

## Chapter 2

# Environmental Sensing

The environment has remained at the forefront of scientific interest for well over four decades, and no other topic will likely captivate our attention in the foreseeable future as we struggle to understand the complexities of this planet, we call home. Understanding is the key, but understanding does not take place in a vacuum. To grasp the significance of our relationship with our environment, we need to comprehend the patterns and processes that characterize its many features; how they interact, how they change, and how they influence behaviors that shape our future. Understanding requires information, which helps to reveal the distinct actors and actions that conspire to define the environment. However, being informed implies not only an improved comprehension of the complexities inherent to the study of the environment, but also a greater sensitivity to the limit of our knowledge, the uncertainties that remain, and the unavoidable realities of our ignorance. In this context, information is intelligence that we not only learn from, but also apply to guide us while we strive to make good environmental decisions. The goal of this chapter is to place the environment into a framework that enables our ability to measure, map, and model its features using remote sensing technology to gain intelligence. Too often remote sensing is discussed from a technological perspective that leaves a gap between the obvious technical aspects of this science and the pragmatic need to obtain relevant data to address a problem. This chapter examines the environment by identifying its descriptive elements that can be explored remotely; characteristics that can not only be measured, but also whose measures communicate essential facts that explain the disposition of the environmental complexity. From this discussion, the notion of environmental sensing is introduced as the conduit between the technology, the myriad of applications it can serve, and our environmental system.

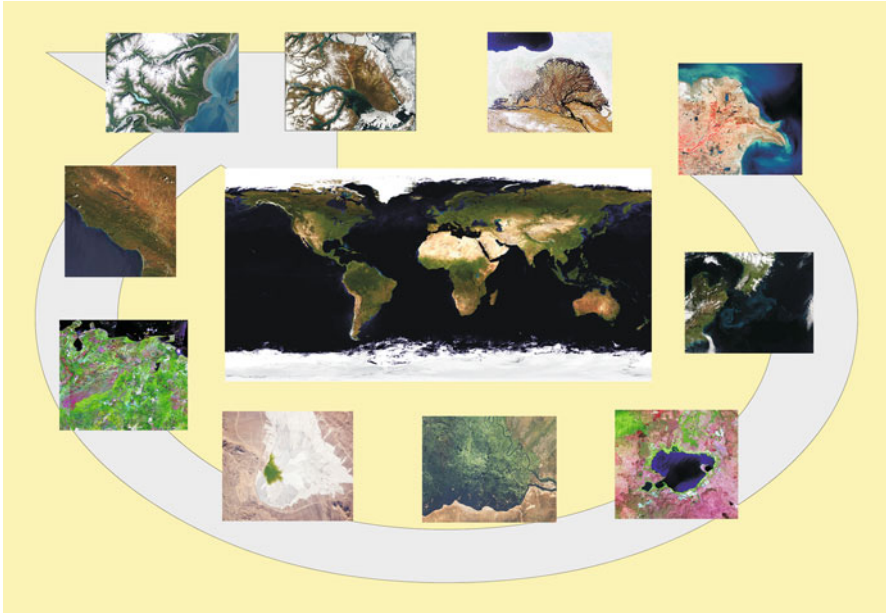
## 2.1 Sensing the Environment

When used in common language the word “sensing” defines any of the faculties, such as sight, hearing, smell, taste, or touch, by which humans perceive stimuli originating from outside our bodies. Sensing, according to this simple definition, means to detect, perceive, or become aware of some phenomena external to us. Remote sensing technology has long been identified as a means of detecting or perceiving phenomena where the measurements taken at distance from objects and surfaces of interest are transformed into information, in a manner analogous to our brain transforming the perception of touch into concepts such as rough or smooth. The data collected remotely satisfies our desire for knowledge and provides needed information to guide us in a similar way that our hand searches for the light switch in a dark room. It may be argued that our present state of knowledge regarding the environment is not unlike an adventure in a dark room, it can also be argued that our capacity to sense our environment will be integral to becoming aware. How well we sense will determine likely how well we learn and understand.

For the purposes of this discussion, environmental remote sensing may be defined as the measurement and representation of earth surface characteristics that support the information requirements for effective environmental management and decision making. This practical definition suggests that there is an underlying rationale that directs the remote collection of data and narrows the scope of the science of remote sensing by focusing on the delivery of information that illuminates the complexities, uncertainties, and dynamic nature of the environmental process. In this regard, environmental remote sensing is an extension of an existing technique that strives to incorporate alternative strategies and sensors that can yield new information and provide new insight into the status of Earth’s environments and detect conditions of critical concern.

## 2.2 The Environmental System

Earth’s environments are complex and varied. In simple terms, they can be characterized as biomes; a defining area of ecologically similar geographic and climatic conditions, which support communities of plants, animals, and soils that assume distinctive relationships and patterns (Fig. 2.1). From a remote sensing perspective, these biophysical patterns explain land covers that form as the outcome of abiotic factors and the biomass productivity of the organizing vegetation types that dominate its spatial expanse (Olsen et al. 2001). Land covers also describe human environments where culture has altered patterns of ecosystem process and biodiversity. Such alterations generate distinct surface characteristics that form as the product of sustained and direct human interaction with ecosystems. These anthropogenic biomes emerge as the consequence of human impact range from settlements, croplands, forested areas, and wildlands subject to human modification (Ellis and Ramankutty 2008). Whether biotic or human-induced, this ecosystem is a



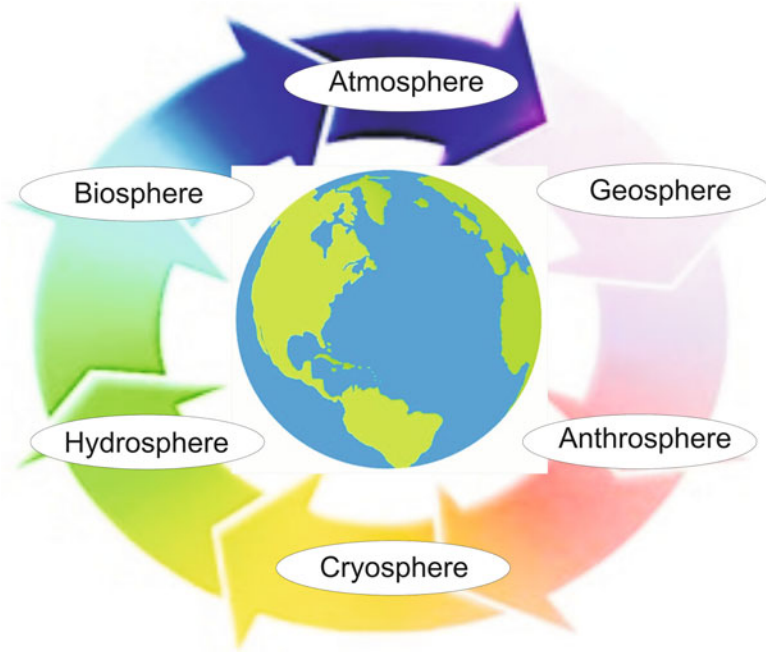
**Fig. 2.1** The patterns of Earth's biomes

thin layer of the earth, estimated at less than 14 km, that supports life (MacKenzie 2010). Recognizing that this has taken over four billion years to achieve the present state of the environment, there is both uniqueness and an element of chance-consequence that underlies the conditions we observe.

As a system, Earth's environments explain a collection of interdependent elements (Fig. 2.2). At the most general level, these are commonly referred to as:

- The *lithosphere*, which contains all of the cold, hard, and solid rock of the planet's crust (surface), the hot semi-solid rock that lies underneath the crust, the hot liquid rock near the center of the planet, and the solid iron core (center) of the planet
- The *hydrosphere*, which contains all of the planet's solid, liquid, and gaseous water
- The *biosphere*, which contains all of the planet's living organisms
- The *atmosphere*, which contains all of the planet's air

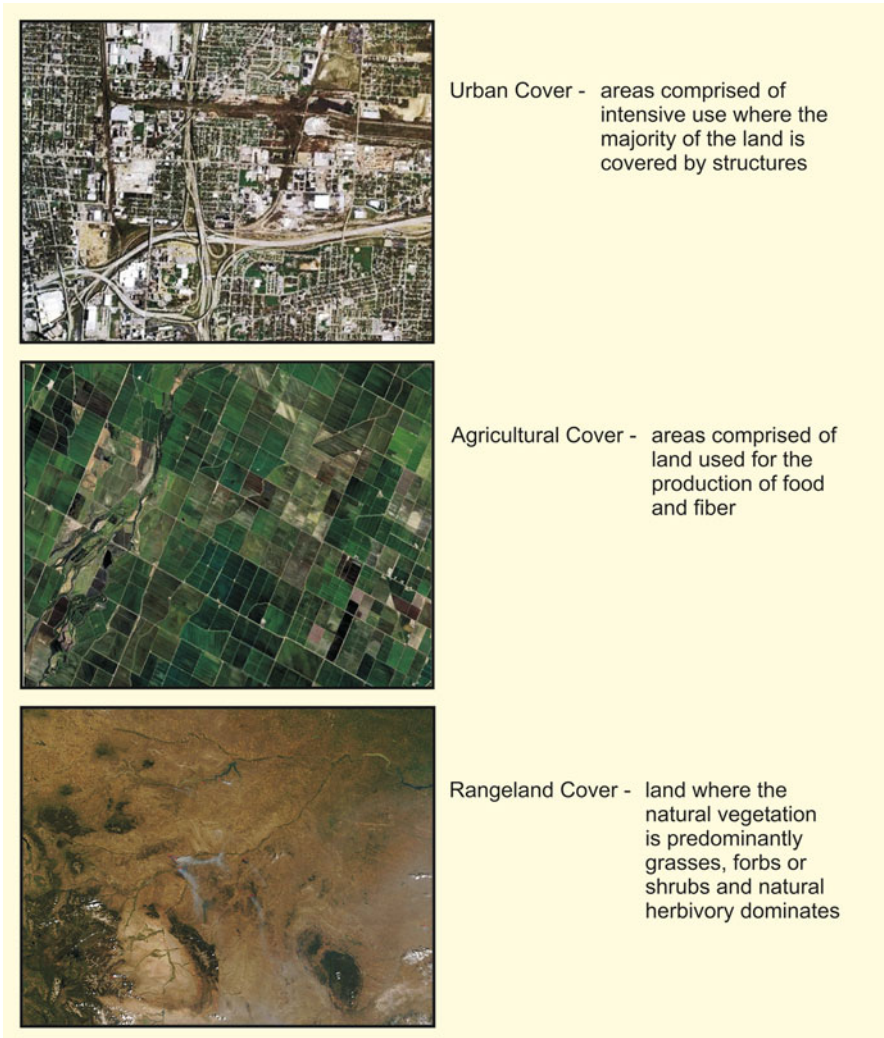
The elements are closely connected and exhibit cyclic patterns of behavior when materials and energy flow across space and over time. This familiar cascade, characterized in relation to the ecosystem, the flux of solar energy that drives climate, and the process-response progressions that punctuate geomorphic and hydrologic activity, demonstrate how environmental components interact with their surroundings and evolve functional relationships that connect components together to form a definable structure (Figs. 2.3a–c).



**Fig. 2.2** The Earth system

In many respects, the land covers observed via remote sensing serve as evidence of these structures, displaying a morphology that permits inferences to be made regarding their disposition, causation, and variation both spatially and temporally.

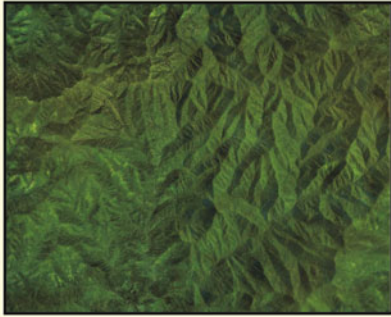
Change and the dynamic processes that propel components of the environmental system are basic attributes of variability that produce contrasting patterns over time and space. As an attribute, environmental change varies in form, size, duration, and areal extent and arises not at random, but as a result of basic biological and physical processes operating on the planet (Hidore 1996). The patterns that emerge are the observable consequence of these occurrences. Changes in the environmental system can be described in several ways. At one level, we can recognize a change as short-term – defining cyclic behaviors occur in less than one rhythm of the system. From here we can also identify medium-term changes that explain seasonal rhythms among environmental attributes. Finally, behaviors may characterize long-term patterns, which may not be easily resolved, transitioning from one dynamic equilibrium state to another, or exhibiting stepped fluctuations punctuated by lag times well beyond the common human scales of reference. More purposeful explanations may be offered that give



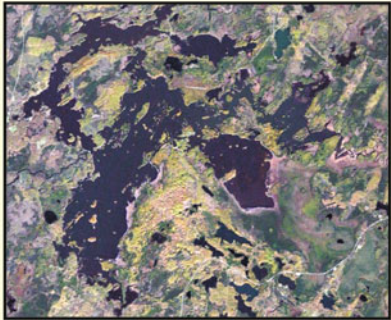
**Fig. 2.3** Characteristic land covers and their definition

better insight into the patterns of change and how they channel environmental process over time. Here, environmental change can be categorized according to one of the five different conditions (Hidore 1996):

1. *Persistent change* – unidirectional trajectories typified by slow, steady progressions over time
2. *Rhythmic change* – displaying regular oscillations where periodic fluctuations occur at regular, predictable intervals



Forest Cover - areas where tree-crown areal density is 10 percent or more and exert an influence on the hydro-climatic



Wetland Cover - areas where the water table is at, near or above the land surface for a significant part of the year

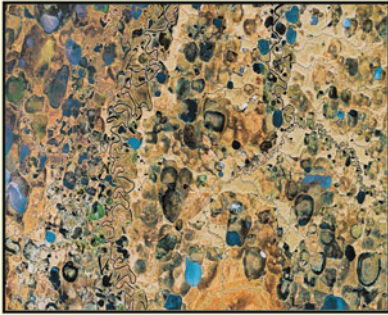


Barren Cover - areas with a limited ability to support life where less than one-third of the area has vegetation or other forms of cover,

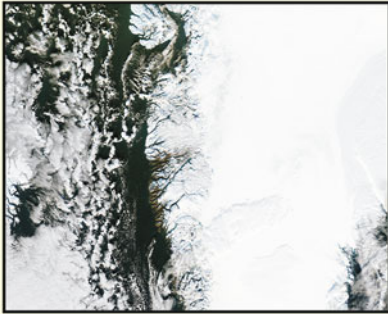
**Fig. 2.3** (continued)

3. *Cyclical oscillations* – where change repeats at irregular intervals with varying intensity, but are not periodic
4. *Short-lived events* – explaining sporadic episodes often identifying deviations from average or expected conditions with durations spanning seconds to several days in length
5. *Anthropogenic change* – exemplified by human-induced effects on natural patterns sustained by trajectories of established social and economic drivers acting over time

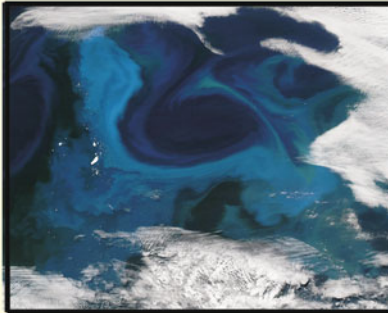




Tundra Cover - describing treeless areas beyond the limit of the boreal forest and above the altitudinal limit of trees in high mountain environments



Perennial Snow Cover



Water Cover

Fig. 2.3 (continued)

As an active force, change contributes to shaping and reshaping of the structure of the environmental system. Since the environment is essentially open to the transfer of matter and energy and generally oscillates between conditions of equilibrium and disequilibrium, an appreciation of the system structure offers a means to observe the environment independent of function or state (Dury 1981). Four general categories of structure, moving from less to greater complexity, can be noted:

1. *Morphological systems* – defined in terms of their internal geometry as expressed by the number, size, shape and linkages displayed by their components, morphological systems have identifiable shapes and patterns such as those descriptive of streams, glacier systems, shorelines, and entire landscapes.

2. *Cascading systems* – explain environments that receive and generate complex inputs and outputs of matter, energy, or both. Cascading systems include some type of regulator and mechanisms that provide storage where the main focus of interest becomes the rate of flow or flux between components.
3. *Process–response systems* – describe environments that alter their internal geometry and/or behavior in response to cascading inputs. Generally process–response systems comprise at least one morphological system and at least one cascading system that are linked and often share common components.
4. *Control systems* – environments in which some aspect of their functions are controlled by intelligence. Such systems vary in scale, but share the inescapable influence of human decision making and a directing force.

From this cursory review, several key concepts emerge that focus an environmental remote sensing investigation. The first is the idea of complexity. As the subject of inquiry, the environment forms as a multifaceted arrangement of living and nonliving elements that blend to create the fabric of a landscape from which our measurements emanate. The differentiation exhibited by the elements of the environment encourage the need for selection and intellectual devices to manage the variety presented to us and organize it in a clear and coherent manner. Through the strategies of abstraction, simplification, classification, and symbolization, complexity is made sensible, which enables representation of the second key concept: structure. Structure is something we can view as having “shape,” whether it is the shape of drainage patterns that provide clues to the underlying geologic structure of the environment or the shape of the boundaries that delineate land units that may be indicative of differences in soil type, climate, or human impact. Through structure we can infer arrangement and connectivity which supports a process view of how the environmental system behaves at any given location. More importantly, behavior moves us to consider change, the last key idea that lends itself to remote detection. Through change, the patterns and processes manifest in a dynamic setting that captures the environment in an active and often transient state. The next section explores these concepts in more detail.

## 2.3 Pattern, Process, and Disturbance

Environmental systems evidence distinctive patterns that develop as the product of energy and material interactions over time. These patterns are identifiable as the communities of living and nonliving elements that not only give rise to a structure, but also define the focus of environmental remote sensing. The agents of the biosphere, atmosphere, hydrosphere, and lithosphere form an interdependence recognizable as the landscape: a land surface of associated habitats that explain an ecology termed as the mosaic (Bissonette and Storch 2004; Huggett 1995; Turner and Gardner 1994). These spatially heterogeneous areas characterize a



dynamic that can be expressed according the “brash” equations (Huggett 1995). Using this conceptual model, we can represent the environmental system as interacting terrestrial life and life-support components where the biosphere ( $b$ ), troposphere ( $r$ ), atmosphere ( $a$ ), pedosphere ( $s$ ) and hydrosphere ( $h$ ) respond over time to each other plus the influence of forcing functions ( $z$ ) that lie outside the landscape. When these agents are expressed mathematically produce the “brash” set (Huggett 1995) such that:

$$\frac{db}{dt} = f(b, r, a, s, h) + z$$

$$\frac{dr}{dt} = f(b, r, a, s, h) + z$$

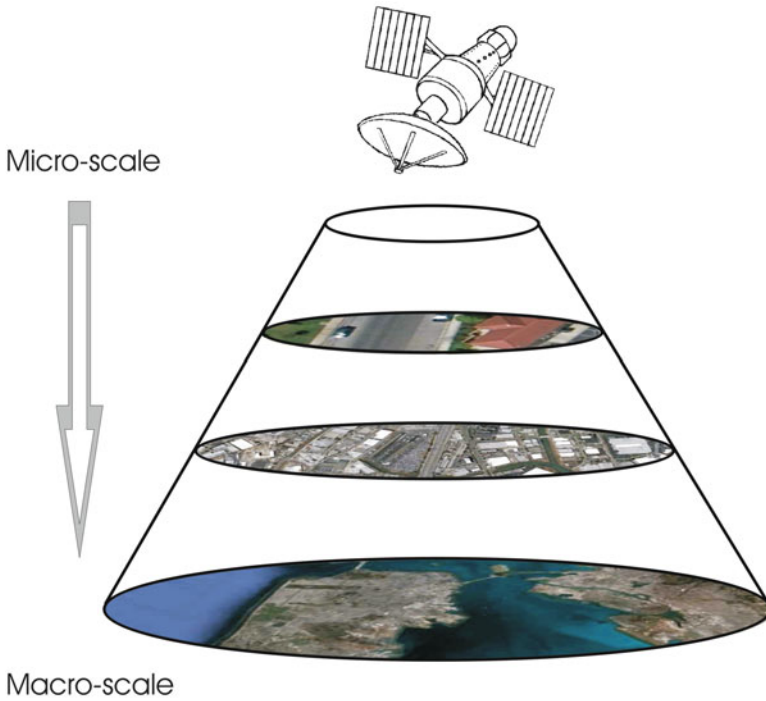
$$\frac{da}{dt} = f(b, r, a, s, h) + z$$

$$\frac{ds}{dt} = f(b, r, a, s, h) + z$$

$$\frac{dh}{dt} = f(b, r, a, s, h) + z,$$

which provides an ideal explanation of the landscape that offers an analytical design for exploring pattern and how pattern changes over time.

Pattern is also a function of scale; a dimension that refines the spatial and temporal characterization of the landscape mosaic. As a unit of observation, the structure, function, and dynamics of the landscape are scale-dependent where the processes and resulting patterns at one scale may be insignificant at another. Traditionally, scale has been described using the “cone of resolution” model (Fig. 2.4). This familiar representation depicts the level of detail synonymous with the scale from the macro-scale through the meso-scale and down to the micro-scale and implies a reference to the size (relative or absolute) at which physical or human structures and processes are observable. Scale in this context is also defined in terms of generalization, where scale controls the apparent detail or complexity phenomena that may assume. Using this conceptual model, the connection between the idea of scale, “visibility,” and the observational detail a remote sensing device provides can be neatly established, which helps to identify the appropriate level of detail required to address an environmental problem and the capacity of a sensor to deliver that detail. At the macro-level, scale defines pattern and process in its most generalized form. Geographically, this can be visualized as a near-continental perspective that explains a comparatively coarse degree of details. In the language of remote sensing, macro-scale conforms to a level of spatial resolution common to sensor platforms such as the advanced very high resolution radiometer (AVHRR) and MODIS. The meso-scale can be



**Fig. 2.4** The cone of resolution model

conceptualized as a regional scale level of detail where spatial resolution improves to a sharper representation of the surface. At this level, representative platforms may include the Landsat, IRS, SPOT, and Aster. The micro-scale introduces the finest definition of pattern and suggests a landscape perspective that would capture details present within a watershed or city. In the hierarchy of satellite remote sensing systems, micro-scale explains spatial resolutions at or below 5 m which are typically found on commercial platforms such as GeoEye, IKONOS, and QuickBird (Fig. 2.5).

Although scale is inherently an imprecise and elastic concept, its role is important and critical to the study of the environmental system (Gibson et al. 2000). First, scale defines the size at which the environmental structures exist and over what extent the environmental processes operate. This interpretation of scale attempts to present the “true” expression of environmental phenomena and recognizes that environmental processes are often scale-dependent, or at the very least, defined in part by a relative scale. However, there can be exceptions to this idea, particularly in the examples where patterns seen at one level of detail may also be observed at another and the possibility that environmental processes often operate at multiple scales. Its inexact nature, therefore, directs us to consider scale in a more pragmatic sense: analytical scale.



**Fig. 2.5** Comparative spatial scale/sensor resolution relationships

Analytical scale refers to the size of the unit at which the problem under investigation is examined. This simple definition is useful in environmental remote sensing since it implies measurement and how measurements are aggregated for data analysis. In this context, analytical scale explains the scale of understanding; and with specific reference to satellite remote sensing, this scale is used to represent the surface whether as a raster (pixel) or polygon (object). Therefore, to observe and study the environmental system accurately, the scale of analysis must conform to the actual scale of the phenomenon, whether expressed over time or across space (Hudson 1992).

Identifying the correct scale can be problematic. Scale insensitivity introduces cross-level confusion, particularly when data at one scale is used to make inferences about phenomena at another or the narrower; an example of the “ecological fallacy” where aggregated data is used to make inferences about disaggregated patterns. In reality, the challenges imposed by the scale often require us to use the data at the “available” scale, which constrains an analysis to the units that are present in the data. While there may be no reasonable alternative, representing the environmental system (however defined) at the “available scale” may contribute to the loss of definition, particularly when the phenomena of interest do not conform well to the units imposed by the data. The result introduces an unavoidable level of error into our analysis, which limits the degree of confidence that can be ascribed to a solution.

Reconciling the issues of scale enables patterns to emerge that illustrate the important associations that bind the elements of the environmental system together. Identifying spatial pattern, therefore, not only supports an understanding of the system under study, but also provides clues that relate observed characteristics to underlying process, which highlight the dynamic nature of the environment (Dale 2002). Process, however, is difficult to capture. Taken broadly, the term suggests a sequence of events that actively shape and reshape the behaviors exhibited by the

system of interest, whether it is a city, watershed, or other geographic entity. The sequence implied may be continuous across time and space, or discrete and observable in finite quanta of time. In both cases, there is also the underlying assumption that the events set in motion are sustained in some definable manner. Through the sustained “behavior” of process, a recognizable consequence is achieved, whether explained as the land surface modified by the geologic cycle of erosion, the establishment of growth and mortality of a plant community of the spread, or human–urban land cover over the landscape. The product of this sustained behavior is change, as the environmental system responds to and is transformed by a process into a set of new relationships. We observe the evidence of process as the generation of a new form in an environment where that form did not exist previously. The mechanisms responsible lurk behind the observed patterns and define the driving physical, economic, or social forces that propel the environment and fuel the trajectories of change.

Sensing environmental change shares a duality of purpose. At one level is the need to resolve a pattern; documenting the spatial expression of process through the contrasting patterns it reveals. At the more complicated level is the desire to infer the process from those patterns; deducing the driving forces that are actively at work within the environmental system. In both instances, the influence of time cannot be ignored, nor removed from the question. Temporal influences, whether explicit or implicit, remain a constant, although best viewed as a relative rather than an absolute quantity (Getis and Boots 1978). In some respect, sensing time in the environmental system is similar to watching an animation. Each frame in the sequence, like each image captured by our sensor, is a complete depiction of the scene at a specific instance in time. Set into motion, the individual scenes blend to characterize the change. The rate of motion between each frame describes, in a limited way, the pace at which a change takes place, and each individual frame influences how animated the action (process) appears. By examining one frame in the sequence, our interest is to describe the direction of motion and anticipate where in the subsequent frames action will take us (Getis and Boots 1978). Complications of course arise; particularly when processes are gradual or when new “actors” are introduced or leave the scene. Perhaps more frustrating to the goals of environmental remote sensing are those situations where a long interval of identical frames are encountered and no action (change) can be observed; begging the question: is the absence of change, change? While this analogy is simple, conceptualizing the idea of environmental change as an animation underscores the fact that, when sensing environmental process more often than not, our understanding is frequently limited by the available frames. In some cases, what we have may be sufficient to adequately capture the “action,” although more typically we are left with an isolated or interrupted sequence that requires us to provide the missing context. Explaining environmental process, like viewing an animation, depends on (1) the subject matter, which in our case are the operative processes that direct environmental behavior (action) and (2) our ability to assemble each frame together into chain of events that complete the story.

The unfolding stories of environmental process that currently direct our concern are those new actors that introduce changes in the sequence that redirect the plot. Familiar examples of these active events include:

- *Deforestation* – the process of destroying or removing forest ecosystems through logging operations or burning
- *Desertification* – the degradation of land in arid and dry sub-humid areas
- *Environmental degradation* – uncharacteristic loss of habitat, biodiversity, or depletion of natural resources contributing to ecological collapse
- *Erosion* – the process of removing sediment, soil, rock, and other material in the natural environment
- *Extinction* – the death of the last existing member of a species where there are no surviving individuals able to reproduce and create new generations

These environmental processes are complex, reflecting the influence of many causal factors that act on environmental systems. The causal mechanisms that contribute to the plot changes that confuse our animation have been neatly summarized by Goudie and Viles (2003) according to a set of:

- *Predisposing factors* – describing features of the natural or human environment that make a system vulnerable to stress (change)
- *Inciting factors* – defining stresses that trigger the change in a system
- *Contributing factors* – explaining the range of additional stresses that render a system's response more noticeable and acute.

Taken together, these factors conspire to direct the environmental system to a new state (frame) where we observe a transformation or a shift as human activities interact with a series of interlocking environmental responses.

The transformations characterizing environmental change can be subtle and slow to emerge, or dramatic and quick to materialize. In either case, they reflect the consequence of disturbances that alter material and energy flows within the environmental system. Here, the concept of a disturbance becomes a convenient way to connect environmental stress to actions that will display both temporal and spatial dimensions. In an environmental context, a disturbance describes an event causing change in the ecosystem that includes environmental fluctuations or destructive events. Along this implied continuum of events, disturbance may emanate from purely endogenous (internal) processes to those that are purely exogenous (external) (White and Pickett 1985). Overall, landscapes may be disturbed by a range of actors from the physical consequence of strong winds, fire, flood, landslide, and lightning; the biological consequence of pests and pathogens; and the impacts of human and animal activities. In some cases, disturbances act at random within the landscape, while other events spread from a beginning point through the system over time. As a sensible quality, disturbances operate in a heterogeneous manner, since some features with the landscape are more susceptible to an event than are others. It is important to recognize that disturbance is an integral part of all environmental systems, and landscapes are defined in part by a common disturbance regime (pattern) (Gordon and Forman 1983). A disturbance

regime represents the sum of types, frequencies, and intensities of disturbance through time in the landscape. When we observe the environmental system, the disturbance causes a given characteristic of an ecosystem (such as diversity, biomass, and nutrient levels) to exceed or fall below its common range of variation.

Landscapes subject to human-modifying actions are the changes by new disturbances introduced by economic and social forces. Human impact, expressed as a disturbance, however is discontinuous and unevenly distributed over the surface. Consequently, human disturbance regimes differ between landscapes and are superimposed on contrasting natural disturbance regimes. As a result, the landscapes produced by human modifications display a wide range of variability, often with sharp and distinct boundaries (Gordon and Forman 1983). The types of modified landscapes produced by human disturbances begin at the lower end of the “gradient” with natural vegetation such as grassland, rainforest, or desert produced by a natural disturbance regime void of significant human effects. Moving upward along this range are the areas recently exploited by human populations which are often characterized by scattered clearings in the natural land cover. Continuing along this gradient are the patterns that reveal managed landscapes where the majority of the surface appears to be composed on natural cover, but is controlled for human activities such as timber harvesting or livestock grazing. Control implies active management that introduces significant differences in species, energy, and nutrient cycles when compared to the natural vegetation. Cropland follows next in the sequence where planted vegetation dominates and may be intermixed with remaining sections of managed vegetation. Following next in this description of modified landscapes are the human settlement patterns characteristic of ex-urban and suburban development where managed vegetation has been reduced and the surface appears as a heterogeneous mixture of agriculture and urban forms. The final frame in this continuum describes urbanized areas where human use dominates. In this pattern, only small remnants of managed or cropland cover types remain visible. As this gradient of human impact is observed, key descriptors of pattern emerge as boundaries and edges shape and fragment the land surface into increasing levels of heterogeneity.

## 2.4 Patches and Progressions

From the altitude of a sensing platform, the Earth’s surface appears as a mosaic of shapes and textures of varying configurations. These configurations assume arrangements that take on meaning in both an environmental and cultural context. This is the landscape and from an environmental perspective, it defines heterogeneous land areas composed of clustered, interacting ecosystems repeated in similar form across a discernable geographic extent. Delineating these surface arrangements is of fundamental interest in remote sensing, but a process that must be guided by an understanding of the mechanisms that contribute to their



formation. Acting within the boundaries of these land surface arrangements are the geomorphic processes, colonization patterns, and local disturbances which, working in concert, produce distinctive, measurable units that display (Gordon and Forman 1983):

- *Structure* – spatial relationships among the landscape elements of energy, materials, and species relative to the size, shape, number, and type of these configurations
- *Function* – interactions among spatial elements in terms of energy, materials, and species flows among the elements
- *Changes* – alterations in structure and function over time

As a physical entity, this landscape reveals three universal characteristics: (1) patches, (2) corridors, and (3) matrix. In the language of landscape ecology these terms take on specific meaning. The term patch is defined as a relatively homogeneous area that differs from its surroundings. Patches serve as the basic unit of the landscape that change and fluctuate, a process called *patch dynamics*. When observed on remotely sensed imagery, patches have a definite shape and spatial configuration and can be described compositionally by internal variables such as number of trees, number of tree species, height of trees, or other similar measurements. Matrix defines the “background ecological system” of a landscape with a high degree of connectivity. Connectivity is the measure of how connected or spatially continuous a corridor, network, or matrix is. For example, a forested landscape (matrix) with fewer gaps in forest cover (open patches) will have higher connectivity. Within this explanation, corridors have important functions as strips of a particular type of landscape differing from adjacent land on both sides. When view in their entirety, a network emerges that defines an interconnected system of corridors forming a mosaic which explains the pattern of patches, corridors, and matrix that form the landscape. These building blocks of the landscape provide simple descriptors to express local influences that identify how landscapes are configured. These descriptors also account for the biodiversity patterns and natural processes that we observe (Dramstad et al. 1996). Thus, while the landscapes foundation reflects its background ecologic pattern, the local “neighborhood” forms as a configuration of patches, corridors, and background cover types revealing the matrix produced by natural processes as well as human activities that alter the mosaic. Alterations include the obvious and well-documented changes such as habitat fragmentation, and also include land transformations such as:

- Perforations
- Dissections
- Shrinkage
- Attrition
- Coalescence, each carrying significant ecological and human implications (Dramstad et al. 1996).

## 2.5 Sensing the Human Dimension

Although the visible alterations evidences in the environmental system induced by human activities have been well documented for over two decades (Mannion 1997; Roberts 1994; Stern et al. 1992), the causes promoting these alterations are more complex and less obvious. Therefore, while a satellite image may reveal patterns indicative of specific transformations in the landscape, the image alone carries little information concerning the how-and-why behind what is seen. The challenge in environmental remote sensing is to connect the patterns detected on the image to the decisions made that now characterize either the direct and purposeful alteration of the landscape or the unintended consequence of human decisions that have generated new, conditions that were not anticipated. This discontinuity rests at the core of environmental decision making and underscores the web of human behaviors and motivations that introduce themselves whenever choices are made, which affect the present or future state of the environmental system (Lein 1997; Chechile 1991). Decision making, however, does not take place in a vacuum. Rather the choices made describe a process driven by interconnected society needs and desires. The driving forces that direct human–environmental decision making fall into five broad categories:

1. *Population demand* – Each of us make demands on the environmental system for food, clothing shelter, and other services in support of our life styles. Greater numbers or increasing concentrations of people expand our ecological footprints and elevate demand for resources needed to sustain our activities.
2. *Economic growth* – The innate desire to improve our quality of life, provide for our needs and realize great opportunities, focus attention on the accumulation of wealth and capital formation to enhance our material standard of living. Expanding economic activity introduces environmental stressors, since the patterns of consumption contribute to both an expanding human footprint on increased consumption of natural resources and an elevated production of wastes and other energy and material residuals generated by these consumptive activities.
3. *Technological discovery* – Discovery impacts the environmental system through the innovations that enable wider exploitation of the resource base and through the types and characteristics of the waste residuals produced.
4. *Political institutions* – Taking the form of policy instruments that direct market influences and encourage social progress, governments and our increasing global political economy generate environmental outcomes by promoting (directly or indirectly) actions that damage environmental functioning, facilitating wider use of environmental resources and ignoring the environmental consequences.
5. *Cultural perceptions* – Individually and collectively, we are the product of values, beliefs, and attitudes that reflect our cultural teachings and experience. Through the lens of culture a world-view takes form, and our relationship to the environment becomes crystallized by the choices we make and the behaviors we follow.



**Fig. 2.6** The spatial expression of urbanization

While none of these forces are sufficient alone to produce changes in the environmental systems, acting in combination they generate definable spatial events adequate in their scale and impact to alter properties of the landscape (Tillman and Lehman 2001; Vitousek 1992).

Incorporating the consequences of human decisions into the analysis of landscape heterogeneity begins with an appreciation of the spatially explicit actors that evidence the human dimension of our environmental system. Although the pathways followed by human activities are complex, they ultimately explain five distinctive decision-driven mosaics:

1. *Urbanization* – The decision to urbanize summarizes a human predilection with origins dating back over 15,000 years. As a spatial phenomenon, urbanization explains the transformation of land cover to a form and composition distinctly anthropogenic in nature, characterized by fragmented landscape dominated by asphalt, concrete, brick, and other manufactured materials. Morphologically, urban cover is typified by a terrain composed of angular forms assuming a planimetric arrangement that extends to a third dimension. As a pattern, urbanization is a physical element displaying a texture and extent wherein the concentration of structures, facilities, and people conspire to express economic and cultural influences that modify or replace “natural” form (Fig. 2.6).



**Fig. 2.7** The spatial expression of agricultural intensification

2. *Agricultural intensification* – As a land cover pattern, agriculture is a mosaic of biological and physical patches within a matrix differentiated by settlement, cultivated land, and background cover that is defined as rural by virtue of its density and intensity. Geometrically, agricultural intensification is typified by a parallel structure and regularity of shape that conforms to land clearing practices and boundaries defined by land ownership. Intensification results in a progressive removal of existing landscape features with agricultural form (Fig. 2.7).
3. *Rangeland alteration* – Surface configurations of this variety explain land areas on which the climax or potential plant cover is composed of natural grasses, grass-like plants, and shrubs suitable for animal grazing and browsing. Rangeland areas are subject to limited management practices which may include deferred grazing, burning, or rotational grazing with little or no use of chemicals or fertilizers. Frequently subject to overstocking and fragmentation, semi-natural and natural rangelands are often adversely impacted by land degradation, loss of biodiversity, altered species connectivity, and intensification that retards recovery (Fig. 2.8).
4. *Deforestation* – Referring to the general process of forest clearing, deforestation characterizes a pattern of logging that expands progressively from an edge, a central cut strip, or patch. Although predicated on the presence of





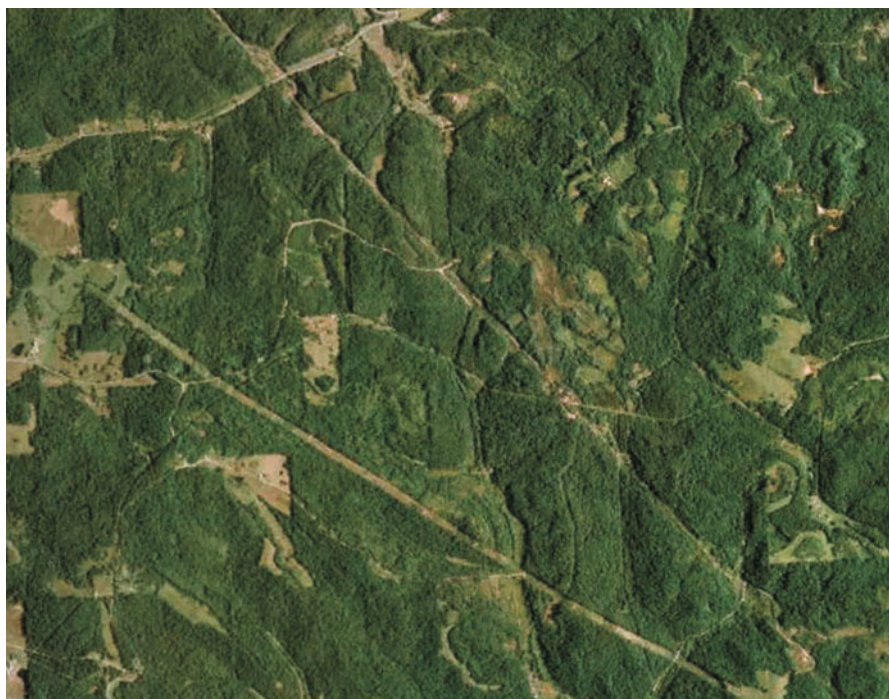
**Fig. 2.8** The spatial expression of rangeland alteration

large forested areas with low population density, effects emanate from policy decisions to open forested regions through instruments such as settlement programs, development projects, plantations, or other extractive industries. This suggests that deforestation may not be the exclusive consequence of timber harvesting. A related land pattern describes the re-establishment of forested areas, which may be planned (reforestation) or unplanned (afforestation). Afforestation is common to areas where soil degradation has occurred following farm abandonment or over cutting. Reforestation explains the large-scale planting of trees in a highly regular and systematic pattern of field-size units. Frequently, tree rows alternate with row crops during the early stages of these programs (Fig. 2.9).

5. *Corridors* – Visually identified as openings in an area that display highly linear patterns, a corridor develops either as the product of a human decision to construct features such as roads, power lines, rail lines, or irrigation canals or a lineation created by geologic and geomorphic factors. Typically, modification spreads and proceeds outward from the corridor on opposite sides penetrating through “natural” cover. Human constructions that create corridor features often include branching as a more complex linear network takes shape as a function of its design (Fig. 2.10).



**Fig. 2.9** The spatial expression of deforestation



**Fig. 2.10** The spatial expression of landscape corridors



## 2.6 Acknowledging Uncertainty

It would be convenient if the environmental system behaved in an unambiguous, consistent, and perfectly predictable manner. Unfortunately this is not the case. Rather, behaviors and processes descriptive of Earth's environments, while not random, are characterized by a complexity colored from a palette of deterministic, probabilistic, and stochastic relationships that vary across space and over time. As processes, disturbances, and natural perturbations in the environment evolve a landscape, even though the initial status or condition is known, there are many possible "realities" to consider, pathways to follow, and multiple potential future states of nature (Stewart 2000). This simple observation shapes our knowledge of the environmental system and invites a careful assessment of the uncertainties inherent to (1) our conceptualization of the environment, (2) the limitations of our knowledge, and (3) our inability to adequately resolve environmental process (Brown 2004). This observation also sustains our motivation to collect data and analyze information pertaining to the environmental system.

Uncertainty pervades all our attempts to ascertain absolutes with respect to the disposition of human–environmental interaction. As a concept uncertainty carries several connotations with important implications to the goals of environmental remote sensing (Regan et al. 2002). First, is the issue of epistemic uncertainty; an uncertainty associated with our present knowledge of the state of the environmental system. This form of uncertainty describes a "changeableness" that emerges due to limitations imposed by measurement devices, insufficient data, extrapolations, and interpolations as well as spatio-temporal variability. A second branch of uncertainty focuses the concern on the problem of linguistic ambiguity that describes the inexactness and vagueness introduced by language. This source of confusion is a product of our vocabulary and the presence of under-specific, ambiguity, and context-dependent terminologies. Both forms of uncertainty are problematic and develop from different sources. Furthermore, since they originate from difference sources, uncertainties are likely to compound. Therefore, identifying the main sources of uncertainty and exploring methodologies to control or minimize its impact are critical to an improved understanding of the environment. Several key sources of uncertainty with relevance to the environmental problem can be noted (Sutter et al. 1987; Regan et al. 2002), and each manifest in different ways:

- *Measurement uncertainty* – defines the limitations imposed by the observations techniques employed to measure environmental variables.
- *Natural variability* – explains behaviors in natural systems that are difficult to predict.
- *Inherent randomness* – identifies the limits of our understanding of process and the patterns that define environmental relationships.
- *Subjectivity* – Influence of judgment and its role in data interpretation can introduce bias, flawed reasoning, and misleading conclusions.
- *Linguistic imprecision* – language branded by concepts that are vague and inexact where the lack of specificity, clarity of meaning, and confusion in

definition contributes to generalities and misinterpretation and weakens communication.

Managing uncertainty, uncertain information, and recognizing its impact is central to the methods used to study the environmental systems. At this point, it is essential to realize that (Marjolein et al. 2002):

- Not all uncertainties can be adequately addressed with existing methods and tools.
- Uncertainty is usually treated as a marginal issue, an additional physical variable, or as a mathematical artifact.
- Little indication is provided relative to the magnitude or sources of uncertainty, and measures of uncertainty can be difficult to understand.

Dealing effectively with uncertainty in the context of environmental remote sensing moves beyond the technical proficiencies of image processing methods and requires the integration and synthesis of new conceptual knowledge together with a willingness to think with incertitude (Brewer and Gross 2002). Given that environmental processes are subject to forces above internal feedbacks, chance anomalies and deviations are as much a part of the environmental system as those aspects we understand (Faucheux and Froger 1995; Reckhow 1994).

Connecting our discussion of uncertainty back to the question of environmental sensing gives definition to the trends that accent our need for a better understanding of system behavior and change. Here, six major foci dominate and help frame environmental remote sensing investigations:

1. The impact of land use transitions
2. The rate of expansion of land use systems
3. The scale-dependent nature of changes in land
4. The reversibility of changes to the land
5. The locality of land change impacts
6. The overlapping, impact reinforcing, and mitigating nature of changes in land use

## 2.7 The Role of Measurement

To measure objects at a distance encapsulates the science of remote sensing. Our ability to understand the complexities of the environment remotely and manage the realities imposed by uncertainty is only as good as the measurement permits. We are reminded that measurement is nothing more than the use of numbers to describe data according to a set of rules. As such, measurement facilitates objective communication of objects and their attributes that can be readily manipulated conceptually. The key to useful measurement involves assigning numbers to object, events, and individuals that aptly characterize them in a precise and meaningful way. In remote sensing, where our measurements are made at a distance, the objects we

sense do not readily lend themselves to numerical treatment. Rather, measurement builds from the isomorphic properties of our tool and the surfaces we seek to understand. From this relationship, insights are extended from one phenomenon (electromagnetic radiation) to the other (landscape) that creates an empirical situation, which can be expressed numerically.

Measurement is further informed by the distinction between the recorded observations and that which is analyzed (Amedeo and Golledge 1975). On the image, recorded observations represent a subset of the larger universe of observations that could potentially be made about the landscape. These recorded observations are derived from selected qualities that can be attributed to the objects we are interested in. Often this data is collected directly by measurement, but in the case of remote sensing, it must be translated into numerical terms before it can be realized as data. This phase of measurement is highly interpretative and directs attention at two problematic issues that are often overlooked:

1. The extent to which the numbers in the relationship are unique.
2. If the translation from the landscape (empirical situation) to its numerical definition retains the identity (uniqueness), order, and internal consistency of the original situation.

Observations of Earth's environments are further defined by the types of measurements made, all of which carry important implications for a remote sensing investigation that not only speaks to the overarching concern for data quality, but also to the larger question as to what the data actually reveal. In terms of types, we can explain a measurement as fundamental (primary) or derived. Primary measures explain measurements that record an existing property of an object. These define the distinguishing attributes of the object that separate it from other features in the scene. Derived measures are those, while expressed in numerical form, are defined on the basis of relationships between properties, such as a ratio or index. The rules used to produce a measure, therefore, affect its meaning, suggesting that the act of measurement is nontrivial since it establishes the basis of our understanding. In a digital world where files often appear as a "black box" read into software, this point is often lost, even though it impacts the simple things such as the stability of our measurements, their transferability from one situation to another, and calls to question concerns about uniqueness, comparability, representativeness, and utility. Each one is of significance; however, when combined they constrain what is observable, and ultimately, what becomes knowable. When considering measurement, it is also useful to make a clear distinction between facts and data. Such a distinction helps frame the problem and offers a more considered view of the remotely sensed images. For practical purposes, a fact may be defined as a statement about some fundamental quality or quantity that is true regardless of where and when it was made. Data, by contrast, are not facts and are valid only for the time, place, and condition under which the observation was made (Jordan and Miller 1996). As we know from experience, a pixel captured for a given geographic location with a digital value of 31 on June 19 is not likely to enjoy that same

value on August 8. To determine its “true” value, we would collect measures of that pixel over different times to predict its disposition; but even in this example, we realize that this number is an estimate and not a fact.

## 2.8 The Logic of Maybe

Despite the technological sophistication of remote sensing science, we can only observe limited aspects of and conditions with the environmental system. The measurements obtained through this technology are samples of dynamic processes influenced by the language of our perceptions as witnessed through the lens of contemporary logic. In the environmental sciences, that lens has been sharply focused on the concept of probability and the theory that reasoning with uncertainty can be accomplished by a set of tenants (rules) that impose order on measurement that illuminates the presence of chance in the situations we observe. Through this lens the realization of an event ( $E$ ) is defined by the proportion of times that event occurs relative to the total number of observations. A condition observed in the landscape, however, generally describes an outcome ( $A$ ) of an event ( $E$ ) having occurred. This connection between outcome and event can be expressed as the conditional probability where,

$$P\left(\frac{A}{E}\right) = \frac{P(A - E)}{P(B)}.$$

The outcome, while never an absolute, becomes understandable by both its probability and the uncertainty ( $U$ ), which we can express in simple terms as  $U = (1 - P)$ . Alternatively, we can apply mathematical expectation to “predict” the likelihood of event ( $E$ ) from the set of variables ( $X$ ) that we think explains its presence. According to this logic, the relationship takes the form:

$$E = a_1X_1 + a_2X_2 + \cdots + a_nX_n + \varepsilon.$$

In both examples, we are contending with estimations that attempt to manage uncertainty, place it into a more definable boundary, and resolve the problem by using a two-valued logic system in which our answers can be satisfied as either “true” or “false.” This form of estimation and statistical representation has guided our study of the environment for well over a 100 years. This are produced problem-solving schemas based on conceptualizations that reflect the way we think things are and encouraged acceptance of the premise that our observations of the environmental system made remotely appear as fact. Consequently, the models we develop are fundamentally probabilistic in nature and should invite alternative conceptualizations based on an “ontology” of flux. This mindset moves us past the rules of probability and encourages a perspective where there are no facts, where time is a

moving point, and reality is based on assumption. Through this lens, variability is an inescapable quality of what we observe; and through the application of approximate reasoning and critical thinking, problem-solving directs us to examine the “whole” of the problem as well as its components. The methods we devise to assist us attempt to assess the effects of change on the whole, as one or more variables cascade their influence through the system. From this alternate frame of reference, sensing the environment is not simply the problems and their solutions, but also the processes involved. Environmental sensing, therefore, is not the application of a technology but the fundamental skills of:

- Problem identification
- Process reasoning
- Questioning basic premises, conclusions, and data
- Adaptive problem-solving
- Explanation of the problem, the solution, and the procedures involved

When these skills are married to the remote sensing technology, they create a method and style of questioning that may culminate in a single solution or as an intermediate step in a larger investigation. These skills and the methods they define are examined in the chapters to follow.

## 2.9 Summary

Remote sensing is often explained with an emphasis on the technical details that underlie this technology. How and where the methods of remote sensing connect to the study of the environment tend to be abstracted from these general principles. In this chapter, the question of how to study the environment remotely was undertaken. The goal of this chapter was to introduce the environmental system and its process–response relationships to identify the topics and targets germane to remote sensing data collection. The patterns, processes, and scale of environmental behaviors and the relations that define human–environmental interaction must be resolvable within the context of remote sensing technology. What are we looking for and how do we look become central questions in the effective use of satellite-based remote sensing when applied in the study of Earth’s environments. By placing the environmental problem before the technology we can better appreciate the how the features of degradation, modification, and human alternation can be understood remotely and how the measurements obtained through our sensor systems can be employed to inform us of changes in the status of the environmental system and to improve our efforts to model environmental process in a proactive manner. In the chapter to follow, we will engage these intellectual activities and undertake a review of the sensor systems called upon to provide these measurements, and guide and support environmental solutions.

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