral Scanner, Thematic Mapper, and Enhanced Thematic Mapper Plus.

of clearing by colonists for crops and grazing. Only a few dozen small patches of uncut forest remain today (M. Davis 1996). Secondary forest cover expanded during the 1900s and covered more than 20 percent of the state in 1992 (mostly on lands of higher topographic relief; see *a* and *c* in plate 4). Now, however, little secondary forest cover is currently being added. Today, an estimated 4.5 million acres of forested land, mostly secondary forest, exist in Indiana, covering about 20 percent of the state (IDNR 1997). Estimated areas at particular dates were taken from Indiana Department of Natural Resources data (IDNR 1997), Jackson (1997), and G. Parker (1997). The data sources available to document these land-cover changes also vary greatly through time (see figure 3.4). The availability of a particular dataset is restricted by the history of the technology that is used to generate it. For example, satellite images from the Landsat Multispectral Scanner (MSS) instrument are mostly available from 1972 to 1992.

Space-Time Diagram

Anthropogenic processes affect trees and forests over a wide range of spatial extents and temporal durations. Figure 3.5, a modified Stommel diagram (Stommel 1963), shows that processes that affect woody plants vary across a wide range of extents and durations. The diagram is constructed such that the spatial extent of a land-cover change process, measured in units of square meters, is plotted along an exponentially scaled y-axis, and the temporal duration of the process, measured in units of days, is plotted along an exponentially scaled x-axis. The figure employs log-log scales of time (on the x-axis in keeping with the timeline's orientation) and area (on the y-axis). The log-log plot is useful in accommodating a wide range of durations and areas on the same plot. Conventional subdivisions (levels) of time are labeled, and corresponding levels of area are given. This space-time diagram is a third key graphic in land-cover change studies (together with the map and timeline). It uses relative scales of space and time (how large or small an area is, or how long or short a time duration is) as opposed to the absolute scales used in maps (geographic coordinates, such as latitude and longitude) and timelines (year A.D. or B.P.). The ovals in figure 3.5 represent our "best-guess" estimates of the range in extent and duration of each episode in which those processes take place; the actual boundaries of these processes in the figure are debatable until actual measures are compiled.

The forest-change processes in figure 3.5 range from felling an individual tree, which might typically take place in one day's time and affect an area of 100 m^2, to the deforestation of a continent, which might take place over several hundred years and affect an area of millions of square kilometers. A forest-change zone (bounded by dashed lines) marks the general range of extents and durations of these processes. The distribution of processes along the diagonal of figure 3.5 reveals that, typically, processes that cover small areas happen during short periods of time (processes of lesser magnitude; see inset in figure 3.5), while processes that affect large areas take longer times to occur (processes of greater magnitude). In general, processes that involve gases (atmospheric phenomena) are located in the upper left portion of the diagram; processes that affect solids (geologic phenomena) are located in the lower right portion; and processes that affect liquids, such as water (hydrologic phenomena), are found along the diagonal. Therefore, process dynamism increases to the upper left of the diagram and decreases to the lower right (see inset in figure 3.5).

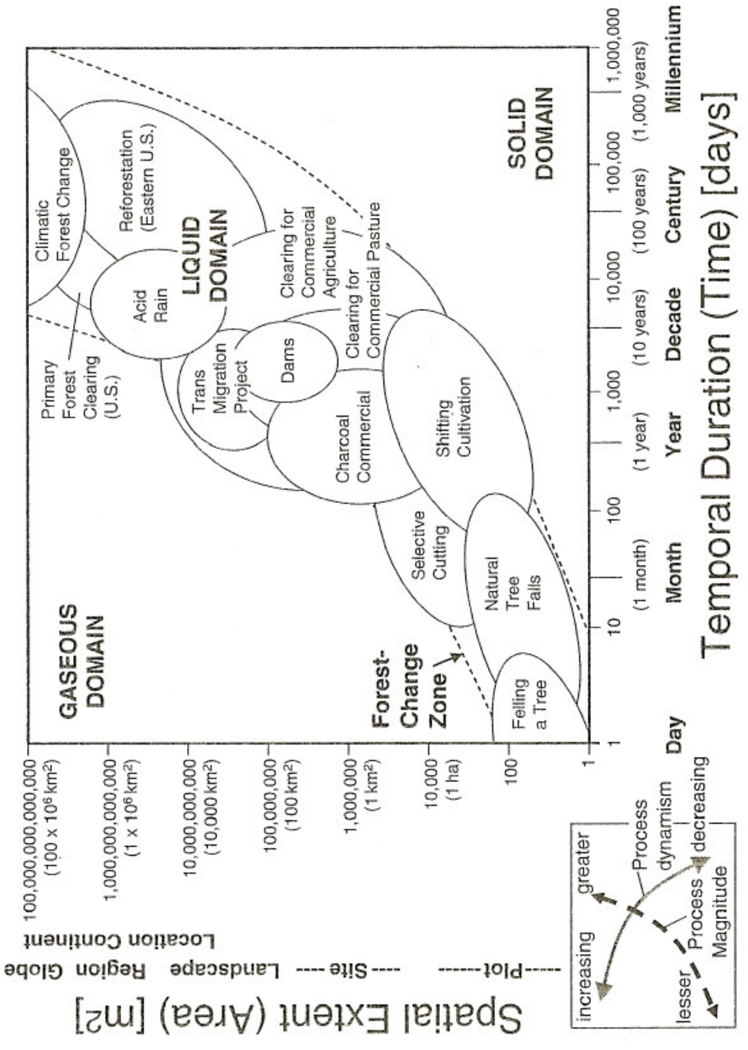

Figure 3.5
A space-time diagram shows how various human-influenced processes that affect woody plants and forests vary across a wide range of spatial extents (in square meters) and temporal durations (in days). Ellipses circumscribe the general range in extent and duration of some examples of land-cover change processes that affect trees and forests (see text for a more detailed description).

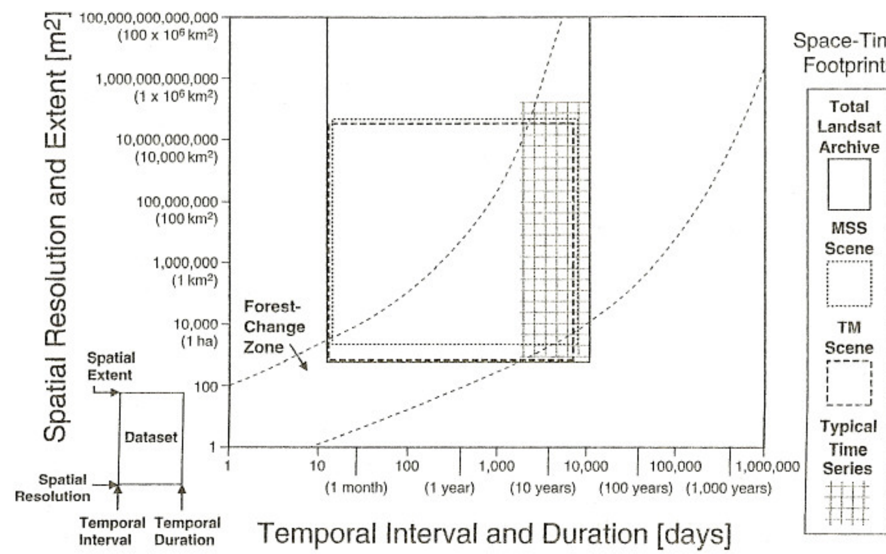

Figure 3.6
Many different datasets can be described by using four important parameters plotted on a space-time diagram: spatial extent, spatial resolution, temporal duration, and temporal interval. The four values determine the dimensions of a space-time footprint of a particular dataset (rectangular areas). The cross-hatched pattern shows the footprint of a typical Landsat image time-series dataset used in a land-cover change study.

Plotting Datasets on a Space-Time Diagram

Space-time diagrams also can be used to explore what datasets would be particularly relevant in examining a given land-cover change process. Figure 3.6 shows an example of how a widely used remote-sensing dataset (Landsat satellite images; see chapter 6) is plotted on a space-time diagram.

Four parameters are particularly useful in describing a dataset (see inset in figure 3.6): (1) *spatial extent* describes the extent of the area it covers; (2) *temporal duration* describes the length of time over which it was collected, such as the time between the oldest and newest images of a satellite image time series; (3) *spatial resolution* describes the smallest spatial unit that makes up the dataset; and (4) *temporal interval*, or sampling frequency, describes the smallest time step used to describe it.

Figure 3.6 shows how these four parameters can be used to describe the Landsat dataset. Each value determines the dimensions of a "sampling footprint." The resulting rectangle in the figure thus represents the spatial and temporal dimensions of the dataset. The figure shows four such footprints for Landsat datasets: (1) the MSS archive for a single location, (2) the Landsat Thematic Mapper (TM) archive for a single location, (3) the entire Landsat archive, and (4) a typical Landsat time series used in a land-cover change study. The spatial extent of the dataset controls the top boundary of the dataset sampling footprints. For example, a single image acquired by the TM covers an area of 170 × 185 km, while the total Landsat system of satellites has acquired images that have inventoried almost the entire extent of Earth's terrestrial surface. The bottom boundary of each rectangle is controlled by the spatial resolution of the dataset. For example, a single picture element, or pixel, of a Landsat 4 TM image covers an area of 28.5 × 28.5 m on the ground, while an MSS image pixel from Landsat 1 is 56 × 79 m. The left boundary of the rectangle corresponds to the temporal interval or sampling frequency of the dataset. For example, Landsat satellites return to a given location and acquire an image as frequently as every 16 or 18 days (see chapter 6). Finally, the right boundary of each rectangle in figure 3.6 represents the temporal duration of the dataset. Landsat data have been collected from 1972 to the present, a period of more than thirty years. These temporal duration and interval values are theoretical maxima, since cloud cover or lack of a receiving station in a particular location, for example, may further restrict image availability (see also figure 6.6). Lack of funds in a given study for images or processing may further restrict a dataset's space-time footprint, often making the duration of a given image time series shorter and the interval between individual images in a time series longer. The cross-hatched pattern in figure 3.6 shows the space-time footprint of a typical Landsat image time-series dataset used in a land-cover change study (sampling every four to five years from 1972 to 2003, in two adjacent locations).

A particular dataset can inform a study on those land-cover change processes (see figure 3.5) whose extents and durations are coincident with that dataset's time-space footprint (see figure 3.6). Landsat satellite images often are important to land-cover change studies because they inform over a significant portion of spatial and temporal parameters that are important when studying forest changes (the forest-change zone in figures 3.5 and 3.6). The sampling footprint of a given Landsat image time series in figure 3.6 may be appropriate to inform how certain land-cover change processes affect woody plants in figure 3.5 (such as building a hydroelectric dam), but that same dataset may be too coarse in resolution and too infrequently sampled to measure other processes (such as a particular farmer felling an individual tree).

Similarly, Landsat data may not be appropriate to study many broader-level atmospheric phenomena.

Temporal duration and interval are analogous to spatial extent and resolution, respectively. The terms *resolution* and *extent* often are used to describe both temporal and spatial levels; however, we have attempted to make these distinctions more explicit so readers will not be confused by which dimensions we are referring to in any particular discussion, and we think these careful distinctions in terminology are important for enhancing future dialogue involving land-cover change.

Land-Cover Change Data Sources

Processes of interest to the land-cover change community occur at spatial extents as small as a fraction of a square millimeter (e.g., the exchange of gases in a leaf) and extend to the entire surface area of the Earth (roughly 510 million square kilometers). A researcher interested in forest change may determine that a Landsat image provides an appropriate spatial extent to capture that phenomenon, or alternatively, a researcher interested in phenomena related to leaf structure (such as gas exchange) might choose to work with a spatial resolution of 10^{-6} m (to view individual cells) and a spatial extent of roughly 20 cm. The same approach applies with respect to time. A researcher interested in studying the climate of a particular region may decide to collect precipitation data at a monthly temporal interval and use data collected over the duration of a year. In contrast, a researcher interested in investigating leaf respiration might choose a shorter sampling interval, such as a minute, and collect measurements for the duration of a day. Figure 3.7 illustrates how some commonly used datasets in land-cover change research may appear when plotted on a space-time diagram. Each dataset informs within a certain region of the space-time continuum, and it is often necessary to use several different datasets in combination to examine a particular land-cover change process. Setting one dataset within the context of another broader-level dataset (overlapping) may help to address questions related to the significance of a given finer-level piece of information in a broader context.

Each rectangle in figure 3.7 is associated with a different data source. The spatial extent of the dataset controls the top boundary of any rectangle in the figure. Sun-synchronous weather satellite images, collected by the advanced very high resolution radiometer (AVHRR), for example, are collected across the entire globe (both land and oceans) and hence have the largest spatial extent of the examples shown. The Landsat dataset, as a whole, has inventoried nearly the entire extent of Earth's

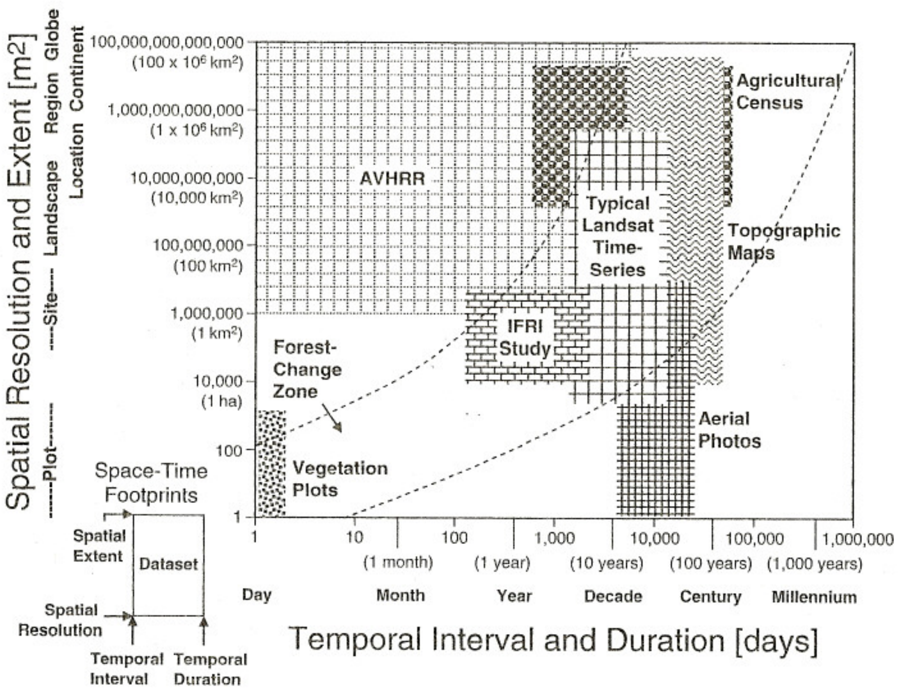

Figure 3.7
The space-time footprints of various datasets commonly used in land-cover change studies. Landsat images provide an important dataset because they cover a central range of both space and time, and can be used to efficiently position the collection of more detailed but costly data, such as vegetation plots or institutional analyses. AVHRR, advanced very high resolution radiometer; IFRI, International Forestry Resources and Institutions. (For IFRI studies, see chapter 4.)

terrestrial surface. Individual agriculture census datasets often cover entire states. The bottom boundary of each rectangle in figure 3.7 is controlled by the spatial resolution of the dataset. For satellite images a convenient measure of resolution is the area of an individual picture element. For example, acquired AVHRR images have a spatial resolution (at nadir) of 1.1 × 1.1 km. In contrast, most bands in a Landsat TM image contain pixels that measure 28.5 × 28.5 m on the ground. Topographic maps sometimes provide resolutions of one hectare or less, and aerial photography often provides resolution of a meter or less. The left boundary of any given rectangle shows the temporal interval of a dataset. Weather satellite images are collected many times in one day. Agriculture census data are commonly collected once a year,

and aerial surveys are conducted about once every ten years. This temporal interval is similar for population census data. Landsat satellites return to a location and record data as frequently as every sixteen days. Finally, the right boundary of each rectangle in figure 3.7 represents the temporal duration of a dataset. For example, the duration of the Landsat data archive is more than thirty years. Agricultural censuses in the United States have been collected for well over one hundred years, for example, in Indiana since 1860.

The datasets shown in figure 3.7 are not inclusive of all possible datasets by any means but are used to illustrate how spatial and temporal attributes of a dataset may be displayed and compared and may help the researcher consider what datasets are appropriate to address a particular research question and phenomenon of interest. Researchers can consider the spatial and temporal dimensions of the datasets available to them and consider which ones apply to various levels of analysis. Landsat images provide an important dataset because they cover a central range of both space and time. Landsat data have a relatively fine spatial resolution and temporal interval, yet Landsat images still cover a relatively broad spatial extent, and image time series can have a duration of thirty years or more. However, no one dataset, including Landsat, can inform at every spatial extent or temporal duration; therefore a multidisciplinary approach using several different datasets in combination can be advantageous. Also, datasets which cover larger extents and longer durations can be used to efficiently position (as in a map) the collection of more detailed but costly data, such as vegetation plots or institutional analyses (International Forestry Resources and Institutions studies; see chapter 4). We also have shown that space-time diagrams can be used to plot contrasting land-cover change processes (see figure 3.5). Though not often stated, one of the keys to effective land-cover change research is ensuring that the dataset one uses to inform a study has the same spatial and temporal dimensionality as the process one is trying to understand. This can be accomplished rather simply, for example, by overlaying figures 3.5 and 3.7.

Conclusions

We feel it is important for researchers to articulate the spatial extent and temporal duration of an analysis clearly to place a particular study in a broader context of space and time. We hope our discussion will help diverse disciplines understand one another better and facilitate more multidisciplinary collaboration. We have presented a short description of three key diagrams: the map, the timeline, and the space-time diagram. For readers planning a research program, approaches like those described in this chapter may help them think through their scientific research strategies—strategies that hopefully will be cognizant of how land-cover change processes change across spatial and temporal levels and which datasets may be appropriate for studying particular processes. We also encourage readers to be particularly careful in their use of terms like "scale" so the results of their future research can cross disciplines more readily and with less confusion. Finally, we present these concepts and approaches because we think they can help to better leverage those resources available to the land-cover change scientist (or student) to produce significant results.