A CARTOGRAPHIC ANALYSIS OF ECOLOGICAL BOUNDARY SYMBOLOGY

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ABSTRACT

Maps are used often in ecological boundary analysis. However, there is a lack of research concerning the relationship between ecological boundary research and the cartography of ecological boundaries. This multidisciplinary study analyzes the ecology, cartography, and philosophy of ecological boundaries. Background literature in these fields is reviewed to establish a holistic view of ecological boundaries. Ecological boundaries are observed in the Thunder Bay Centennial Botanical Conservatory. Observations are analyzed in a cartographic context using a new tool, the Ecological Boundary Symbology Matrix. The symbology matrix is a flexible research tool used for cartographic analysis. Guidelines for ecological boundary symbology are presented. A map series is constructed that incorporates strategies presented in the guidelines and reflects findings of the symbology matrix. Observations and matrix analysis established that ecological boundaries interact with a number of phenomena, described in this study as 'modes', which may not be limited by the boundary in the same way. The extent to which a boundary limits its modes depends on the spatial characteristics of that boundary and the characteristics of the modes. This means that ecological boundaries can be mapped in greater detail based on boundary-mode characteristics. New boundary terms based on observed boundary characteristics are presented including: definite boundary, indefinite boundary, perforated boundary, interface boundary, and medial boundary.

Key words: ecological boundary, boundaries, cartography, symbology.

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Finally, special thanks to Dustin. Thank you for believing in me during the moments when I failed to believe in myself.

DEDICATION

Mom, thank you for the hours you spent editing as well as your valuable input and suggestions. Thanks for always keeping your eyes open for information that might have contributed to my research. Thanks for cooking supper when I was too swamped to make myself a proper meal, and for the many café mochas and chai tea lattes that we shared during the course of this demanding time.

Mom, I dedicate my thesis to you.

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1.1 Introduction

This thesis applies cartographic theory and design to ecological boundary symbols. I argue that mapping ecological boundaries requires the cartographic design process to portray boundaries as accurately as possible. I also describe the necessity of understanding boundary properties, how this translates to map symbology, and ensuring that resulting maps are accurate and reliable. This thesis operates around the central goal of determining the most appropriate cartographic approach to symbolizing and mapping ecological boundaries.

Maps are one of the more versatile tools ever invented. We rely on them as reference guides and decision-making aids for countless reasons. Like consulting a dictionary, we look at maps seeking accurate and reliable information about almost anything about the world. Maps convey their information visually through symbology; everything in the real world is represented symbolically on maps. It is through this visual language that maps convey their information. Symbol design is a fundamental component of map making, as such, it is the map maker's job to choose symbols with the utmost care and consideration during map design production.

In a broad sense, maps can offer the field of ecology two fundamental tools: visualization of complex ecological concepts and systems, and cartographic analysis and investigation into the spatial nature of ecological phenomena. Maps afford researchers the opportunity to "see" their ecological data in a spatial context. Spatializing data can make ecological patterns and relationships visually apparent and generate further observation and measurement. For example, mapping the spatial distribution of vegetation on the landscape creates a visual representation of its geographic extent and mapping the extent of the vegetation means mapping vegetation boundaries. This information can help researchers determine, among other things, why a specific vegetation type is found in some geographic locations and not others, or what relationships might exist between specific vegetation communities and climate, soil conditions, animal species, and so on. This in-depth spatial view of the ecological data can provide extensive comprehension of these data and contribute to a better understanding of the aforementioned ecological relationships. It can also help planners make decisions regarding ecological management and protection.

Often, maps constructed in an ecological context focus on ecological extent of contrasting ecological units (Freeman & Buck, 2000; Miller & Pierce, 1995). By association this means that they are interested in and mapping ecological boundaries. However, the implications of the symbols chosen to represent those boundaries may not be considered in the mapping process. Sometimes, symbols are chosen unconsciously – not for what the symbol may imply but for the familiarity as a common boundary symbol. For example, a boundary between two vegetation types may be difficult to pinpoint through observation because it is very subtle and the transition from one vegetation type to the other occurs gradually over a large geographic area. However, an inexperienced map maker portrays that subtle transitional boundary as a solid thin line, a common boundary symbol on many maps, because the mapper uses this symbol often to represent other boundaries, such as political boundaries. In this example, the ecological boundary was not consciously mapped to reflect its real world characteristics: the boundary is transitional and spans a large area. Perhaps this boundary would have been better represented as a broad and gradual gradient with the symbol of one vegetation type transitioning with the symbol of another. Instead, the map maker chose (consciously or unconsciously) a boundary symbol that is commonly used and familiar to the mapper as a boundary symbol. It is, therefore, not an accurate portrayal of the real world boundary, nor is the map helpful as a research tool because of its imprecision because the thin boundary line does not accurately convey to the map reader what type of boundary is out there in the real world.

Work by Freeman and Buck (2000) represents a similar example (see **Figure 1.1**). They created an urban ecological land cover map for Dunedin, New Zealand using geographic information system (GIS) software. They acknowledge that land cover boundaries, especially between natural or semi-natural land cover types, are most often transitional without a clear definition. Freeman and Buck identify this as a problem area of their research, especially in boundary detection, but they do not explicitly address how this relates to mapping the land cover classes. Although, the final map depicts the land cover as discrete parcels with thin solid black lines defining the limits between adjacent land cover types. This symbol choice may give the map reader a false impression that all the land cover classes in the real world are separated by abrupt boundaries, like the map symbol suggests. Perhaps Freeman and Buck could have addressed the problem they identified regarding gradual boundaries by using different symbols for gradual and abrupt boundaries. For example, gradual land cover boundaries could be represented using a colour or symbol gradient while abrupt boundaries could be thin solid lines. This would let the map reader know that some boundaries are gradual while other boundaries are abrupt.

The choice of the boundary symbol and lack of a discussion in the corresponding literature regarding why this solid line symbol was chosen (despite the researchers describing some of the land cover boundaries as gradual) suggests a disconnection between their understanding of the real world phenomenon and how they represent it on the map. There could be a number of possible reasons why the boundary symbol does not effectively represent the real world phenomenon. One explanation could be that the map maker lacked a cartographic background. Another explanation could be that the GIS software used to make the map was not flexible enough to create multiple boundary symbols; or that the GIS map maker did not have enough experience using the software and therefore did not know how to create multiple symbols. While there are many potential reasons, many of the reasons likely stem from a lack of cartographic design principles. For example, if a map maker is aware of how symbol choices can influence the map reader's interpretation of map information, then the map maker would likely do their best to use symbols that appropriately represent the real world phenomenon, regardless of software limitations or their ability to use the software.

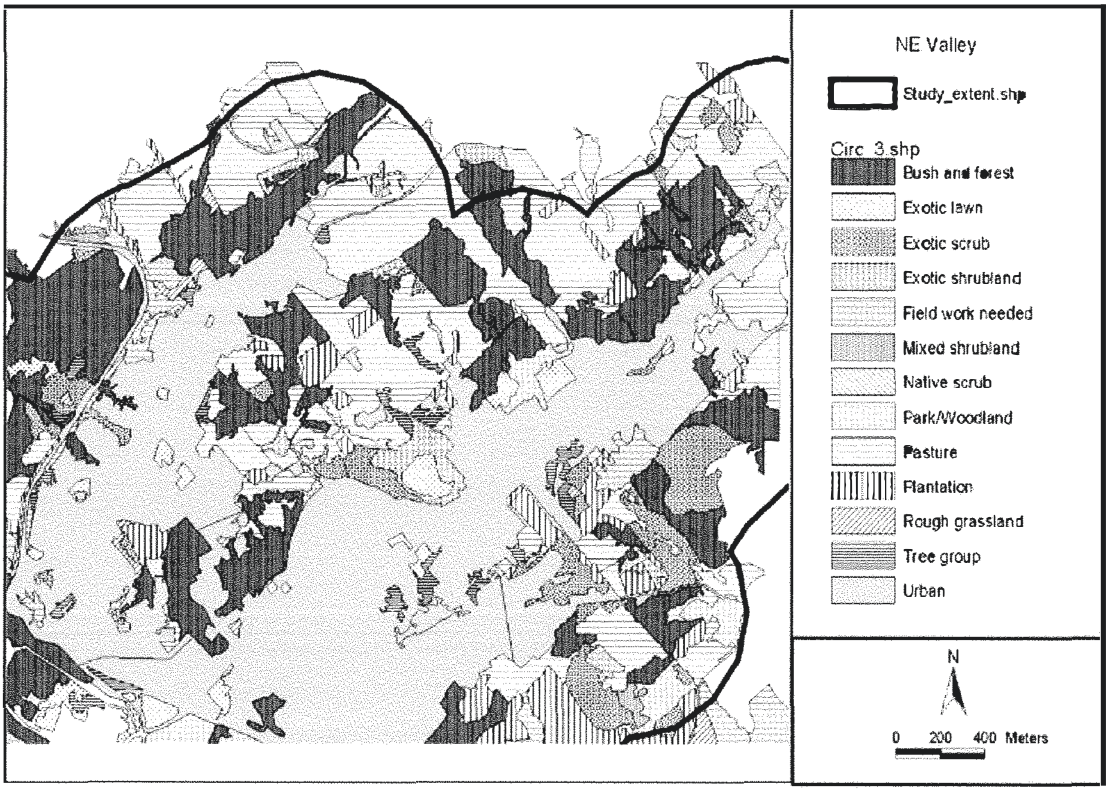


Figure 1.1. An ecological land cover map of an urban area from Freeman and Buck (2000). In the corresponding literature, Freeman and Buck acknowledge that natural or semi-natural land cover classes often have gradual boundaries. They identify this as a problem area in their research but they do not deliberately describe how they attempt to address it. However, on the map they constructed (above) all of the land cover classes are separated by thin black lines.

Many researchers may do themselves and their research a disservice when mapping their ecological data by choosing symbols that poorly represent boundaries because they lack the cartographic skills and knowledge necessary to make informed mapping choices. This lack of expertise is often compounded by an overreliance on pre-programmed default symbol selections in mapping or geospatial software (e.g. a GIS software package). This dependence means the mapper may decide to use a default boundary symbol provided by the mapping software (and again, it is most often a solid line), or the map maker chooses from a small selection of boundary symbols offered in the mapping software that may or may not reflect the boundary's real world properties more accurately. As a result, further analytical opportunities that maps, as visual aids, offer may be missed.

While ecology has made great strides in recent decades identifying, developing, and understanding the nature of ecological boundaries on the landscape, maps constructed using the data may not be utilized to their greatest potential due to a lack of cartographic awareness. Mappers who do not depict ecological boundaries according to boundary properties may not contribute to ecological research as they had intended.

1.2 Defining Maps: Constructions of Concepts

Maps may be broadly described as cultural texts communicating information through visual or graphic representations of spatial phenomena (Harley, 1989). This all-encompassing definition is necessary to describe the many forms through which spatial information can be communicated. Each map is the creative output of its map maker and it is constructed for a specific user. It also has a unique data set and symbology dedicated to portraying these data. As such, it is reasonable to suggest that no two maps are completely alike. Furthermore, not all maps are created equal or are even of the same quality. Map veracity, or truthfulness, is reliant on data quality, the symbology used, the cartographer's skill and knowledge, and so on.

Maps are constructed using a cartographic creative process and are ultimately the product of the mapper's conscious and unconscious decisions throughout the mapping process (Kitchin & Dodge, 2007). Shortcomings within the map making process, at any stage, can negatively impact the veracity and effectiveness of a map (Kuchler, 1956). Despite this, maps are often regarded as unbiased or neutral information sources by the majority of map readers, possibly because some maps are the products of scientific research and data collection. Contesting these often unfounded views of map neutrality are a number of respected cartographers including Harley (1989), Wood and Fels (2008), and Kitchin and Dodge (2007). These cartographers argue that a map is a compilation of signs and symbols rather than mirror images of real world phenomena. Furthermore, some of these cartographers also believe that maps are far too ideological to ever be considered truly neutral or unbiased (Harley, 1989; Wood & Fels, 2009). I agree that maps are conceptual creations comprised of symbology, and I believe it takes careful planning and a cartographic awareness to construct maps that are as unbiased as they possibly can be.

1.3 Mapping Nature

The common perception that maps are neutral and completely trustworthy is especially prevalent regarding maps of natural subjects, such as wilderness, vegetation, topography, sea ice extent, and so on. Wood and Fels (2009) focus on this misconception in their book, *The Nature of Maps: Cartographic Constructions of the Natural World*, where they argue that maps of natural subjects are not literally made of wildlife, vegetation, lakes, and other natural features. Instead, these maps are composed of symbols that *represent* natural things. To map the natural world (as with mapping anything), Wood and Fels say the mapper must first deconstruct the real world phenomena, attempt to understand them, and then put the information together in a cartographic form. They believe that this process is based on Western reductionist methodology, which attempts to understand a complex natural system by breaking it down into smaller, more recognizable parts, then reconstructing it in a comprehensible way.

In my thesis, mapping ecological boundaries exists within the realm of mapping "natural" subjects. This is because ecological boundaries are considered natural elements on the landscape. I aim to increase awareness of ecological boundary research, both ecologically and cartographically speaking. I seek to marry these two fields of research, which are intrinsically connected, but I believe that this relationship is often neglected in the process of creating maps. I discuss how ecological boundaries have been represented on maps in the past and suggest some alternatives, while remaining conscious of the power and the misconceptions associated with mapping nature.

1.4 The Importance of Cartographic Theory and Design

A lack of background knowledge in cartographic theory and the design process can undermine the veracity of maps. Much has been discussed recently in the cartographic community regarding a noticeable and disconcerting shift away from the practice of cartography in map making (Cassettari, 2007). Cartography is the art and study of maps and, until recently, only cartographers were skilled enough to make good quality maps. However, GIS has drastically changed the way maps are made and who can make them. Anyone with a computer and GIS software can now make maps and no cartographic expertise is required. Thus, map making is hardly a cartographic endeavour anymore.

Unfortunately, the practice of cartography and the quality of maps has been impaired with the deluge of GIS mappers (Cassettari, 2007).

As mentioned earlier, lending to this concern is the limited selection of pre-set symbols available to map makers in GIS mapping software (Schnabel, 2007). If mappers do not wish to rely on pre-designed symbols, they must create their own using graphic design programs, like Adobe Illustrator or CorelDraw, or program symbols into GIS software using software extensions. Both of these options are time consuming and require an intermediate understanding of symbol design and the ability to operate the additional software.

To successfully construct good quality maps, especially maps that seek to depict data in new ways, a mapper cannot rely solely on his or her data source and the default, or limited, settings in mapping software. A foundation based on cartographic theory and design is essential to ensuring information is mapped concisely and communicated effectively (Cassettari, 2007; Forrest, 1999). For these reasons, mappers require both practical and theoretical cartographic knowledge to represent and symbolize real world spatial data when using mapping software or graphic design software.

In cartography, the map design process consists of five steps (Slocum, McMaster, Kessler, & Howard, 2005). The process begins before a map is constructed with three planning steps: first, the mapper considers what the spatial phenomena look like in the real world; second, the purpose and intended user of the map is determined; third, the mapper collects appropriate data. Once data are collected, the fourth step is map construction. The fifth, and final step, includes gathering feedback from the intended map users to determine if the map successfully serves its purpose. If the map users recommend changes to the map, then revisions should be made accordingly (Slocum et al., 2005). These five steps facilitate a thorough and systematic approach to constructing maps and may be applied to all mappable subjects, including ecological boundaries.

1.5 Ecological Boundaries

Boundaries are truly thought-provoking phenomena and have long been studied by such great thinkers as Leonardo da Vinci, who contemplated the fundamental nature of the boundary between water and air (Varzi, 2000). Understandably, boundaries generate interesting philosophical and scientific questions that have, thus far, been difficult to answer. What are they exactly? Are they an entity separate from whatever they bind? Is the boundary between water and air composed of the two elements, or of neither? Are there two boundaries next to each other? Is one side bound by the other?

A boundary is generally defined as a zone where change is greatest between adjacent locations (Cadenasso, Pickett, Weathers, & Jones, 2003; Fagan, Fortin, & Soykan, 2003; Fortin et al., 2000). In cartography, a boundary is considered a spatial feature, or structure, on the landscape. This could be a political boundary, a park boundary, a lakeshore, or the edge of a species range, to list a few examples. In ecological terms, a boundary is a key feature on the landscape marking the limit, or edge, of a process or entity. That parcel of land (or patch) and its boundary may neighbour many other parcels on the landscape creating a patchwork, or mosaic effect. Internal structure, composition, and ecological maturity of a parcel of land often distinguish what is on one side of the boundary from whatever is on the other side.

A great deal of variation exists among ecological boundary features on the landscape. Ecological boundaries may be structurally abrupt, or gradual and less apparent. The contents within the boundary may be completely or partially enclosed by it. Boundaries may be determined by topography or by environmental processes. They may be physical or areal (perceived) features on the landscape. They are natural or artificial, occur at any geographical extent from fine to broad, and can exist across terrestrial and aquatic landscapes. Because of this diversity in boundary types, a number of terms exist in scientific literature to describe ecological boundaries. Some examples of these terms include ecotones, gradients, clines, interfaces, edges, and transition zones.

Integrating this knowledge of ecological boundaries from an ecological context into the cartographic design process is crucial to the success of constructing reliable maps. It is then possible that carefully constructed maps of ecological boundaries may help answer important questions, confirm possible relationships, and aid in further ecological research.

1.6 Centennial Botanical Conservatory: Fieldwork and Case Study

It was necessary to observe and interpret boundaries in a controlled environment to better understand the structure and characteristics of ecological boundaries. The Centennial Botanical Conservatory in Thunder Bay, Ontario, was chosen as the fieldwork site because it offers a number of ecological boundaries to examine. Furthermore, these Conservatory boundaries can act as analogues for real world boundaries on a landscape. An example of such a boundary would be the glass roof and walls of the Conservatory which could represent sea or lake ice and its boundary characteristics and properties. A real world landscape was not used in this study because it is beyond the scope of the field methods of this specific project. Using the closed and microcosmic environment of the Conservatory allowed me to focus on a select number of ecological boundaries and how symbology could be applied on maps. Other benefits to choosing this location include its accessibility, its hours of operation, and cost-effectiveness of doing research locally.

The Conservatory is a cold climate conservatory built in the late 1960s that houses sub-tropical, tropical, and arid plant species in permanent, semi-permanent, and seasonal exhibits (City of Thunder Bay, 2010). Many of the plant species of the Conservatory could not survive the seasonal extremes of Northwestern Ontario, most notably the winter season, without the protection of the Conservatory. The building is primarily a glass structure (exterior walls, roof, and interior walls) containing three main areas. Permanent (planted) and semi-permanent (planted or potted) tropical vegetation are located in a large, central atrium. Notable features within the atrium include a pond, a bridge, a large tiered waterfall, a nine-foot tall terraced garden, benches, and cement walkways.

A smaller sunroom in the western wing, off the atrium, houses arid and semi-arid permanent or potted cacti and other succulents. A second sunroom of similar size is located in the eastern wing. It serves as a "seasonal" room for temporary plants and exhibits that are culturally appropriate for the time of year. During field observations in December 2008 and January 2009, a Christmas theme occupied the seasonal room and all the plants, poinsettias (*Euphorbia pulcherrima*), were temporarily potted.

The atrium is separated from these two sunrooms by glass walls and wooden doors. Sprinkler and heating systems run throughout the Conservatory and the climate varies slightly from room to room, depending on vegetation requirements. Areas within the Conservatory that are not open to the public are not included in this study. This is primarily because these areas were restricted or were not relevant to the premise of my research.

1.7 Research Objectives

In this thesis I provide an appropriate symbology to depict ecological boundaries on maps, when they are important to the purpose of the map. The techniques used to determine the map symbols in this study required the use of a theoretical case study of ecological boundaries, construction of a research matrix, and symbol development using research matrices, graphic design software, and cartographic theory and design. Guidelines, or best practices, are provided based on cartographic analysis. To test the results of my investigation, these new boundary symbols are applied to maps of the Conservatory to demonstrate their utility.

The practical purpose of this thesis is to present a collection of carefully constructed ecological boundary symbols, and indicate the cartographic knowledge required to use them. These symbols are intended to demonstrate to cartographers, mappers, and ecologists that ecological boundaries may be depicted in detail according to their characteristics and properties showing what they limit, partially limit, or do not limit at all. As such, this thesis demonstrates a new approach to mapping ecological boundaries. I argue that this approach is necessary for detailed studies of these features due largely to the fact that maps are powerful information tools often consulted for decision-making purposes. Providing more detail about the ecological nature of boundaries on maps will serve to enhance this tool for researchers, which, in turn, has the potential to facilitate a better understanding of the ecology of the mapped areas. These enhanced maps may also prove useful for decision-makers in the planning stages of ecological resource management.

I will also argue that mapping ecological boundaries in detail requires the construction of several maps, or overlays, of the same area of interest. That is to say that a single map of ecological boundary typically cannot communicate its contents as effectively as multiple maps because of the highly selective portrayal of the data (Rossum & Lavin, 2000), or there is too much information one map

(Maki & Kalliola, 2000). In support of this strategy, Monmonier (1991) suggests that a single map often represents only one of an indefinitely larger number of maps constructed for the same purpose, using the same data. I believe that constructing a series of maps depicting a single ecological boundary is necessary to ensure that the characteristics and properties of said boundary are discernable and that symbols are easily identifiable, simple to differentiate, and are communicated effectively.

I will conclude my thesis with suggestions for future research in ecological boundaries and their cartographic symbols based on boundary properties. While this thesis investigates a number of ecological boundaries in the case study, many more remain uninvestigated and open for further research.

1.8 Summary

This chapter introduced important aspects of mapping ecological boundaries and the complexities of mapping natural subjects to the reader. I argued that a background in cartographic knowledge and design is essential when symbolizing and mapping ecological boundaries. I have also indicated that the success of cartographic design relies on the map maker's level of knowledge regarding the properties and characteristics of ecological boundaries.

Researchers can gain and communicate meaningful information from maps constructed using their ecological data. In order to relay effectively the properties and characteristics of the ecological data through symbology, specifically ecological boundaries, it is first necessary to understand the properties and characteristics of those data, as well as possess a sound knowledge of cartographic theory and design. Finally, I introduced the Centennial Botanical Conservatory chosen as the fieldwork location where ecological boundaries are observed.

The purpose of Chapter 2 is to provide a philosophical investigation into the nature of ecological boundaries studied in ecology. In Chapter 3, I explore the concept of boundaries within cartography, discuss challenges, find similarities, and attempt to piece together the multidisciplinary nature of the cartography of ecological boundaries. Chapter 4 describes the methodology followed in this thesis, including fieldwork at the Conservatory; the boundary symbology matrix; boundary symbology design and construction; and boundary symbol guidelines. Chapter 5 presents the results of my research, including the introduction of new terms and definitions, extensions of existing terms and definitions; results of matrix work; the symbology guidelines; and resulting maps. Last, Chapter 6 discusses results, summarizes the conclusions of this research, and recommends possibilities for future research.

Chapter Two: An Ecological and Philosophical Review of Boundaries

2.1 Introduction

Mapping ecological boundaries requires a familiarity with mapping software, and cartographic expertise. However, I argue that mapping ecological boundaries also requires a sound knowledge of the ecological nature of those boundaries to communicate them effectively. Therefore, expressing ecological boundaries on maps becomes a multidisciplinary task combining mapping software literacy, cartographic skill and graphic design, as well as some level of understanding of the ecological nature of the boundaries.

This chapter, Chapter 2, and the next chapter, review the background literature relevant to my research objectives. Much like the overall investigation of my thesis, this literature review bridges multiple disciplines including ecology, landscape ecology, philosophy, cartography, and geographic information systems. Chapter 2 explores the theoretical and philosophic characteristics of ecological boundaries and boundary delineation. Chapter 3 reviews the portrayal of boundaries on modern ecological maps. In Chapter 4, I combine all knowledge to provide an in-depth explanation of a resulting cartographic methodology that I argue should be used when making maps of ecological boundaries.

2.2 Ecological Boundaries

While ecological boundaries are routinely used in many subdisciplines of ecology, including landscape ecology, macroecology, and biogeography, boundary research, from an ecological perspective, largely remains uncharted territory. Limited by the scope of this thesis, I focus on the significance of ecological boundaries in landscape ecology. Within landscape ecology, landscape components such as ecological boundaries are discussed and defined in the literature. Variation exists among definitions or characterizations of concepts in landscape ecology due to a lack of knowledge or research, and this will be explored here.

Landscape ecology research focuses on the spatial structure of the landscape, patterns that exist across it, and the ecological processes that occur across the land (Kent, 2007; Pickett & Cadenasso, 1995). Pickett and Cadenasso (1995) describe landscapes as ecological systems that operate on a large geographical extent, often measured in kilometres (or miles). Furthermore, landscape spatial structure, including ecological boundaries, may have a functional role in organizing ecological interactions and the formation of ecoregions on the land (Borcard, Legendre, Avois-Jacquet, & Tuomisto, 2004; Ries, Fletcher Jr., Battin, & Sisk, 2004). Landscape ecology is an important area of research for conservation and environmental management (Christensen et al., 1996). Some argue that managing or conserving areas on the landscape is limited by a lack of information about ecological boundaries and their role in landscape systems (Ries et al., 2004), insufficient information of biological diversity across the landscape, and ignorance of how ecological systems function and interact (Christensen et al., 1996). Additionally, variation exists around some fundamental terms and definitions in landscape ecology that suggest a lack of standards within the field (Omernik, 2004; Jax, 2006; Martin, De Pablo, & De Agar, 2006). Three fundamental landscape ecology terms discussed here are *ecoregion*, *mosaic*, and *patch*. The following ecological boundary terms are also discussed: *ecotone*, *riparian zones*, *edges*, *gradients*, *transition zones*, and *borders*.

An *ecoregion* is defined by Omernik (2004) as an ecological region sharing interrelatedness between its human, biotic, abiotic, terrestrial, and aquatic parts on the landscape. He argues that a lack of standards exists for the definition of an ecoregion, which therefore undermines efforts to conserve or manage ecologically significant environments. Omernik describes how this absence of commonality affects the size and shape of ecoregions with even the slightest changes among criteria. Consequently, ecoregion boundaries are affected by these changes. **Figure 2.1** is from Rossum and Lavin (2000), who compiled fifty variations of the geographic extent of the Great Plains onto a single map to illustrate the spatial variation of the ecoregion depending on the criteria, or variables, used to define and map it. Omernik argues that ecoregion boundaries differ depending on the variables used to map them (e.g. soil, vegetation type, etc.), boundaries are often mapped from a single variable, and that this variable is frequently based on a mapper's area of expertise. As an alternative, Omernik believes ecoregions should be delineated by considering all their ecological aspects. Furthermore, he argues that the depiction of ecoregion boundaries as thin lines on a map is problematic because these boundaries are areas of gradual change across the landscape; rarely are boundaries abrupt enough to be depicted as a line on a map.

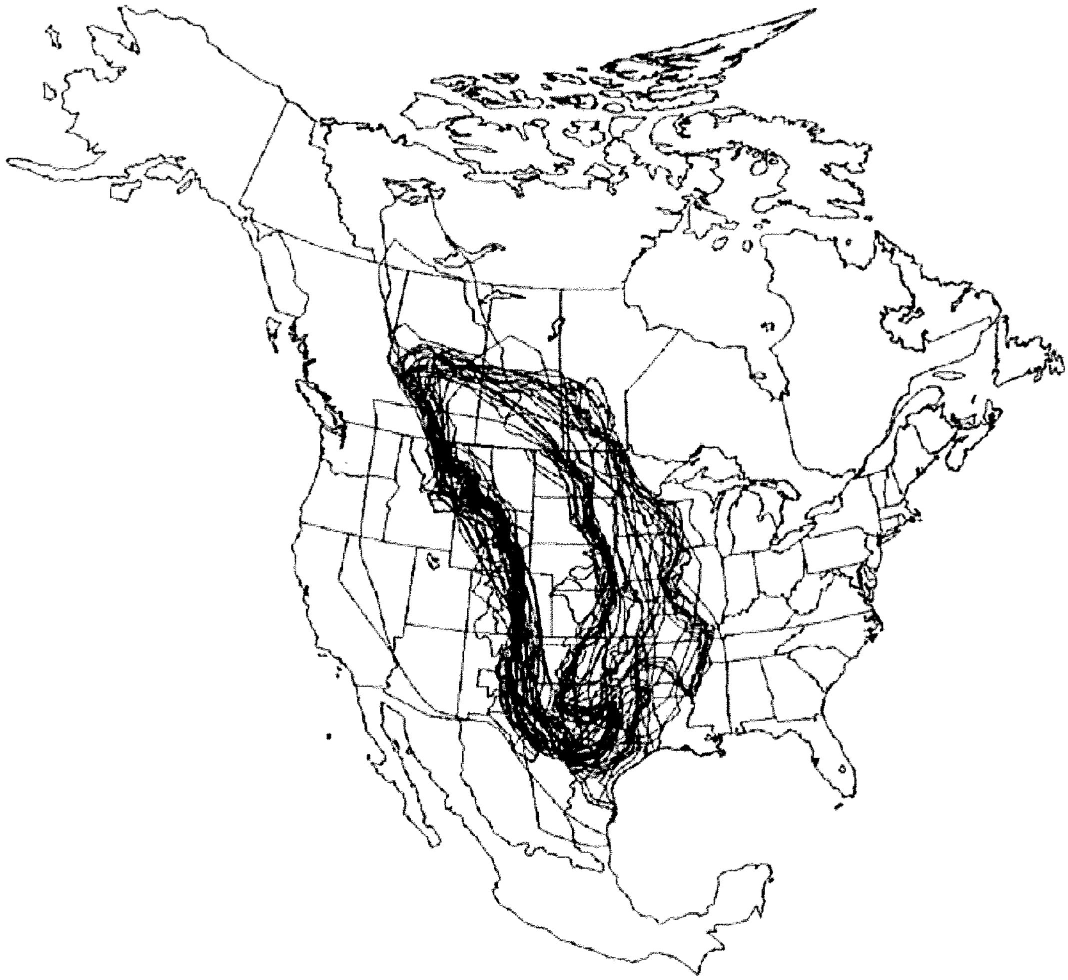


Figure 2.1. A map depicting 50 variations of the Great Plain ecoregion boundary symbolized as a series of thin black lines from Rossum & Lavin (2000).

In landscape ecology, a *mosaic* refers to a patchwork effect created on the landscape. It is created by the assortment of ecologically distinct *patches* covering the landscape caused by the interactions between adjacent patches occurring across their boundaries (Martin et al., 2006). Pickett and Cadenasso (1995), argue that boundaries between patches in the mosaic result from natural and anthropogenic (human-caused) disturbances on the land. These disturbances and land-use practices change the landscape, which Martin et al. argues causes boundary change as well. Therefore, they suggest that resource management and planning should consider boundaries between patches and across the mosaic, rather than basing decisions on land uses alone.

According to Jax (2006), part of what defines one ecologically distinct patch from another is the boundary between them. Jax argues that two types of boundaries exist, determined by either topography, or by processes and functions on the land. He defines *topographic boundaries* as discrete units, while boundaries created through processes, what he calls *functional boundaries*, are gradual. Furthermore, he argues that boundaries delineated by spatial discontinuities (topography), or by processes, do not coincide easily.

Yarrow and Marin (2007) suggest that the *ecological boundary* has recently become an inclusive concept that replaces previous concepts such as *ecotone*, *ecocline*, and *edge*. They describe boundaries as zones of ecological flow and interaction or control points; boundaries are also related to the ecological concepts of edges, corridors, and borders, of patches in a mosaic. Yarrow and Marin argue that using a single boundary concept can be detrimental when trying to understand ecological boundaries and their role in the flow of energy, materials, and organisms because boundaries are complex.

To describe the concept of an *ecotone*, Yarrow and Marin (2007), and Kent et al. (Kent, Gill, Weaver, & Armitage, 1997) review background literature from Livingston (1903) who first wrote about a "zone of tension" between vegetation communities he studied in Michigan. Clements (1905) later used the term *ecotone* to describe these zones. The concept further evolved when Weaver and Clements (1929) described an ecotone as a transitional or mixed community between two communities. Yarrow and Marin (2007) identify that the common connection between these early ecotone concepts was that the concepts involved a noticeable change in composition of vegetation species from one area to another.

In 1936, Clements introduced the concept of the *ecocline* which, like the ecotone, represented a zone of change between one vegetation community and the next. Unlike the ecotone, which is a noticeable or abrupt transition, the ecocline occurs at broader geographical extent. Yarrow and Marin (2007) note that the ecocline concept is rarely used outside of plant ecology research.

The *edge* concept, like the ecotone, describes an abrupt change between two communities or patches (Yarrow & Marin, 2007). In the edge concept, a boundary is comprised of two edges, one from each patch, on either side of the boundary. Interestingly, external conditions surrounding the patch prevent edges from having the same ecological composition as patch interiors (Yarrow & Marin, 2007). For example, wind may be a stronger ecological influence at the edge of a forest stand than in the centre of the stand where it is generally less influential due to many obstructions, like trees. Similarly, Ries et al. (2004) describe edges as "ecologically distinct" (p. 491) from the interior of the patch that often offer less favourable conditions to many of the species within a patch. Furthermore, they suggest that understanding edges is important to landscape management and conservation.

Scale is discussed in the background literature as an important aspect of studying ecological boundaries (Christensen et al., 1996; Edmunds & Bruno, 1996; Dungan et al., 2002; Gustafson, 1998; Kent, 2007). In fact, Levin (1992) identifies scale as one of the fundamental issues in ecological research. Perhaps the most important reason for this, as Gustafson (1998) suggests, is that ecological systems are spatially heterogeneous and can vary in complexity over space and time. Similarly, Christensen et al. (1996) warn that ecological processes operate over more than one temporal and spatial scale; therefore, no single scale or timeframe is most appropriate for management. They argue that widespread ignorance of ecosystem dynamics exists, and could be a major challenge to management because of the changes which occur over different scales of time and space. Any study of landscape patterns, such as spatial heterogeneity or patch-level processes, are scale-dependent on grain (resolution) and extent (geographic scale), but multi-scale analysis is the most effective method of resource management on a landscape (Kent, 2007).

As the literature suggests, ecological boundaries are a key element in landscape ecology and are therefore important from a mapping perspective. After all, they have a functional role on the landscape as places of ecological interactions, limitations, and energy flow (Fortin et al., 2000; Yarrow & Marin, 2007). This is further complicated as they are constantly undergoing change on both a temporal and spatial scale (Martin et al., 2006), and no single scale is the appropriate scale at which to study or map (Christensen et al., 1996). Perhaps this is why Yarrow and Marin (2007) warn that a single boundary concept is detrimental to landscape ecology. As Omernik (2004) describes and Yarrow and Marin demonstrate in **Figure 2.1**, the same ecological boundary often differs depending on the variable used to delineate and map it. The significance of this background literature is this: the challenge anyone mapping ecological boundaries is that they must find cartographic ways, to account for and depict the complex characteristics that ecological boundaries possess.

2.2.1 Ecological Boundary Theoretical Work

Delineating ecological boundaries can be a challenge and there is extensive research into frameworks, classifications, and theories associated with determining ecological boundaries (Belnap, Hawkes, & Firestone, 2003; Cadenasso, Pickett, Weathers, Bell, et al., 2003a; Cadenasso, Picket, Weathers, & Jones, 2003b; Strayer, Power, Fagan, Pickett, & Belnap, 2003).

According to Cadenasso et al. (2003a; 2003b), ecological boundaries are three-dimensional transitional zones that can vary in width (which reflects the severity of the gradient) and the gradient of the feature, creating a contrast that is more severe in the boundary than in the surrounding areas. They introduce a framework that they say covers all boundary types by focusing on the flow of energy, materials, information, and organisms across a landscape. The framework pays particular attention to differences between patches, direction of the flow, and the structural nature of the boundary. Furthermore, the tools outlined in their study can be used in boundary studies spanning multiple scales. Cadenasso et al. (2003a; 2003b) believe future research into ecological boundaries should include a characterization of the criteria that control boundary features, links between boundary structure and function, temporal variability that may occur in the determination of boundary function and structure, and a comparison of anthropogenic boundaries with other boundary types. However, they do not discuss the importance of depicting boundaries on maps based on their characteristics.

Strayer et al. (2003) furthered the research of Cadenasso et al. (2003) by developing a classification system that investigates the origin of a boundary, how it is maintained, its spatial structure and function, and its change over a temporal scale. They stress that the term *boundary* may have different meanings depending on the context, and that researchers should define how they use it within their research.

Belnap et al. (2003) conducted a small extent examination of soil-atmosphere and soil-root boundaries with the intention of comparing these small-scale boundaries at the landscape level boundaries. They suggest their investigation of small-scale boundaries is analogous to landscape patch boundaries discussed by Cadenasso et al. (2003b). Belnap et al. recognize that ecological boundaries exist at any scale. However, they also recognize that a boundary at one scale may not be visible at another scale. Despite this, they argue that their study of small-scale systems could advance boundary theory within ecology and that fundamental principles learned through small extent study could be tested further on boundary systems at greater scales.

2.2.2 Philosophic Perspectives

Interestingly, boundaries are also discussed in the philosophical literature. For instance, according to Varzi (1997), boundaries are the beginning and the end of most things. Furthermore, Smith (1997) believes that boundaries do not exist without something for boundaries to bind, enclose, or obstruct. Varzi also believes that gaps exist in the philosophical literature regarding boundaries because questions of their theoretical nature have not been easy to answer. He notes that the philosophy behind boundaries has long been on the minds of great thinkers like Leonardo da Vinci who contemplated the fundamental nature of the boundary between air and water (Varzi, 1997).

Varzi (1997) proposes that boundaries could be one of two types: *fiat* or *bona fide* (see similar work by Strayer et al., 2003). The first type, fiat boundaries, Smith (2001) defines as objective and imposed through human demarcation. These boundaries are perceived in the mind, by cognition, and can differ from natural, bona fide, boundaries. Fiat boundaries are generally anthropogenic, well defined, and closed (Smith, 1995). An example of a fiat boundary is the provincial border of the province of Saskatchewan. View any conventional map of the province, political or otherwise, and this boundary is superimposed on the land with (unnaturally) straight borders and angled corners irrespective of any natural features on the landscape, such as rivers or shorelines. Subsequently, fiat boundaries also give rise to fiat objects, such as the province of Saskatchewan itself (Smith & Varzi, 2000; Smith, 2001). The equator and the international dateline are also examples of fiat boundaries.

Smith (2001) defines bona fide boundaries as physical boundaries, independent of human demarcation. For example, the shoreline of Baffin Island in the Canadian Archipelago is a bona fide boundary where the boundary between water and land lays along the island's shoreline.

In addition, fiat and bona fide boundaries can also exist as portions of the same boundary (Smith & Varzi, 2000; Smith, 2001). The boundary limits of Hudson Bay, for example, is a fiat-bona fide boundary combination because the southern extent of the bay is bound by a shoreline, a bona fide boundary, while the northern limit is merely open ocean with a human-delineated boundary that separates it from other water bodies, like Foxe Basin and Hudson Strait (International Hydrographic Organization, 1953).

In the ecological literature, similar boundary theory work by Strayer et al. (2003) describe boundaries as *investigative* or *tangible* boundaries. Investigative boundaries, like fiat boundaries, originate in the mind. Tangible boundaries are described as natural boundaries. Realistically, ecological boundaries are often a combination of tangible and investigative boundaries. Strayer et al. believe that many ecologists see boundaries as investigative boundaries or as "lines on a map drawn by a scientist that may or may not correspond with any obvious physical discontinuities in nature" and that the "arbitrary placement of boundaries for the convenience of a scientific study is a central tool in ecology" (p. 723). However, Strayer et al. say there are also ecologists that believe tangible boundaries can be identified in nature. Because of the fundamental differences between tangible boundaries and investigative boundaries, Strayer et al. emphasize the importance of identifying how the term *boundary* is used in future ecological boundaries research.

2.2.3 Ecological Boundary Delineation

Boundary delineation is an important precursor to mapping ecological boundaries. While this thesis does not use boundary delineation in its methodology, a strong understanding of delineation techniques and theories are required to better understand the scope of ecological boundaries and how to accurately portray them cartographically.

A number of delineation methods are used to locate ecological boundaries (Fagan et al., 2003; Fortin et al., 2000). Fortin et al. (2000) assert that data types used in the delineation process, either quantitative or qualitative, or both, determine which boundary delineation method are utilized. Fagan et al. (2003) suggest that a research study area (geographically speaking) must include the area within a boundary, as well as adjacent patches, to ensure adequate data for the boundary delineation process. The most common methods are largely based on statistical analysis including moving split window, wombling techniques, etc (Fagan et al., 2003; Kent et al., 2006). The moving split window technique is a one-dimensional method that involves locating a boundary along a transect. Wombling is a two-dimensional technique that involves superimposing a grid over the landscape and then computing the rate of change of an ecological variable among neighbouring cells on the grid (Fagan et al., 2003). Further details and exact methods behind many boundary delineation techniques can be found in Fortin et al. (2000), Fagan et al. (2003), and Kent et al., (2003). **Figure 2.2** is from Fagan et al. (2003) and displays boundary delineation methods based on data type. Fagan et al. (2003) note that some delineation methods are limited to delineating sharp boundaries, which may be a disadvantage because natural boundaries are not always distinct; while other methods they discussed could delineate boundaries as gradual or sharp.

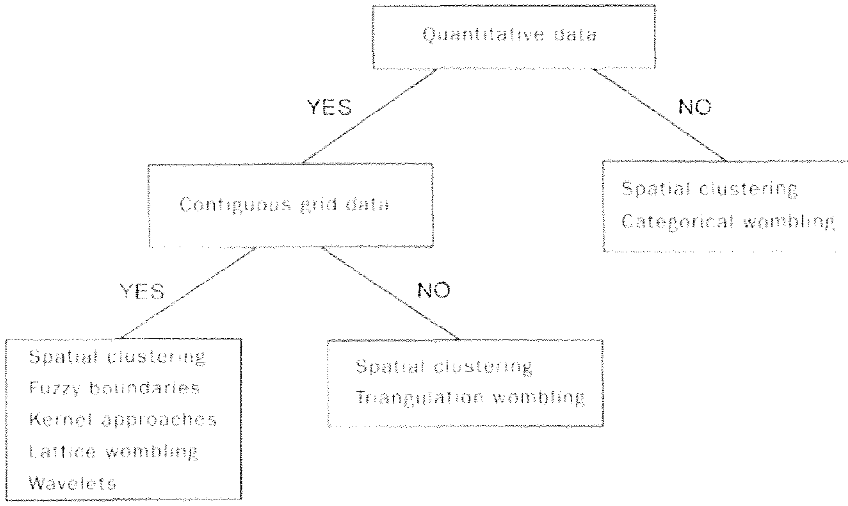


Figure 2.2. Selection of boundary delineation methods based on data type from Fagan et al. (2000).

Fortin (1997) tests the effectiveness of lattice-wombling on a two-dimensional data sample in her research. She did this to determine the consistency in the boundary delineation method when using different vegetation data types and species assemblages. Data used for delineation include density, percentage cover, and presence-absence of the vegetation. Overlap statistics were used to determine the degree of variation between the boundaries delineated by density, cover, and presence-absence. Her results demonstrate that the delineated boundaries are similar, despite the differences in the data used in the delineation process (Fortin, 1997).

Hall and Maruca (2001) apply boundary analysis techniques using BoundarySeer software to investigate patterns of change over space and time in forested wetlands. Two boundary delineation methods were used, wombling and spatial clustering, to examine the similarities of vegetation boundaries delineated by each method. Spatially restrained clustering is a technique that locates the boundary of a homogeneous patch. It groups data locations into clusters based on spatial proximity and shared similarities. They conclude their research by suggesting that boundary delineation techniques require further investigation for mapping vegetation. See section 3.4 and Figure 3.2 of Chapter 3 of this thesis regarding the cartographic output of their study.

Arnot, Fisher, Wadsworth, and Wellens (2004) delineate an ecotone boundary using the fuzzy classification technique with satellite imagery to classify the landscape of the Bolivian savannah-forest transition zone. Fuzzy classification is a commonly used boundary delineation method that involves assigning sample points to a set of predetermined classes (Kent et al., 2006). This type of boundary delineation is appropriate for continuous, or raster, data sets like satellite imagery used by Arnot et al. (2004) and is often best at creating transitional boundaries on maps. Interestingly, Arnot et al. (2004) did not employ any of the boundary framework or theories put forth by Belnap et al. (2003), Cadenasso et al. (2003b), or Strayer et al. (2003), in their research.

Most of the studies mentioned thus far (Fortin, 1997; Martin et al., 2006; Fagan et al., 2003; and Fortin et al., 2000), used or reviewed GIS software to perform boundary delineation techniques. Accad and Neil (2006) are no exception; they mapped the wet tropics of Northeastern Australia using ecological, statistical, and data models developed and analyzed using GIS. Through this work, they argue that they can produce an accurate vegetation map with gradient boundaries depicting vegetation of the study area prior to deforestation. However, they also admit to incorporating "arbitrary, though often unrealistic, sharp boundaries" (p. 85) over top of the original transitional boundaries. This study demonstrates the significance of rapid data analysis using GIS, but from a cartographic perspective, there is no rationale offered as to why the boundaries are portrayed as sharp boundaries and not transitional. See **Figure 2.3**.

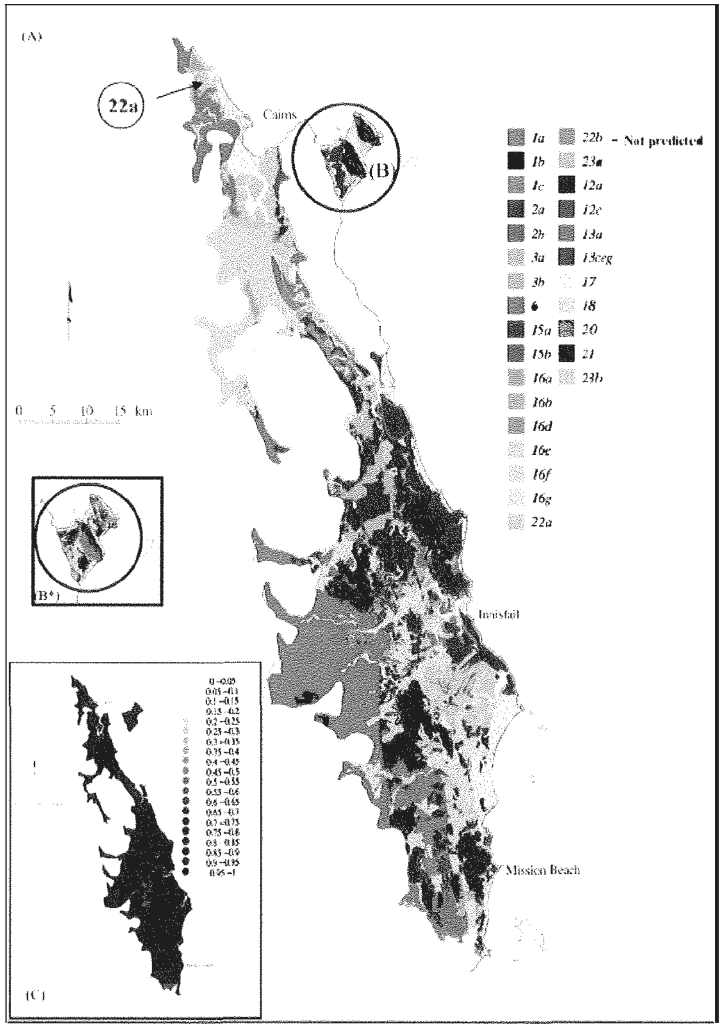


Figure 2.3. Vegetation types predicted in Innisfail Lowlands of northeastern Australia prior to vegetation clearing by Accad and Neil (2006). The boundary symbol used to differentiate one vegetation type from adjacent vegetation types is a solid line created by the colour change between the adjacent vegetation types. For example, one vegetation type is represented by the colour red on the map and an adjacent vegetation type is coloured green. The boundary between these two vegetation types is established where the two colours meet creating a colour contrast.

McCoy, Bell, and Walters (1986) delineate boundaries in four case studies by applying Monte Carlo simulations to presence-absence (qualitative) data. Monte Carlo simulations involve repetitive calculations of random numbers and probabilities. While their procedure is devised to determine biotic boundaries using presence-absence data, they admit that their method requires qualitative data and cannot utilize quantitative data. Similarity matrices (locations vs. species) were used to find boundaries and establish their strength, i.e., weak or strong. Furthermore, McCoy et al. define a boundary as an absolute barrier and argue that a boundary cannot be a transition zone. Rather, they argue that if a sample species was present on either side of a potential boundary, then a boundary does not exist in that particular location for that particular species. Their method produced consistent results in all cases (it was tested in four scenarios with data from previous studies) and they insist that two researchers using this method would arrive at the same conclusions. The work of McCoy et al. in this field has been cited throughout later literature, suggesting that it has been influential in the development of modern boundary delineation.

Mac Nally (2005) chose a statistical Bayesian technique to compare non-hierarchical models adapted to calculate the probability of boundary locations along linear gradients. Mac Nally describes the delineation method, Bayesian model selection, as calculating the probabilities of potential boundary locations based on data such as vegetation cover or bird distribution. He suggests that this technique could be used to locate multiple boundaries and broad ecotones, as well as analyze the relationships between biotic distribution and physical or biological factors.

2.2.4 Ecological Scale

Just like in cartography, scale is a fundamental element of ecological studies. Fortunately, concerns and issues of study scale in ecology and landscape ecology research are well known (Accad & Neil, 2006; Kent et al., 2006; Levin, 1992; Pickett & Cadenasso, 1995; Wagner & Fortin, 2005; Yarrow & Marin, 2006). No one scale is believed to be "correct" when in ecological research. Nonetheless, the level of scale can influence which ecological patterns are apparent and observable (Christensen et al., 1996; Dungan, et al., 2002; Kent, 2007; Levin, 1992; Suarez-Seoane & Baudry, 2002). Issues of scale highlighted in the literature are important to mapping ecological boundaries, especial on a northern landscape where ecological units tend to function on much larger scales (Stevens, 1989).

In an influential article, Levin (1992) argues that a fundamental problem in ecology is the concept of scale because organisms and physical objects experience the environment at many geographic and temporal scales. Levin also argues that researchers must understand the relationships as they translate between fine and broad scales. Furthermore, Levin believes that researchers must determine the degree of simplification they will conduct their study at so that patterns are observable without being obstructed by unnecessary details. This means that research objectives should include a determination of the amount of detail that can be ignored without skewing results and observations on the scale of interest (Levin, 1992).

Dungan et al. (2002) present four case studies in their research to demonstrate how ecological processes and structures could be altered by changing the scale of the research. They argue that changes to observational or analytical scale and extent could also change data results such as mean, variance, and patch-matrix sizes. Furthermore, they do not agree with Levin (1992) that scale is a singular problem for ecological research. Instead, they argue that "scale" is too much of a general or ambiguous term that encapsulates a number of distinct spatial variables including extent, grain, resolution, cartographic ratio, lag, and support. The authors believe that future researchers should adopt these terms to more clearly define the scale parameters of their research. Complementarily to the Dungan et al. study, Kent et al. (2006) suggest that the best scales to study landscape ecology could be broken down into three levels: landscape scale at 1 kilometre to 100 kilometres; patch or community scale at 10 metres to 1,000 metres; and individual species or plants scale at 0.1 metre to 10 metres.

Multi-scale analysis is a potential alternative to single-scale analysis. Cain, Ritters, and Orvis (1997) constructed maps derived from Landsat Thematic Mapper images at different resolutions, attribute detail, and boundary delineation, using multivariate analysis of landscape metrics to observe whether the resulting measures were comparable. Interestingly, they found that diversity, texture, and fractal dimension were generally consistent, while measures of average patch shape or compaction varied between maps. This suggests that scale can affect ecological boundary location.

Suarez-Seoane and Baudry (2002) recognize that mapping is a fundamental component of landscape research and also advocate the use of multi-scale analysis. They believe that in the process of mapping their data, the researchers (and/or map makers) must consider the ecological process they are interested in, the availability of data, and the spatial and temporal extent of the research. Furthermore, they hypothesize that the best results can be achieved when the scale of the landscape unit is equal to the scale of the ecological process of interest. Suarez-Seoane and Baudry (2002) conclude that highly mobile species are best mapped at coarse scales, while less mobile species can be mapped at finer scales.

Johnson, Seip, and Boyce (2004) are also concerned with scale and they constructed patch-scale and landscape-scale maps in their study of mountain caribou (*Rangifer tarandus caribou*) in central and southern British Columbia. Using GIS and data from surveys and radio-telemetry, a final map was produced based on caribou occurrence in a patch. Johnson et al. conclude that this method worked well for their study, but may not be best for all species and geographical locations; they recommend the use of expert opinion in the development and interpretation of models and maps. While this research has a strong focus on mapping the distribution of caribou, they did not comment on the map design process, or the symbol selection of the boundaries related to caribou distribution.

Fischer, Lindenmayer, and Fazey (2004), use multi-scale analysis by overlaying species habitat contour maps, because, they argue, current models (patch-matrix or gradient) are limited in explaining patterns of complexity across multiple scales of different species. See **Figure 2.4** for an example of Fischer et al. (2004) species contours. They believe that habitat contour maps are useful conceptual tools in understanding the relationship between pattern and process in landscape ecology. Furthermore, they suggest that this approach may provide a more holistic way of thinking about modified and managed ecological landscapes.

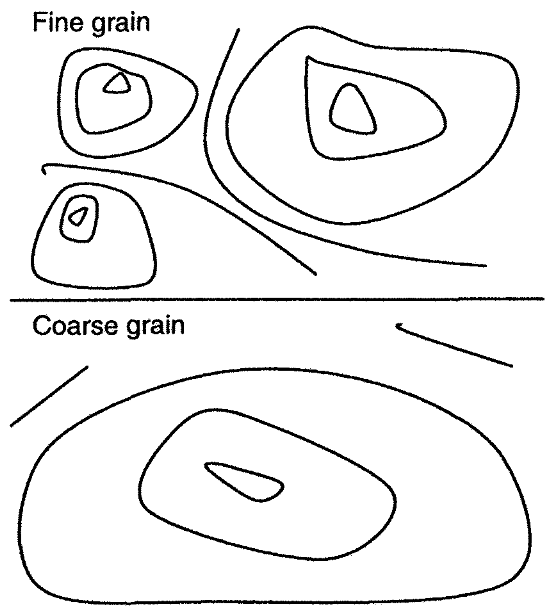


Figure 2.4. Illustration of species abundance contours at fine and course scales from Fischer et al. (2004). The centre of the contour represents the highest abundance for a species.

Gaucherel (2007) proposes another multi-scale method that he uses to capture local and broad scale variations across patchy or continuous landscapes. It includes boundary delineation via a wombling technique, a multi-scale map, and a heterogeneity profile (graphed as: scale vs. heterogeneity) in each place, at each scale. Gaucherel argues that commonly used heterogeneity indices (specifically Shannon information theory indices) were unable to identify or quantify patterns on a landscape at different scales, while his methodology could. Interestingly, Gaucherel did not review or critique the techniques of Cain et al.(1997), Johnson et al.(2004), or Fischer et al., in his article despite their common efforts to further the study of multi-scale analysis.

2.2.5 Multivariate Ecological Data

Another issue of importance regarding spatial patterns is the management of multivariate data. An increased emphasis on data management using GIS is what Cassettari (2007) argues has diverted the focus away from cartographic theories in contemporary mapping.

Research by Guo, Gahegan, MacEachren, and Zhou (2005) indicates that multivariate spatial patterns could still be detected and visualized through computational, visual, and cartographic techniques. Computational methods refer to the use of statistical analysis to find relationships within the data. Visual methods rely on human vision to determine patterns, but if too many variables are present, patterns can be difficult to recognize. Guo et al. (2005) recognize that cartographic display of multivariate data is challenging; however, they focus on the creation of a two-dimensional colour scheme to depict the multivariate data. They developed this approach to help minimize what they call “weaknesses” that computation, visualization, and cartographic methods have on their own. Their approach includes a self-organizing map, a parallel coordinate plot, a mapping tool, and a two-dimensional colour tool. They suggest that this approach could be used prior to developing a hypothesis because it provides insight into multivariate data relationships. Although there is a heavy data management component to the Guo et al. study, cartographic display is also a significant part of their research.

A similar study was conducted by Kraak and van de Vlag (2007), who argue that visualization of data sets could reveal important questions, confirm possible relationships, and be used to generalize and present findings. They developed an integrated method, similar to that created by Guo et al.(2005), visualizing spatial and temporal multivariate data sets, in the belief that this technique could answer questions about the data. This method, presented in the form of dynamic mapping, includes an interactive map, a parallel coordinate plot, and a temporally ordered spatial matrix. Kraak and van de Vlag suggest that linking these three views could help researchers discern space, objects, and time of spatiotemporal data.

2.2.6 Vegetation Mapping Before the General Use of GIS

Kuchler (1956; 1988) and Wagner (1957) focus their research on cartographically depicting vegetation types on vegetation maps. In early work, Kuchler (1956) depicts vegetation boundaries as solid black lines enclosing parcels of vegetation that give the maps a patchwork or mosaic-like appearance. However, he does not describe why or how this linear symbol was chosen to represent the vegetation boundaries.

Wagner (1957) does not specifically address boundary symbology in his work either. Instead, he creates a series of symbols representing different vegetation types and demonstrates how they would be used on a map by creating "snapshot" of a hypothetical map seen in the far right sketch of **Figure 2.5**. The boundary between different vegetation types is represented, or perhaps better described as created, by a change of the vegetation symbol from one symbol type to another – where this change over occurs is where the boundary is. Wagner is of the opinion that many vegetation boundaries in the real world are gradual across the landscape and should be represented this way on maps. He argues that gradual vegetation boundaries should not be represented as linear features on maps and calls linear vegetation boundary symbols an "embarrassing necessity", mostly to accommodate scale, creating "artificial sharp boundaries in broad transition zones" (p. 396) on many vegetation maps (see examples by Accad and Neil, 2006; Kuchler 1956). Wagner suggests this may be avoided by creating a gradual change from one vegetation symbol to another (again, see **Figure2.5** for a visual description of Wagner's method).

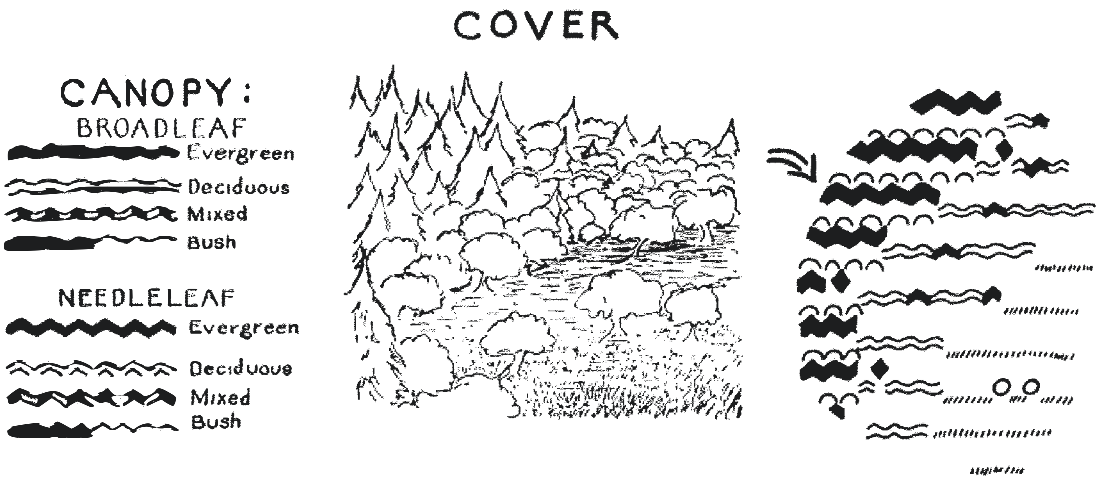
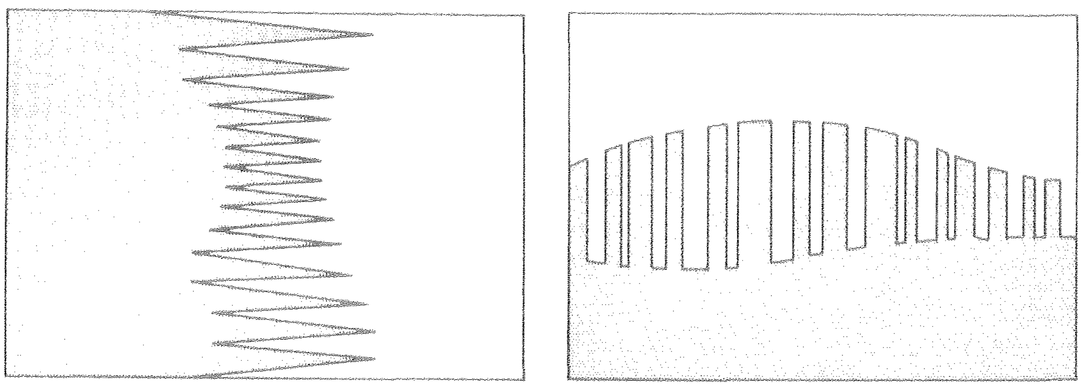


Figure 2.5. Illustration of vegetation symbols designed by Wagner (1957). A legend, at left, of the symbols used to describe the hypothetical landscape (middle sketch) are put in a "snapshot" (at right) of a map showing how these symbols would be used to represent the hypothetical landscape.

Perhaps influenced by Wagner (1957), Kuchler's later work (1988) indicates more awareness of boundary symbology between vegetation types. Kuchler, like Wagner, acknowledges the gradual nature of real world vegetation boundaries and offers a few sample symbols to represent gradual boundaries (see **Figure 2.6)**. However, Kuchler believes that using simple linear symbols to represent vegetation boundaries produces a cleaner map and improves the ease of use as a decision-making tool, even if the real world boundaries are gradual transitions (1988). This opinion is even evident in sample transitional boundary symbols presented by Kuchler (**Figure 2.6**): the transitional boundary symbols have (a) jagged and, (b) angular appearances between grey and white tones, reinforced with a solid black line. Kuchler's (1988) boundary symbology is discussed further in the Chapter 3.



(a) (b)

Figure 2.6. Two examples of transitional vegetation boundary symbols suggested by Kuchler (1988). Both boundary symbols, the jagged (a) or angular (b) transition between the two grey tones, are reinforced by a thin black line.

2.3 Summary

This chapter discussed ecological boundaries. It reviewed theoretical and philosophical aspects of boundaries, delineation, and discussed mapped ecological boundaries in applied ecological research. Within the background literature ecological boundaries are most often depicted as single, solid lines (Kuchler, 1988; Ries et al., 2004), but they are also represented as fuzzy lines (Jacquez, Maruca, & Fortin, 2000), changes in greyscale (Mansaeu, Rennie, &

Mondor, 2001), changes in hue (Accad & Neil, 2006), gradients or contours (Fischer et al., 2004), and indirectly using symbols (Wagner, 1957). Yet, the symbolic depiction of boundaries or the cartographic design processes by which boundary symbols are assigned are rarely (Fischer et al., 2004; Kuchler, 1988; Wagner, 1957), or never (Accad & Neil, 2006; Jaquez et al., 2000; Kuchler, 1956; Mansaeu et al., 2001; Reis et al., 2004), discussed within these literature sources. This suggests that boundaries symbology has not been a key aspect of ecological boundary research despite that maps and spatial analysis are often an integral part of ecological boundary research.

The next chapter, Chapter 3, focuses on the cartography of ecological boundaries. It explores the current state of cartography and opinions of modern mapping methods. Cartographic theory and application are discussed as they pertain to ecological boundaries. Symbology is explored in the cartographic literature and symbols are investigated in GIS and other software types.

Chapter Three: Current Cartographic Boundaries

3.1 Introduction

The previous chapter examined ecological boundary theory and the role and function of boundaries on the landscape. It provided a brief overview of philosophic perspectives in boundary concepts and their real or areal nature. Last, I provided a brief description of popular boundary delineation methods and an overview of boundary depiction in modern ecological studies. Chapter 2 demonstrated that ecological science consciously makes boundaries a priority in efforts to understand the interconnectedness of the ecological landscape.

In this chapter, I review cartographic theory and design, the recent opinions of contemporary mapping, and the role of symbols, in an attempt to determine whether boundaries in cartography have kept up with the boundaries in the ecological literature. To do this, I analyse the depiction of boundaries in traditional cartography and GIS-based mapping.

3.2 Cartographic Theory and Design

3.2.1 Critiques of Modern Mapping

Are maps mirror images of the real world? Influential cartographer Harley (1989) does not believe so. He argues that maps are something like the written word, but in a graphic form, resulting from human views of the world. Furthermore, Harley contends that while scientific maps are the product of methodical research, they also stem from values and familiarity of social traditions; in essence, maps are cultural tools. Harley argues that the interpretation of the nature of cartography requires an epistemological approach because, he says, "cartography is seldom what cartographers say it is" (p. 1). Furthermore, he asserts that art – which he argues was once a fundamental element of cartography – has been reduced to something superficial, at best. A cartographer's artistic ability is inherent to map creation, especially when making maps by hand. However, most maps are now constructed using computer software and artistic ability is no longer a prominent aspect.

Perhaps one of the most fundamental issues of mapping in recent years is the loss of a cartographic foundation which a mapper can draw upon when constructing maps. Forrest (1999) attributes this loss to the emergence of computer mapping and GIS. These computer programs have shifted mapping away from the specialization of cartography and into the realm of the layperson that is unfamiliar with the basic principles of map design and cartography. Cassettari (2007) addresses similar issues and challenges in his Presidential Address at a British Cartographic Society Annual Symposium. He argues the need to maintain high cartographic standards when working with modern mapping technology like GIS. Cassettari believes that one reason cartographic quality has declined since the advent of GIS is the improvement of data management, storage, and analysis. He argues that the data management component of mapping has become the focus of geographic information instead of effective cartographic presentation. Therefore, he believes present and future challenges lie in improving cartographic content so that maps communicate information effectively and information is enhanced, not degraded.

3.2.2 Cartographic Edification & Research

Evidently, a need exists for contemporary mappers to build the necessary foundations of cartographic design principles which Harley (1989) and Cassettari (2007) believe have diminished in recent decades. Perhaps this why for more than 10 years, a number of researchers (Forrest, 1999; MacEachren, 1995;

Monmonier, 1996) have attempted to bring about an awareness of a needed improvement in cartographic techniques and maps.

In *How to Lie with Maps*, Monmonier (1996) provides an overview of the most common cartographic manipulations, both deliberate and unintentional, map makers incorporate into maps. Choices of colour, symbols, data representation, classification, generalization, intended audience, and other factors can influence the look and interpretation of a map. Monmonier also argues that in an attempt to present truthful and useful information, maps must lie. For example, relatively small objects, be it a stream or a landmark, may not appear on a coarse-scale map because at that cartographic ratio the amount of detail is different than what might appear on a map of a smaller extent (finer scale). This is mostly because it is impossible to accurately include everything from the real world onto every map at every scale. While all maps distort reality in some manner through symbolization and generalization, intentional deception can lead map users to draw false conclusions in the same way that inadvertent mapping choices can mislead.

According to MacEachren (1995), the concept of representation is essential to all cartographic approaches. Sharing a similar outlook with colleagues in his field (Monmonier, 1996; Maki & Kalliola, 2000), MacEachren argues that maps are often viewed as visual sources of information, and that map users can draw from these sources during the process of decision making. Such an argument was transformed into a hypothesis by McKendry (2000), who proposes that decisions based on mapped data can be influenced and altered as cartographic display changes. McKendry suggests that poorly designed maps shift the burden of data interpretation from the map maker to the map user – a burden that can be avoided with appropriate cartographic techniques. Interestingly, however, results from McKendry's research suggest that variations of visual display do not significantly impact decisions based on map information, as was originally hypothesized. But this conclusion is not supported in other sources in the background literature (Brewer, MacEachren, Pickle, & Herrmann, 1997; Bunch & Lloyd, 2000; Lloyd, 1997).

There are many aspects of map construction that some researchers (Lloyd, 1997; Kent, 2005) agree make a difference in effective map communication. Lloyd investigates the search processes of map users when locating information on maps. Results indicate that a map user's ability to interpret a map is largely influenced by colour, symbol size, and location of symbols on the map. Thus, cartographers who are aware of the cognitive search processes of the map users can construct more effective maps. Therefore, Lloyd suggests a relationship may exist between map usability and map aesthetics, though some believe (e.g. Kent, 2005) this relationship is not fully understood. Kent goes further, suggesting that aesthetically pleasing symbols are most visually effective. To be so pleasing, a cartographer's aesthetic principles play a key role in the symbolic representation of features and symbol design, as well as the entire map (Kent, 2005). Factors that affect the success of an aesthetically pleasing map include: an awareness of the creative possibilities in cartography, a sensitivity regarding mapped features, the skill to create symbols which express features in an aesthetic way, and the visual expectations of the intended map user (Kent, 2005).

Incorporating colour is almost certainly a component of constructing a visually pleasing and effective map. Brewer et *al.* (1997) explore the use of colour on choropleth maps by assessing the accuracy of map users' abilities to interpret maps as the colours on the map are changed, and the colour preferences of map users. Results of their research suggest that colours can affect the accuracy of map reading, and that map users prefer colour to black and white maps.

Bunch and Lloyd (2000) also investigate how boundary colouring influences or controls a map user's visual search of a map. Results indicate that boundaries were best viewed when their colour was distinct from other mapped objects and set on a simple background. They also found that user search time was best improved by red and yellow colours surrounded by boundaries of lighter or darker colours of the same hue.

As previously mentioned, the line is one of the most common symbols used to depict boundaries on maps. Buttenfield (1985) explores the use of the line in cartography, as well as its visual aesthetics and effectiveness. She contends that a cartographer's intention to maximize clarity of necessary information requires the separation of the data from "noisy", or unimportant data. The division of the data may be subtle in regards to the cartographic generalization of a line, particularly when traditional cartographic generalization refers to the elimination of some mapped detail.

Cartographic manipulation is also possible through changes of map projection. According to Nyerges and Jankowski (1989), projections are critical to the study of cartography, as well as to the usability of maps and they provide the knowledge required to select an appropriate map projection in the hope of assisting novice mappers and map users in their research paper.

The main purpose of Maki and Kalliola's (2000) research was visualization and communication of map making while incorporating ecological and physical data. A major finding from their research was recognizing the difficulty in constructing good quality maps of heterogeneous landscapes. In other words, they found it difficult to portray multiple variables on a single map while maintaining map readability. Maki and Kalliola recommend that further research must include careful consideration of the purpose of the map in a study such as theirs, as well as consideration for the requirements of the intended map users in the initial phase of map production.

3.3 Symbology

Symbols represent real world phenomena on maps and they are used to visualize the spatial distribution of data. The importance of symbols is obvious because maps are used in decision making and planning processes. A cartographer's choices of symbol size, shape, colour, placement, and accuracy affect the appearance and reliability of their maps. Schnabel (2007) argues that the quantity of symbol choices has decreased since computers have become the main tool in map construction. He argues that the pre-programmed symbol choices within GIS and mapping software are often limited, and the extent to which the mapper can alter the pre-programmed symbols is restricted (Schnabel & Hurni, 2007). Furthermore, Schnabel and Hurni (2007) suggest a possible consequence of limited symbology choices could be misrepresentation of the data and misinterpretation of the map information by the map user.

3.3.1 Boundary Symbology

Kuchler (1988) offers a traditional cartographic perspective on boundary symbology for vegetation mapping. He believes that the cartographer's objective is to depict vegetation units on a map and to accomplish this task the units must have boundaries.

Furthermore, it appears logical that a map user should be able to venture into the field and find the real world location of the vegetation boundary identified on a map. In reality, however, Kuchler says this is not necessarily the case. He identifies boundaries as a "problem" (p. 105) that mappers must address when mapping vegetation and describes the concept of vegetation boundaries as "vague" (p. 105). This is most likely because these vegetation boundary limits depend on an individual map maker's interpretation. Kuchler defines a boundary in vegetation mapping as "separating two different types of vegetation" (p. 105). Therefore, the mapper must determine where the boundaries are located, what characteristics the boundaries possess, and how best to depict them on the map so that the map suits the map user's requirements.

Kuchler (1988) identifies two common interpretations of vegetation boundaries including, 1) a transitional zone where one vegetation unit follows into another, and 2) a sudden and distinct change in vegetation type. To locate these boundaries, Kuchler suggests consulting topographic, geologic, and soil maps, remotely sensed data, climate data, and hydrological data because changes among these variables are often reflected as changes in vegetation types. The presence or absence of certain plant species, known as indicator species, is also used to establish vegetation boundaries (Kuchler, 1988). These variables can contribute to sharp or transitional vegetation boundaries between plant types. Therefore, the cartographic challenge must be deciding how to depict or symbolize boundaries based on available data.

Recognizing this difficulty, Kuchler (1988) suggests a number of methods that cartographers can adapt to meet their requirements. One common method of depicting vegetation boundaries is to represent them as lines. An advantage of using lines to symbolize boundaries is that they contribute to map precision (or the appearance of) – an important requirement, says Kuchler, when using maps for ecological management planning. Boundary lines should be clearly visible, but also quite thin, as thick lines may detract from map quality and are particularly unsuitable for maps at coarse scales. Hueck (as cited in Kuchler, 1988) uses three types of lines for a Venezuelan vegetation map: solid lines symbolize known boundaries, dashed lines represent less certain boundaries, and dotted lines denote vague boundaries. All three line formats are displayed on the map in grey, not black, to ensure that the boundaries are subtle but still visible. Another visually pleasing method used by Gaussen (as cited in Kuchler, 1988), displays adjacent vegetation types by using contrasting colours, grey tones, or patterns. Therefore, the boundary is located where the colour or pattern changes from one vegetation type to another. Given the articulate appearance of lines, Kuchler believes that they best represent boundaries on maps that will be used for scientific purposes. However, it was described earlier (see **Figure 2.3**) that this boundary symbol is not necessarily an accurate reflection of the real world phenomenon; Accad and Neil (2006) used the technique favoured by Gaussen, described by Kuchler (1998), despite that the vegetation boundaries they mapped were described as transitional boundaries on the landscape.

Regarding transitional boundaries between differing vegetation types, Kuchler (1988) suggests that the depiction of boundaries should depend on the width of the transition between adjacent vegetation types in relation to the scale (cartographic ratio) of the map. In other words, if the transitional area is quite thin (perhaps less than 1 km across on the landscape), then it may be best to symbolize that boundary as a solid line on a map covering a very large area (1:1,000,000 map scale). Alternatively, if the same boundary is found on a map covering a small local area (1:10,000 map scale), a different set of symbols may portray the transitional area more effectively than a solid line. In the situation where the transitional boundary is best symbolized as something other than a solid straight line, Kuchler suggests broken lines, zigzags, alternating bars, or arrow-shaped extensions, as seen in **Figure 2.6**. He also proposes the incorporation of colour and other symbols to represent dominant vegetation types as they change across the transition.

In conclusion, Kuchler (1988) takes a traditional cartographic approach to mapping vegetation boundaries. He offers some simple cartographic solutions for sharp and transitional plant boundaries on vegetation maps. It is a good idea for any cartographer concerned with mapping ecological boundaries to be familiar with the symbol possibilities at their disposal to construct high quality vegetation maps. This is only possible by reviewing traditional cartographic sources such as Kuchler's work (1956; 1988).

3.4 Cartography and Modern Mapping with GIS

Constructing maps using GIS software is relatively easy. Many types of mapping software, such as ArcGIS, are meant to be user friendly so that a large number of computer literate people can use the software to create maps that suit their needs, even if they are cartographically illiterate. This is one reason why mapping software has transformed the process of mapping from the highly specialized craft of cartography, to a generalized and limited software application (Cassettari, 2007). GIS software provides the user with most of the elements required to make a map; the software user simply enters data and then makes some basic selections and modifications to construct a map (Environmental Systems Research Institute [ESRI], 2010).

ArcGIS software comes equipped with a symbol catalogue of more than one thousand symbols that can be searched by name, keywords, or by browsing the full catalogue (ESRI, 2010). ESRI (2010) categorizes four basic symbol types: lines, fill, markers, or text. These symbols are used to depict lines, polygons (enclosed areas), points (locations), and text. Line symbols are often used to outline map features, such as polygon boundaries. Fill symbols are simply colours, greys, or patterns used to shade map areas like polygons. Marker symbols are generally used for specific location and are often mapped using point symbols. They can also be used continuously in a line to form line symbols or to adorn other symbols. Lastly, text symbols are most often used to label map features as well as text on the map (ESRI, 2010). In addition to belonging to one of these four categories, symbols also vary in the complexity of their structure.

Structurally simple symbols may be composed of a single layer, like a thin black line. More complex symbols are composed of additional layers. For example, a symbol such as a blue circle with a black outline is comprised of two layers: one layer is a circle with blue fill, and the other layer is a translucent circle with a black outline that surrounds the blue circle.

ArcGIS symbols can be modified somewhat if need be, and simple alterations such as colour and size are easy to perform. Other alterations are more limited: rotating the symbol on its axis; offsetting symbol placement from the original location of the spatial data; creating a mask (or fill) behind the symbol to increase symbol visibility; and adding, removing, or rearranging layers that form the symbol (ESRI, 2010). Unfortunately, the mapper cannot modify symbols beyond these basic alterations. Interestingly, ESRI's (2010) online help manual for the latest desktop software, version 10, suggests creating new symbols only by modifying existing symbols. In essence, there is no true option to create new symbols using ArcGIS software which is currently the most popular GIS software.

In an attempt to integrate cartography back into mapping, and specifically into GIS, software extensions such as MAPublisher and Geographic Imager have been developed for the graphic design programs Adobe Illustrator (Avenza

Systems Incorporated, 2010). These mapping extensions add GIS software tools into graphic design software that does not have mapping capabilities otherwise. The attraction of a program like MAPublisher is the ability to take advantage of the capabilities of graphic design software while using GIS data and spatial precision. The user is able to import and edit data from some of the most commonly used GIS programs, such as ArcGIS data files, while maintaining the geospatial qualities (like coordinates and scale) of the original data (Avenza, 2010). MAPublisher software appears to be a wise choice for serious mappers.

Unfortunately, the expensive cost of all off this software (ArcGIS software, MAPublisher software, Adobe software) and the time required to learn and use it appropriately is difficult to justify unless the user makes maps regularly. One single-use licence of ArcView version 10 (the most basic software package of the three ArcGIS desktop software packages) is $1500 United States Dollars (USD) (ESRI, 2011); one full licence version of MAPublisher 8.x is $1399 USD, upgraded licences start at $599 USD, and bundled options start at $1499 USD (Avenza, 2011); and one full licence version of Adobe Illustrator CS5 is $599 USD, or $1299 USD for CS5 Design Standard (Adobe 2011). If it is possible to purchase and use these programs, the map maker can assume more control of symbol and map design, which I consider highly advantageous for boundary mapping.

Boundary-specific GIS software, like BoundarySeer, was developed to detect and map geographic boundaries. It was created to address the absence of boundary detection and analysis techniques in standard GIS software (TerraSeer, 2010). This type of program is intended for researchers who are looking to identify and examine boundaries in their data using statistical techniques, and then project this information onto maps. Hall and Maruca (2001) use BoundarySeer to compare and map the distribution of bird and vegetation in their research. Unfortunately, the maps produced in the Hall and Maruca (2001) study are not map user friendly. **Figure 3.1** shows the result of the spatial analysis and depicts bird and vegetation boundaries in the study area. These boundaries are represented as dashed and solid lines. Note that the boundaries are not closed; instead, they are locations within the study area where a significant rate of change (i.e. a boundary) is detected.

From a cartographic perspective **Figure 3.1** is much more abstract than most map makers and map users are accustomed to. Therefore, it is not intended for general population map use (e.g. a road map); instead, it is intended to convey spatial information to the researchers who use, or are familiar with, boundary detection analysis and BoundarySeer software.

This software does not offer the freedom to construct a variety of boundary symbols or the ability to create high quality cartographic maps. Also, BoundarySeer software is expensive at $2400 USD for one commercial licence (TerraSeer, 2011); it also requires the time and effort necessary to master the software and interpret the analysis results.

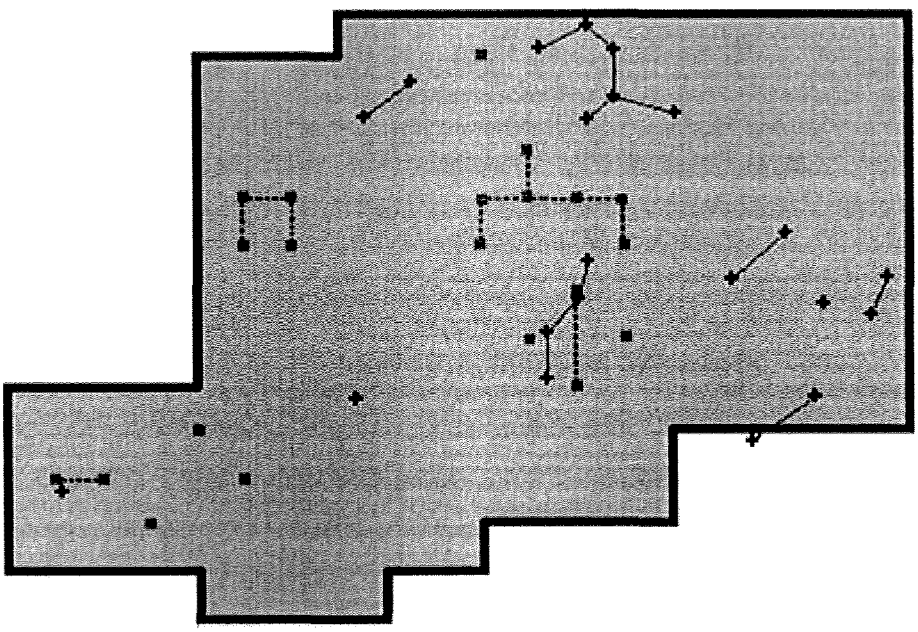


Figure 3.1. Bird and vegetation boundaries detected using BoundarySeer software from Hall and Maruca (2001). Dashed lines connected by grey squares represent vegetation boundaries. Solid lines with '+'s represent bird boundaries. The solid line perimeter marks extent of study site.

3.5 Summary

This chapter explored cartographic theory and design and modern cartographic opinions of mapping. It reviewed symbols in cartography, and traditional cartographic opinion of ecological boundary symbolization. This chapter also evaluated GIS and cartographic mapping software relevant to mapping ecological boundaries. I do not believe that all-purpose mapping software such as ArcGIS has kept up, cartographically speaking, with advances in ecological boundary research. It does not offer the flexibility necessary to create new symbols, only the option to modify existing symbols that are available in the software library.

Similarly, specialized boundary detection GIS software, like BoundarySeer, is nearly devoid of cartographic capabilities. Alternatively, MAPublisher appears to be more progressive and its marriage of graphic design and GIS software is a legitimate option for ecological boundary mapping. Regrettably, the monetary cost of working with a GIS program, graphic design software, and a software extension like MAPublisher may be unjustifiable on a restrictive budget. Furthermore, the user requires the additional skills set necessary to use the software effectively.

The next chapter describes the methodology followed in my cartographic analysis of ecological boundaries. It includes descriptions of field research, the research matrix, the Ecological Boundary Symbology Matrix, symbol design and creation, map construction, and the establishment of symbol guidelines

Chapter Four: A Cartographic Methodology

4.1 Introduction

Chapters 2 and 3 introduced the reader to the ecological, cartographic, and philosophically literature of ecological boundaries. This multidisciplinary literature review was conducted to gain knowledge of the principles of cartographic theory and design, as well as to asses the status of ecological boundary research in ecology.

In this chapter, I provide details of the methodology applied in this multidisciplinary study determining appropriate cartographic symbology of ecological boundaries and establishing guidelines for ecological boundary cartography. Research is divided into three stages, as seen in **Figure 4.1**. First, the literature review was conducted (see Chapters 2 and 3). Second, I conduct a cartographic exploration and evaluation of the symbolic portrayal of ecological boundaries to gain an understanding of appropriate symbolization. Field research and a research matrix, or learning tool, is constructed for this purpose. Third and last, results from the cartographic research matrix and literary research are applied to a series of maps and aid in the development of the guidelines, or best practices.

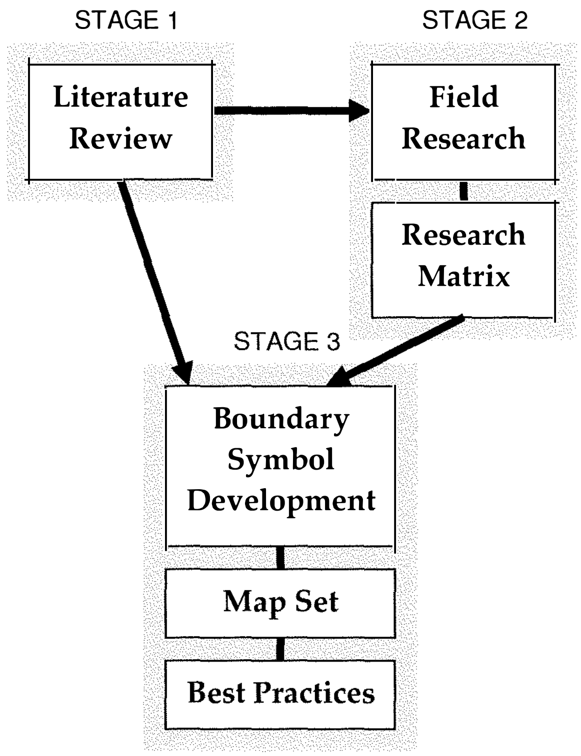


Figure 4.1. Diagram illustrating methodology implemented in the cartographic analysis of ecological boundary symbology.

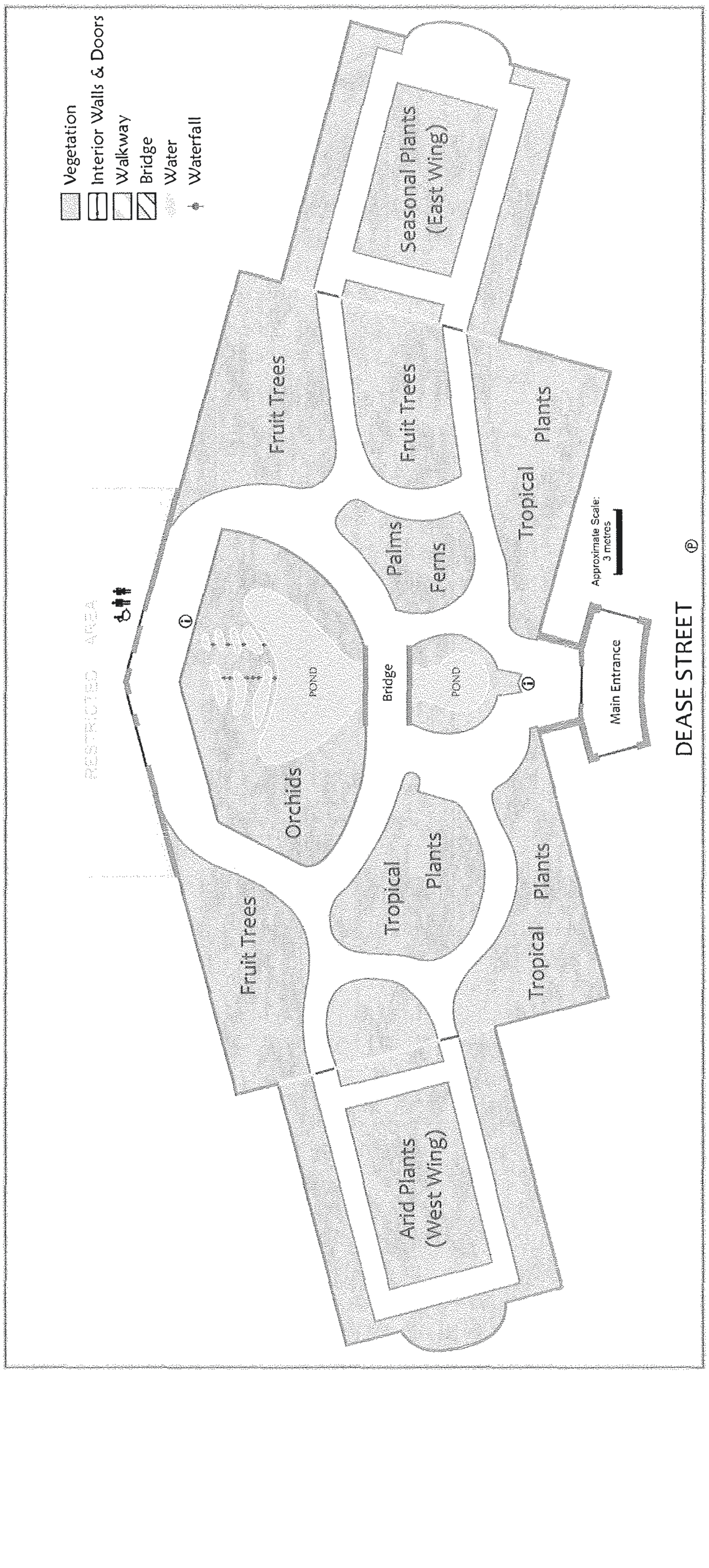
4.2 Centennial Botanical Conservatory: Fieldwork and Case Study

To begin the second stage of this thesis it was necessary to observe and interpret boundaries in a controlled environment to gain a better understanding of the structure and characteristics of ecological boundaries and how this could translate to map symbology. For these reasons, the Centennial Botanical Conservatory was selected as the location for gathering information and determining characteristics and the structures of ecological boundaries to be used later on in the research matrix, mapping Conservatory boundaries, and mapping a case study (see **Map 4.1**). Observations made at the Conservatory took place during December 2008 and January 2009.

A digital point-and-shoot camera (Sony Cybershot W120) and a notebook were used to document observations made at the Conservatory. Photos were taken of scenes, specific non-living objects, and vegetation where an ecological boundary was observed. Brief annotations were made to accompany each photograph taken including a photo number, a description of the photographed object or scene, a rationale for photographing the object or scene, and any other observations made at the time the photo was taken. The photo series was stored electronically on a computer hard drive and a USB flash drive, and 4 x 6 inch photographs were professionally printed to use in the matrix development. Supplementary notes included a description of the boundary, a description of the phenomenon or process that the boundary limited, and any other noteworthy aspects.

Six boundaries were studied in the Conservatory and included in the matrix. Through fieldwork observations, the following were considered ecological boundaries: 1) the roof, 2) exterior glass walls, 3) interior glass walls, 4) the pond surface, 5) soil/stone retaining walls/walkways, and 6) the building floor/ foundation. These boundaries were chosen because they were observable and a number of phenomena were in contact with them. These phenomena included things such as light, soil, and vegetation which are described in the next section as the various boundary 'modes'.

Map 4.1. A map of the Thunder Bay Centennial Botanical Conservatory.



4.3 Research Matrix: Structure, Characteristics, and Cartography of Ecological Boundaries

Work by Slocum et al. (2005) depicting the visual variables of basic cartographic symbology was selected as the foundation of the Ecological Boundary Symbology Matrix. Similar work by Dent, Torguson, and Hodler (2009) was also consulted for this purpose.

The matrix was constructed with x and y-axes adapted from "Figure 4.3" and "Color Plate 4.2" by Slocum et al. (2005). These figures were chosen as the foundation of the learning tool because they are accepted in the cartographic community as basic principles of cartographic symbology. See **Figures 4.2** and **4.3** for the original Slocum et al. (2005) figure and colour plate. Data collected in the Conservatory were then used in cartographic analysis of the symbolic portrayal of observed ecological boundaries.

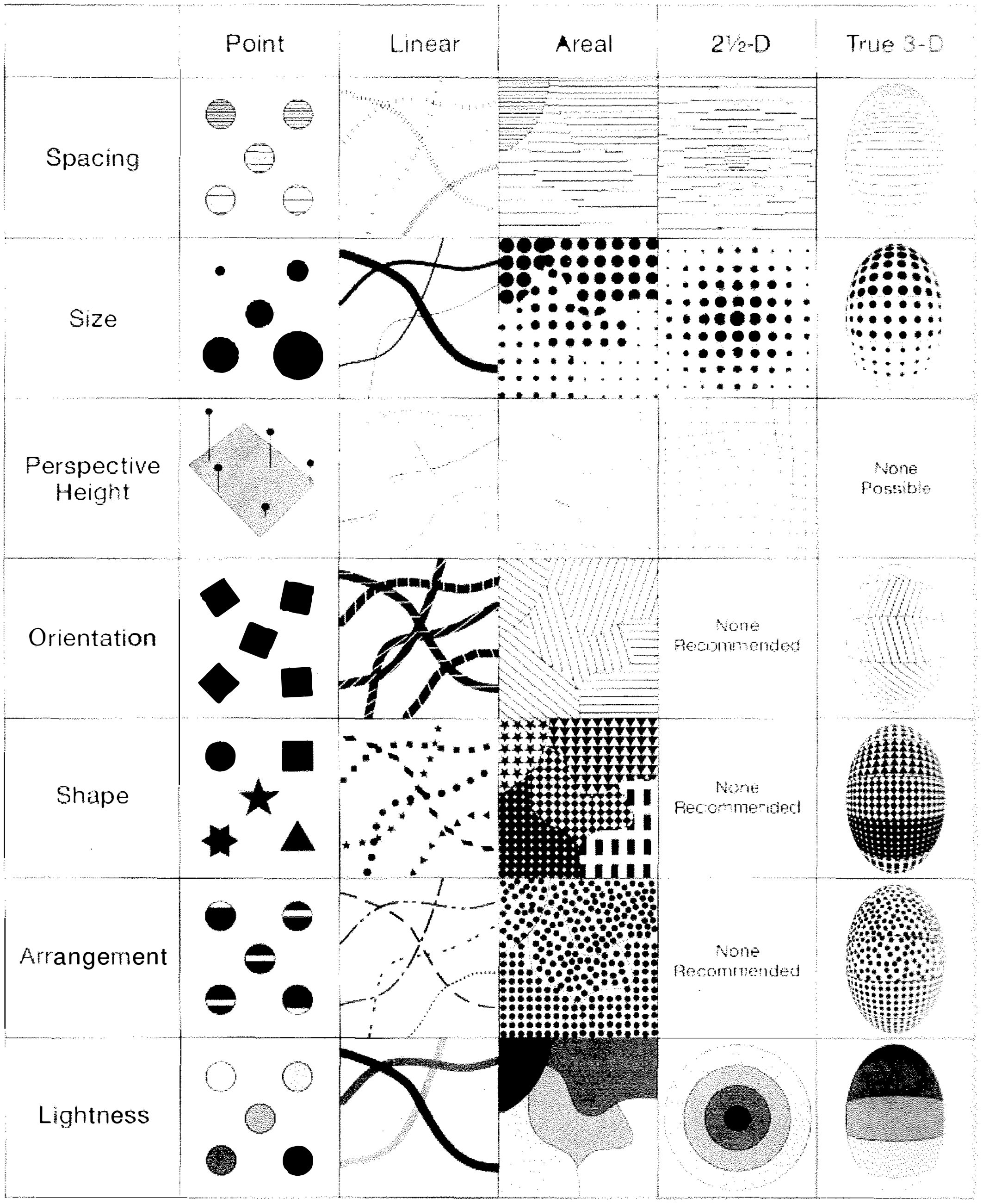


Figure 4.2. Cartographic visual variables for grey scale maps by Slocum et al. (2005).

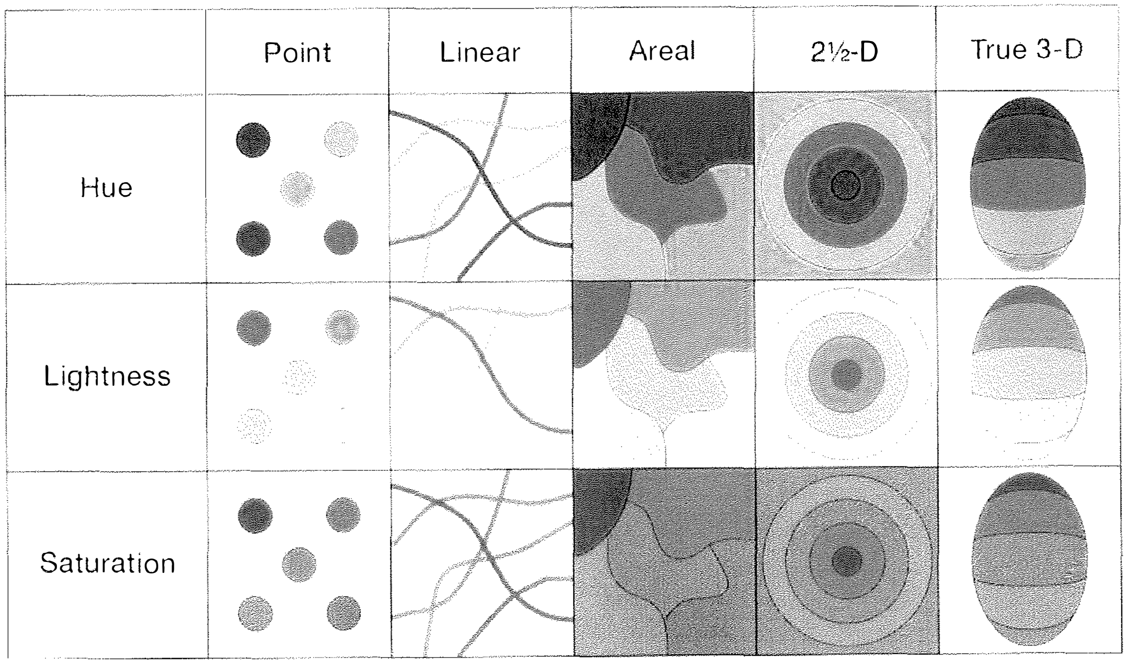


Figure 4.3. Cartographic visual variables for colour maps by Slocum et al. (2005).

The horizontal axis (x-axis) of **Figures 4.2** and **4.3** denotes various types of geographic spatial phenomena: linear, areal, two-and-a-half dimensional (2½-D), and true three-dimensional (True 3-D). The following paragraphs provide a brief description of what each of these terms mean.

Linear phenomena have length, but are without physical width, and thus have only a singular dimension and spatial extent. *Areal phenomena* have both physical length and width, and are usually enclosed objects. *Two-an-a-half dimensional phenomena* (2½-D) are characterized as having a geospatial location (x, y) as well as a volumetric attribute (z). Last, true 3-D phenomena have a location (x, y), a volumetric attribute (z), and one or more associated values (Slocum et al., 2005). A fifth heading from Slocum et al., *point*, was omitted from my research because boundaries are not single-point phenomena.

All visual variable headings on the vertical axis (y-axis) from the original figure and colour plate by Slocum et al. (2005) were included in my research matrix. Cartographic visual variables include spacing, size, perspective height, orientation, shape, arrangement, lightness (grey scale), hue, lightness (color), and saturation. *Spacing* refers to the distance between the marks that make up a cartographic symbol. *Size* can be depicted in two ways: changes in symbol size, or changes to the marks that make up a symbol. *Perspective height* gives a three-dimensional appearance to a symbol. *Orientation* refers to the direction of the marks making up a symbol. Similarly, shape refers to various shaped marks making up a symbol. When matched with a linear phenomenon, *arrangement* refers to the splitting of lines into a series of dashes, dots, or other shapes; when matched with areal or three-dimensional phenomena, arrangement refers to the distribution of marks making up a symbol. The *lightness* of a symbol depends on the amount of black shade it contains. Similarly, *colour lightness* is the lightness or darkness of a colour as hue remains constant. *Hue*, the dominant visible wavelength, refers to the variation in hue (or colour) of a symbol or the marks that make up a symbol. Finally, *saturation* refers to the mixture of hue and grey within a symbol (Slocum et al., 2005).

Slocum et al. (2005) also describes limitations to the use of various techniques for particular data types. For instance, they did not recommend depicting 2½-D phenomena with visual variables orientation, shape, or arrangement because the depiction method works for some data (like numerical data), but is not suitable for other types (such as nominal data). In addition, they note that it is not possible to pair true 3-D phenomena with perspective height because perspective height is meant to create a 3-D effect for a symbol already and true 3-D phenomena requires the three dimensions to locate such phenomena on a map.

It is also worth mentioning that shapes in **Figure 4.3** that represent the changes of the visual variables such as hue, colour lightness, and saturation with areal, 2½-D, and true 3-D phenomena should not depict black lines separating the coloured polygons because this represents the mixture of one type of visual symbol, lines, with another, colour. What is actually being depicted in the table, with the use of the black lines, is a situation where the coloured polygons are separated from one another and the white background by a third symbol, represented by the black lines. However, in the discussion on page 63 of Slocum et al. (2005), they indicate that these symbols were meant to represent the adjacent nature of the first two entities, without the presence of the line symbol. It is interesting to note that, in a recently published edition of this widely used textbook, this error has been corrected and the black lines are not present (Slocum, McMaster, Kessler, & Howard, 2008). However, this example demonstrates how easily prejudices can be embedded into images.

To construct the research matrix used in my study, all headings from the horizontal and vertical axes from Slocum et al. (with the exception of point data) were handwritten on 5 x 8 inch cue cards and fastened, in order according to the original figures by Slocum et al., on a large corkboard (1.5 metres wide by 4m long) using push-pins. This method was employed to ensure the research matrix possessed the flexibility and adaptability (e.g., cue cards could be moved and mixed easily) necessary to work through the exploratory process of symbol analysis and the Ecological Boundary Symbology Matrix construction.

All cue cards placed within the body of the research matrix were labelled using a specific format system. An example of this cue card template and notation system is shown in **Figure 4.4**. On each card, the designation of a single phenomenon, linked to an observed boundary in the Conservatory, was recorded in the top left corner of the cue card; the associated boundary was written in the top right corner; map perspective and the coordinates (notation system) of the cue card within the research matrix were recorded in the lower left and right corners, respectively; the centre of the card was reserved for note taking; and the reverse side of the card was used for sketches related to the boundary and related phenomena. Map perspectives were restricted to either azimuthal or cross-sectional; perspective or oblique views were beyond the scope of this thesis and not explored further in the research matrix. All cue cards created in this project can be found in Appendix B.

FRONT REVERSE SIDE

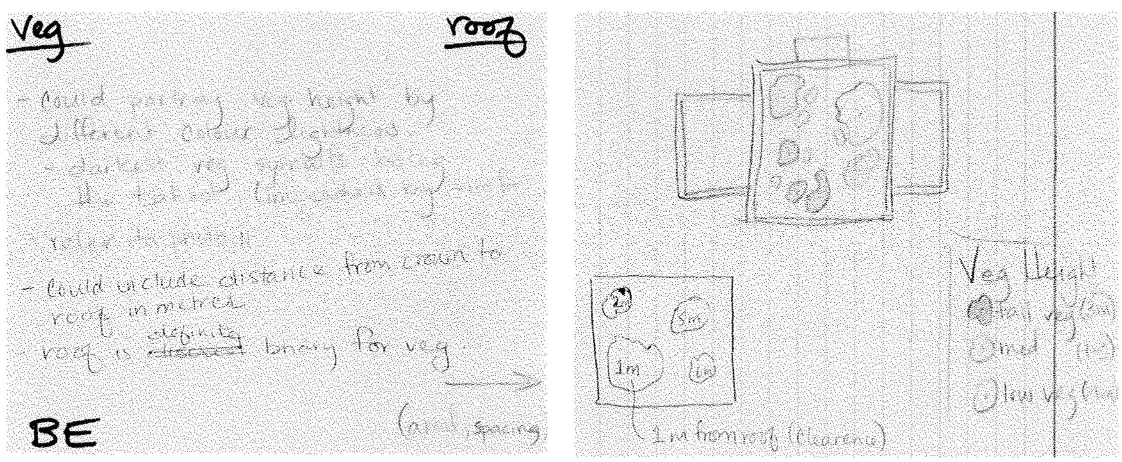


Figure 4.4. Cue card constructed for use in the research matrix. The format of the cue cards is described here. The front of the cue card includes the following information: top left corner denotes a spatial phenomenon, the mode, that comes in contact with the boundary phenomenon, denoted in the top right corner. A map perspective (either azimuthal or cross-sectional) is described in the bottom left corner, and the location of the cue card in the research matrix is written in the bottom right corner. The centre of the front of the card is reserved for supplementary notes. The back of the cue card is reserved for sketches.

An analysis of the photos and notes accompanying the field data from the Conservatory indicated that a single physical boundary could limit multiple phenomena. Each of these phenomena are thus referred to as a *mode* (again, located in top-left corner of cue cards, front side) of a boundary. A single cue card included only one mode, its boundary, and one of the two map perspectives. For this reason, there were multiple cards each denoting the same boundary (e.g. roof), but with a different mode (e.g. vegetation, water, nutrients, or temperature, etc.), and perspective (azimuthal or cross-sectional).

As mentioned, the cue cards representing the boundaries and their modes were placed within the research matrix according to the spatial characteristics of the mode (e.g., linear, true 3-D, etc.) on the x-axis, and visual variables that may depict the boundary on the y-axis. The resulting matrix was then recorded in a Microsoft Excel database.

4.3.1 Ecological Boundary Symbology Matrix

The original electronic version of the cue card research matrix in Excel, based on Slocum et al. (2005), was modified to include my research-specific categories, and subsequently developed into a new matrix to suit the requirements of this thesis. These categories included all of the headings from the cue card template: boundary, mode, map perspective, and comments; as well as the categories derived from the Slocum et al. (2005) matrix: portrayal of the mode, portrayal of the phenomenon, and a visual variable.

In addition to these categories, four additional columns were added to the database to describe the boundary-mode sets based on new terms and definitions, as well as fiat and bona fide boundaries. This is described in the Results chapter. **Table 4.1** describes what information was recorded in the Ecological Boundary Symbology Matrix. This information was used to determine what symbols represented the boundary-mode sets best.

Table 4.1

Explanation of content in the Ecological Boundary Symbology Matrix

Matrix Header	Description of the Header
Boundary	A boundary observed during Conservatory fieldwork
Mode	The spatial phenomenon limited by, or passing across, the boundary
Definite, Indefinite, or Perforated	Boundary is classified as either definite, indefinite, or perforated based on characteristics observed at the Conservatory
Fiat or Bona fide	Boundary is classified as either fiat or bona fide, based on observation
Interface or Medial	Boundary is classified as either an interface or medial boundary, based on observation
Spatial Phenomenon of the Mode	The mode is either a 2 ½-D or true 3-D spatial phenomenon.
Map Perspective	If a map was constructed of the mode and boundary, it would be in either a cross-sectional (XS) or azimuthal (BE) perspective
Portrayal of Boundary Phenomenon	The boundary is a spatial entity that can be depicted on a map as a linear, areal, 2 ½-D or true 3-D phenomenon based on its characteristics. Based on Slocum et al. (2005).
Visual Variable	Cartographic visual variables that can be used to portray the boundary include spacing, size, perspective height, orientation, shape, arrangement, lightness (grey scale or colour), hue, and saturation. Based on Slocum et al. (2005).
Supplementary Notes	Any additional information I have included

4.4 Boundary Symbology Design and Construction

A set of ecological boundary symbols were created based on the findings of the Ecological Boundary Symbology Matrix. Symbols were constructed using CorelDraw X4. Basic cartographic design principles were employed in the process (Dent et al., 2009; Slocum et al., 2005), as well as consultation with other cartographic sources (such as Kuchler, 1988; Wood & Fels, 2008). The symbols were designed to represent the phenomenon (the boundary and the mode) and its characteristics most effectively. Often, this meant incorporating a defining characteristic of the phenomenon. For example, if a boundary between two adjacent vegetation types is a gradual but measurable change from one vegetation type to the other, a gradient symbol can effectively represent the boundary. Obviously, constructing a symbol for every entry in the Ecological Boundary Symbology Matrix was beyond the scope of this thesis. Also, I wanted to generate a flexible symbol set.

4.5 Mapping the Conservatory and remapping the Long Point component of the proposed Manitoba Lowlands National Park

Symbols designed and constructed in the previous section were then applied to maps of the Conservatory study area using CorelDraw X4. A single boundary was selected to be mapped, the exterior glass walls, with a number of its modes. Each boundary-mode combination was depicted on a single map using symbols that best portrayed the boundary-mode characteristics. This yielded a map set consisting of five maps of the same boundary, each depicting the boundary with symbology based one of its multiple modes. These maps were constructed to make each boundary-mode combination stand out via the unique symbology that represented the boundary-mode characteristics best. Then another map was produced that included all the symbols created for that boundary (and its multiple modes), shown on the previous five maps. This map was constructed to show the reader how these symbols could be complied onto a single map and still convey the detail of each boundary-mode combination.

Next, the symbology was applied to a map from Manseau et al. (2001), shown in **Figure 4.5**, to illustrate that effective symbology can improve the readability of a map and interpretation of the map data. The map from Manseau et al. was intended to convey two main aspects: a proposed boundary of the

Long Point component of the proposed Manitoba Lowlands National Park, and conservation target areas (CTAs) that should be considered when determining the national park boundaries. CTAs are areas that are determined to meet habitat requirements for local, regional, and coarse scale terrestrial and aquatic species to maintain viable populations as well as preserve aquatic and plant communities by incorporating unfragmented wilderness areas and aquatic connectivity of the interlake area between Lake Winnipeg and Lake Winnipegosis (Manseau et al., 2001).

There are five individual CTAs on the Manseau et al. map: an aquatic CTA, a wilderness CTA, a caribou CTA, an elk/warbler CTA, and a vegetation CTA. The boundaries of these CTAs are all symbolized as dashed lines of the same thickness in various grey tones. Overall, the map supports the argument of Manseau et al. that the proposed park boundaries for the Long Point component do not sufficiently cover the CTAs. However, the lack of visual variation between the five CTA symbols decreases map effectiveness because the map reader cannot make the distinction between the boundaries of the CTAs.

A comparison to this map (Figure 4.5) and those drafted within this thesis will be made in section 5.4.2.

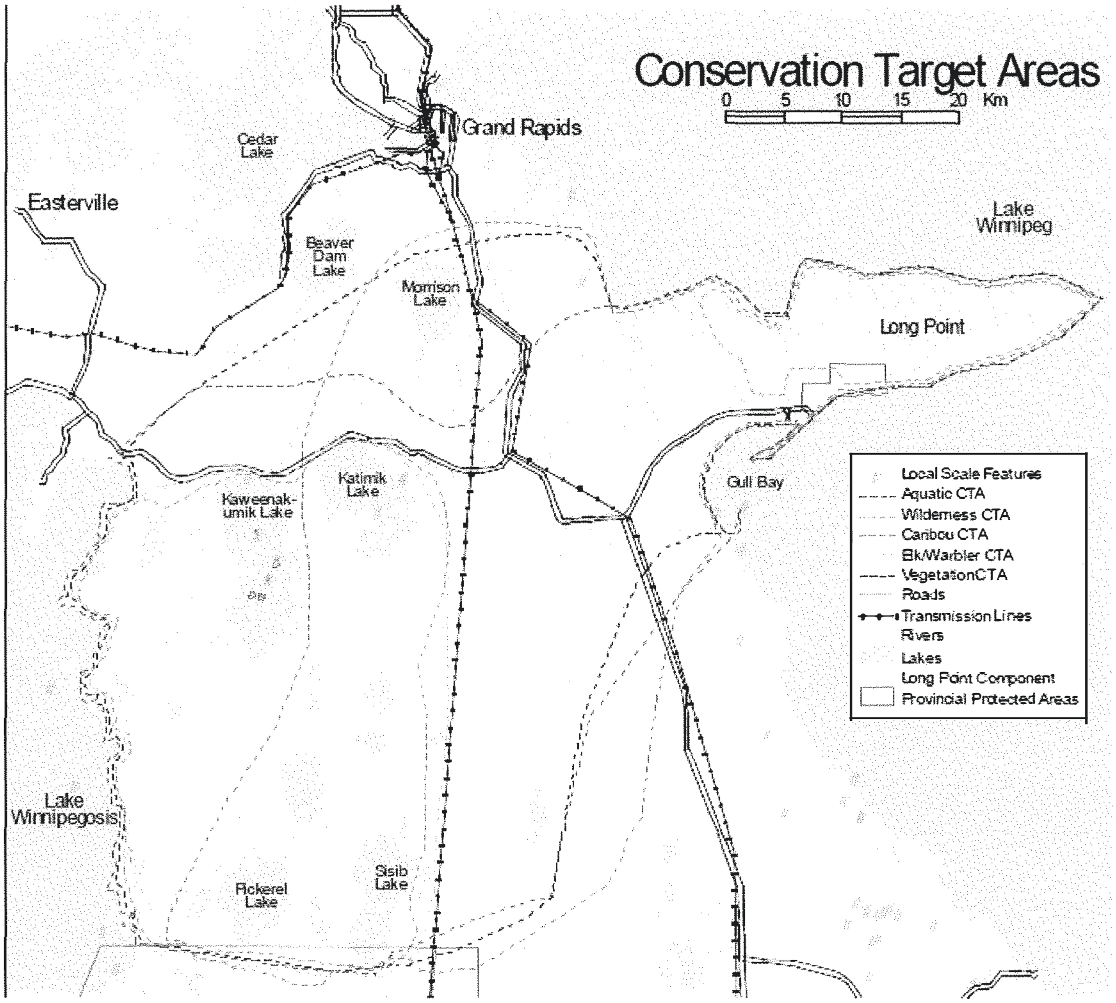


Figure 4.5. Map from Manseau et al. (2001) depicting ecological conservation target area (CTA) boundaries associated with the creation of the proposed Manitoba Lowlands National Park, specifically the Long Point component of the proposed National Park.

4.6 Preparing Boundary Symbology Guidelines

The purpose of these guidelines is to assist map makers in the construction of detailed ecological boundary maps. The guidelines were created by consulting the Ecological Boundary Symbology Matrix, my new terms and definitions, and the boundary symbology developed in this thesis. Work by Strayer et al. (2003) on ecological boundary theory and classification was also consulted. These guidelines are intended to provide a theoretical rationale to mappers enabling them to map ecological boundaries effectively. To map a specific ecological boundary, the guidelines can help the map maker determine what type of symbology to use based on the characteristics of the boundary-modes they are studying.

4.7 Summary

This chapter detailed the methodology used to address the research objective of effectively mapping ecological boundaries through the development of cartographic symbols. It described the fieldwork required, and the construction of a research matrix used as an analytical tool to examine ecological boundary properties and spatial characteristics. It described the design and construction of ecological boundary symbols, the implementation of the boundary symbols on a map series of the Conservatory, a map of the Long Point component of the proposed Manitoba Lowlands National Park, and the construction of guidelines.

Chapter 5 presents the results of this research. It provides new definitions and builds on existing ones. Results of the Ecological Boundary Symbology Matrix, symbology construction, and guidelines are provided.

Chapter Five: Results

5.1 Introduction

The last chapter presented the reader with the methodology used in this cartographic analysis of ecological boundaries. It described field research, the construction of the Ecological Boundary Symbology matrix, boundary symbol design, map construction using the symbols, and the preparation of guidelines.

This chapter provides the results of the analysis described in my methodology. It begins with new definitions and builds on existing terms applied throughout my research. Results of the Ecological Boundary Symbology Matrix, boundary symbology construction, guidelines, and the case study boundaries are also presented here.

5.2 New Terms & Definitions

It was necessary to develop new boundary terms and definitions to describe some significant characteristics of the ecological boundaries observed in the Conservatory.

The term, *mode*, was chosen to describe a spatial phenomenon that comes in contact with the boundary. Ecological modes observed and recorded during the Conservatory field research included water, water vapour, light, temperature, nutrients, gas, and vegetation. This term is important because it allows ecologists and mappers to single out a phenomenon and label it; labelling something helps work toward defining the phenomenon as well.

A *definite boundary* marks a clear and definitive limit of the mode. The mode does not pass through the boundary into the space beyond it. For example, a stone retaining wall separating the vegetation from the concrete walkway observed in the Conservatory is a definite boundary when the mode is soil nutrients. This is because the soil nutrients can not effectively flow through the stone retaining wall to the space beyond.

If the mode is less restricted by the boundary, the boundary is described as an *indefinite boundary*. An example of an indefinite boundary is the glass roof when the mode is air temperature. In this instance, the air temperature outside and inside the Conservatory are weakly bound by the glass; there is some transfer of thermal energy across the boundary. However, the glass is still a boundary for temperature because a significant difference can exist between the temperature inside the Conservatory and the temperature outside – especially with seasonality.

A *perforated boundary* is segmented with definite and indefinite sections so that the mode is able to pass through some sections of the boundary but not others. An example of a perforated boundary is an interior wall of the Conservatory when the mode is water vapour. In this study, I define the interior wall as the glass wall and wooden doors, windows, and vents located along the wall. Segments of the wall that allow water vapour to pass through the boundary include doors, windows, and vents; in these areas, the boundary is characterized as indefinite. The remaining portion of boundary, the glass sections, is characterized as definite because the water vapour does not pass directly through the glass wall at a significant rate or amount.

Furthermore, I determined that a boundary is one of two types: an interface boundary or a medial boundary. An *interface boundary* is a meeting place of two or more distinct and discrete objects/entities. The soil-air boundary observed at the Conservatory is an interface boundary; it is the interface of the surface of the soil and the atmosphere of the Conservatory. A *medial boundary* is an entity, or object of its own, in-between two or more distinct and discrete entities. Furthermore, a medial boundary consists of two interface boundaries. For example, the interior walls that divide the Conservatory into three smaller greenhouses are medial boundaries between the greenhouses because they are boundary objects between the phenomena that occur on either side of the walls. This medial boundary is composed of two medial boundaries, which is most obvious at a fine scale, where the glass surface and the atmosphere of the Conservatory meet on both sides of the glass wall.

The various boundaries observed in the Conservatory are also classified as bona fide or fiat. *Bona fide boundaries* exist as physical entities on the geographic landscape and are independent of a theoretical human demarcation (e.g. the shoreline of Hudson Bay is a bona fide boundary between the land and the water). I interpret this definition to include the physical (natural or artificial) ecological boundaries observed within the Conservatory. *Fiat boundaries* are human-demarcated and exist in an imaginary plane on the landscape. It is important to note that human-demarcated and human-constructed boundaries are not synonymous; as mentioned, human-demarcated boundaries exist in an imaginary dimension on the landscape while human-constructed boundaries are physical boundaries on the landscape and are therefore bona fide. See **Table 5.1** for the terms and definitions that were developed and used to describe ecological boundaries observed in the Conservatory.

Table 5.1

New terms and thesis-specific definitions of ecological boundaries

Term	Definition or Extension
mode	A spatial phenomenon that comes in contact with a boundary. Characteristics/properties of the boundary and the phenomenon dictate how the boundary limits the phenomenon. A boundary can have one or more modes.
simple physical boundary	A place where perceptual change occurs between one object, entity, phenomenon, and another.
definite boundary	The boundary marks a clear and definitive limit of the mode. The mode does not cross into the space beyond the boundary.
indefinite boundary	The boundary does not fully limit the mode. To what extent the mode passes through the boundary depends on properties of the mode and the boundary.
perforated boundary	The boundary is segmented with definite and indefinite sections based on the characteristics of the boundary and the mode.
interface boundary	The boundary is a meeting place of two or more distinct and discrete entities or objects.
medial boundary	The boundary itself is an entity or object between two or more other distinct and discrete entities or objects. This boundary is composed of two interface boundaries with an object in between them.
bona fide boundary	The boundary is a physical entity or object on the landscape. It exists independently of human-demarcation (Smith & Varzi, 2000). In this thesis, this definition includes physical boundaries on the landscape that are natural, human-constructed and demarcated.

fiat boundary	The boundary is human-demarcated and exists as an imaginary layer on the landscape. Fiat boundaries may or may not be linked to bona fide objects that are natural or human-constructed (Smith, 1995;Smith & Varzi, 2000).

5.3 Fieldwork Results and the Research Matrix

As mentioned in my methodology chapter, six ecological boundaries were studied in the Conservatory and included in the research matrix. They were: 1) the roof, 2) exterior glass walls, 3) interior glass walls, 4) the pond surface, 5) soil/stone retaining walls/walkways, and 6) the building floor/ foundation. **Figure 5.1** is a photograph of one of the ecological boundaries, the glass roof, studied in the Conservatory and used in the research matrix and the Ecological Boundary Matrix. See photographs of the other ecological boundaries in the Conservatory in Appendix A.

Figure 5.1. A photograph of the glass roof boundary taken inside the Conservatory.

Cue cards containing information related to each boundary-mode combinations were constructed and placed on the research matrix. The research matrix was used to construct the Ecological Boundary Symbology Matrix. See **Figure 5.2** as one example of a cue card used in the research matrix and Appendix B to view all of the cue cards used in the research matrix.

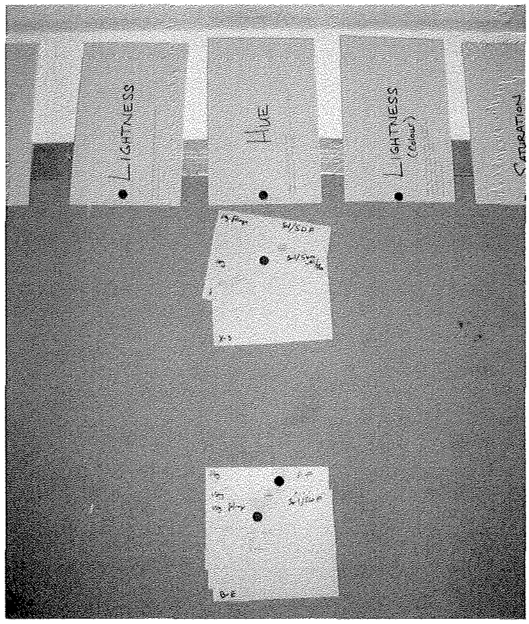


Figure 5.2. Photograph of a portion of the research matrix consisting of cue cards arranged according to visual variables described by Slocum et al. (2005). See Figure 4.2 and 4.3 in Chapter 4 for an explanation of the visual variables.

5.4 Ecological Boundary Symbology Matrix

The Ecological Boundary Symbology Matrix was constructed to create symbols that carefully reflected ecological boundary and mode properties while adhering to cartographic theories and design principles. Multiple modes were studied with each boundary and this yielded several matrix entries for the same boundary. Primary modes studied with all boundaries included gas, nutrients, temperature, water, vegetation, and light. Also, each unique boundary-mode set was matched with an azimuthal or cross-sectional map perspective. This yielded 76 exclusive combinations in the matrix consisting of a single boundary, a single mode, and a map perspective. In the interest of conciseness, I will not go into detailed descriptions of each boundary-mode set. See Appendix C to review all 76 entries of the Ecological Boundary Symbology Matrix. **Table 5.2** details the six boundaries studied in the Conservatory and the modes I show to study with each boundary.

I found that determining the appropriate visual symbols for each boundary-mode depended on the properties and spatial characteristics of the boundary and mode, as well as the map perspective. To assist in this determination of symbols, the spatial phenomena of the modes were identified and recorded in the matrix. Thirty-eight modes were true 3-dimensional spatial phenomena when depicted in an azimuthal (bird's-eye-view) map perspective. This is exactly half of the modes studied. The other 38 modes were 2 ½ dimensional spatial phenomena when depicted with a cross-sectional map perspective.

Table 5.2

Boundary-mode sets studied in the Ecological Boundary Symbology Matrix

Ecological Boundary Observed at the Conservatory	Associated Modes
Roof	Temperature Precipitation (Water) • nutrients (from precipitation) Gases Vegetation Light
Exterior glass walls	Temperature Water Nutrients Gases Vegetation Light
Interior glass walls	Temperature Water • water vapour Nutrients Gases Vegetation Light
Pond surface	Temperature Water Nutrients Gases Vegetation (terrestrial) Light
Soil/stone retaining wall/walkways	Temperature Water Nutrients Gases Vegetation • foliage • roots Light
Floor/foundation	Temperature Water Nutrients Gases Vegetation Light

According to the new terms and definitions in section 5.2, nearly half of the 76 boundary-mode sets exhibited spatial characteristics and properties which establish that their boundaries are *definite*; about a third of the boundary-mode sets have *indefinite* boundaries; the remaining boundary-sets have *perforated* boundaries. Half of the boundaries were deemed *interface* boundaries and the other half are *medial* boundaries. Similarly, the majority of boundary-mode sets exhibited the spatial characteristics and properties of *bona fide* boundaries; a small portion of the boundary-mode combinations have *fiat* boundaries. See **Table 5.3** for further details or refer to the Ecological Boundary Symbology Matrix in Appendix C for the exact breakdown according to boundary-mode sets.

Table 5.3

Boundary-mode characteristics

	Number of Modes
True 3-D modes	38
2 ½-D modes	38
	No. of Boundaries
Definite	34
Indefinite	28
Perforated	14
Interface	38
Medial	38
Fiat	12
Bona fide	64

The Ecological Boundary Symbology Matrix was constructed in Microsoft Excel using the boundary-mode characteristics described above, as well as consultation of **Figure 4.2** and **Figure 4.3**. **Table 5.4** provides an example of one entry in the Matrix. See Appendix C to view the Ecological Boundary Symbology Matrix.

Table 5.4

Explanation of content in the Ecological Boundary Symbology Matrix

Matrix Header	Example from Matrix
Boundary	Exterior glass wall
Mode	Vegetation
Definite, Indefinite, or Perforated	Definite
Fiat or Bona fide	Bona fide
Interface or Medial	Medial
Spatial Phenomenon of Mode	True 3-D
Map Perspective	Azimuthal (bird's eye view)
Portrayal of Boundary Phenomenon	Linear
Visual Variable	Size, Perspective Height, Lightness (grey scale or colour), hue, saturation
Supplementary Notes	Solid gray line to symbolize exterior glass walls

5.4.1 Boundary Symbology Design & Construction

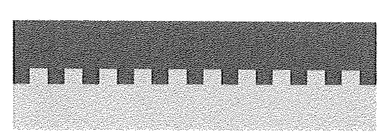
Symbols were designed based on findings of the Ecological Boundary Symbology Matrix and terms described in **Table 5.1**. The symbols in **Table 5.5** were constructed to represent various ecological boundaries and associated modes. Symbols were designed to best reflect the phenomena they represent. For example, if a boundary studied in the Ecological Boundary Symbology Matrix is described as a *definite boundary* then a solid, unbroken boundary symbol is an effective cartographic depiction because it communicates the definitive nature of the boundary to the map reader. Similarly, if the mode transforms as it crosses the boundary, like a change in temperature or vegetation type, the boundary may best be cartographically depicted as a colour (or greyscale) gradient.

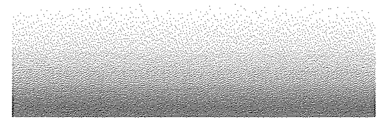
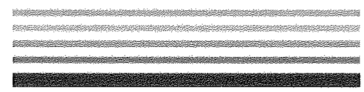
Next, I constructed five maps (**Map 5.1 to 5.5**) depicting the exterior walls of the Conservatory, as a boundary, with five modes using CorelDRAW X4. Modes include vegetation, soil nutrients, temperature, light, and air. The symbols were constructed based on the spatial phenomena (boundary- modes sets) and corresponding cartographic visual variables described by Slocum et al. (2005). Then a single map (**Map 5.6**) was constructed as a compilation of the boundary symbols from **Map 5.1 to 5.5**.

Map 5.1 depicts the exterior glass walls as the ecological boundary when vegetation inside the Conservatory is the mode. On this map the boundary is a solid line around the vegetation within the Conservatory. This solid line symbol is intended to give the map reader the impression that the vegetation (the mode) does not pass though the glass walls (the boundary) because it is a definite and bona fide boundary. It is also a medial boundary because it is an object between two other objects: the interior of the Conservatory and everything outside of the Conservatory. Other features within the Conservatory other than

Table 5.5.

Boundary symbology

Symbol Description	Symbol
Symbol is a solid line that represents a definite boundary; the mode does not pass through. It is a medial boundary, and can be bona fide or fiat, depending on the scenario. Depicted as a solid colour or using grey scale (shown here).	
Symbol is a dotted or dashed line that represents an indefinite boundary; the mode flows through the boundary. It is a medial boundary, and can be bona fide or fiat, depending on the scenario. Depicted as a solid colour or using grey scale (shown here).	
Symbol is a solid line with dashed portions that represents a perforated boundary; the mode may flow through portions represented by dashes, but not through portions of depicted as a solid line. This is a medial boundary that is bona fide or fiat. Depicted in solid colour or grey scale (shown here).	
Symbol is a solid line with dashed line above, it represents a boundary that may let the mode flow through, depending on the conditions. Medial boundary, bona fide or fiat.	
Symbol consists of dashes of alternating colours, representing an indefinite, interface boundary. Bona fide or fiat. Depicted in colour (shown here) or grey scale.	

Symbol consists of a change in hue (shown here) or grey-scale along a gradient. It represents an indefinite, interface boundary. It can be bona fide or fiat.	
Symbol is composed of isolines with colour gradient (shown here) or grey scale, it represents an indefinite boundary where the mode passes through. It can be a medial boundary, bona fide or fiat.	

vegetation (represented in green), like the interior glass walls, door, pond, and pathways, were not included on the map because they are not the main map subjects. Vegetation outside of the Conservatory was not mapped because this study focused on ecological boundaries and phenomena within the Conservatory, not outside of it. The restricted area includes all areas that are not accessible to the public.

Map 5.2 depicts the exterior glass walls as the ecological boundary when the soil nutrients within the Conservatory are the mode. The boundary symbol on this map is a solid line around the soil. This symbol is intended to give the map reader the impression that the soil nutrients (the mode) within the Conservatory do not pass though the glass walls (the boundary) and that the boundary is a definite and bona fide boundary. It is also a medial boundary. Soil nutrients are represented in brown.

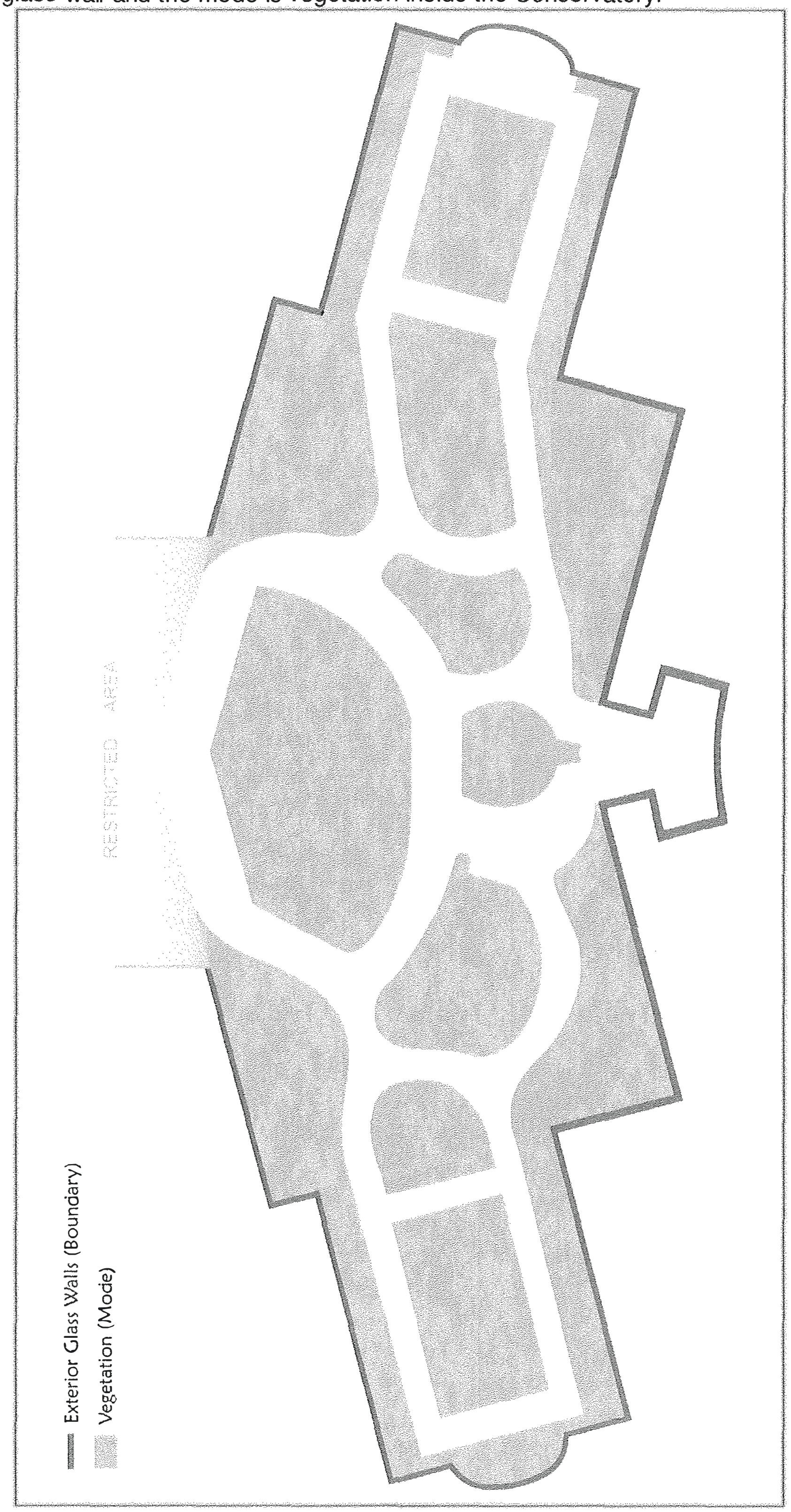
Map 5.3 depicts the exterior glass walls as the ecological boundary when the air temperature is the mode. On this map the boundary is a series of concentric lines (or isolines) in the general shape of the Conservatory's exterior walls. Each isoline is a different hue between red and blue, this symbolizes a gradual temperature change across the boundary between the interior temperature and the exterior temperature. At the time that field research was conducted (December 2008 and January 2009) the temperature inside the Conservatory was much warmer (approximately 23°C) than the temperature outside (approximately -20°C). On the map, the warmer temperature within the Conservatory is represented using the colour red, the colour blue is used to represent the colder temperature outside the Conservatory. The boundary is represented as a colour gradient of isolines to give the map reader the impression that the exterior glass wall does not fully prevent the movement of temperature across the boundary. This means that the boundary is an indefinite and bona fide boundary. It is also a medial boundary. No features within the Conservatory are included on the map because the map subjects are the boundary and the mode only, not vegetation, interior walls, soil nutrients etc.

Map 5.4 depicts the exterior glass walls as the ecological boundary when light is the mode. On this map the ecological boundary is depicted as a dotted line. The dotted line was used to give the map reader the impression that the boundary is vague because the mode (light) passes through the boundary because the exterior Conservatory walls are semi-opaque glass. This boundary is an indefinite, fiat, medial boundary. No features within the Conservatory are included on the map because the map subjects are the boundary and the mode only.

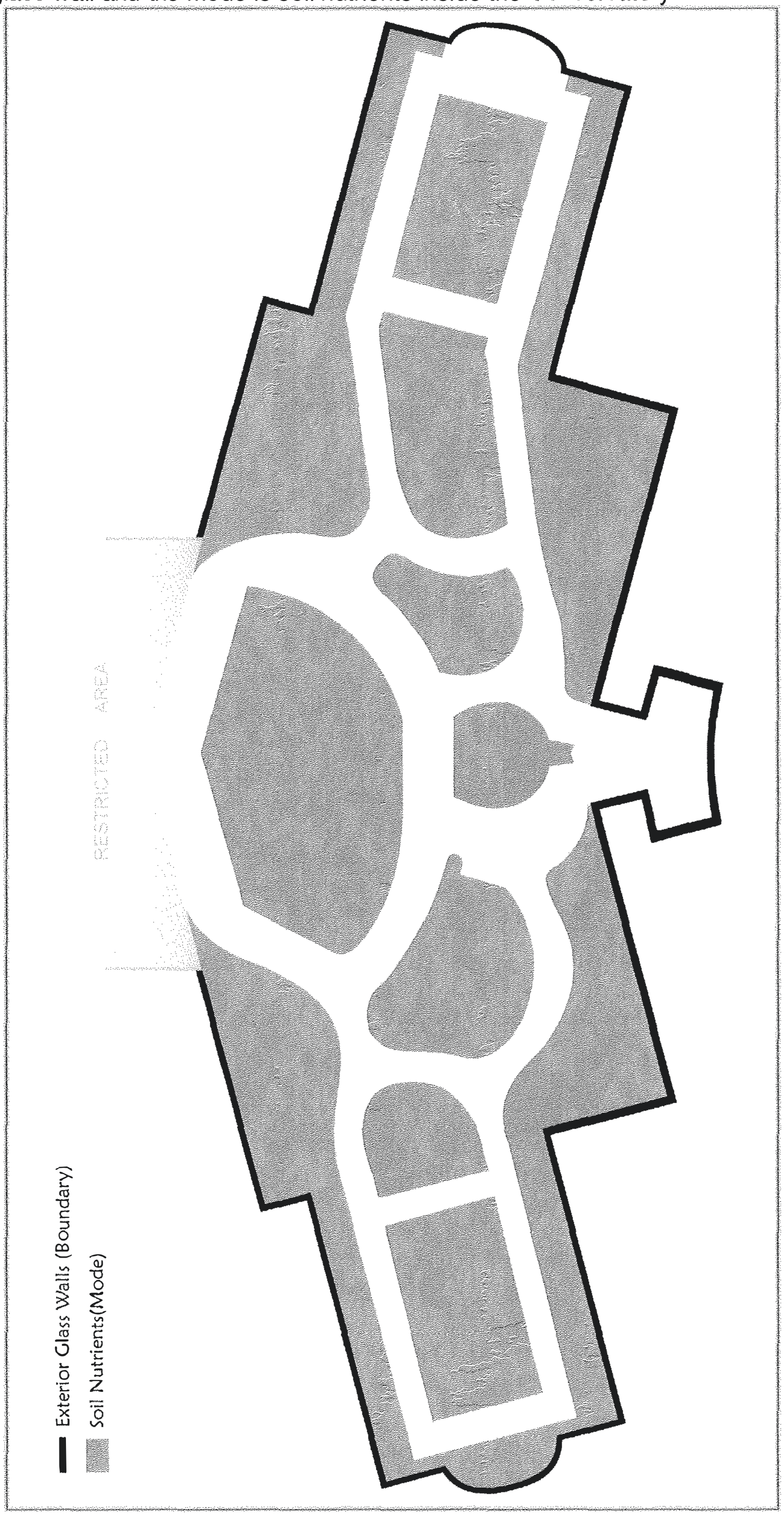
Map 5.5 depicts the exterior glass wall as the ecological boundary when the mode is air temperature. The boundary symbol on this map is symbolized as a solid black line and the exterior doors situated within the outer glass walls are symbolized as solid line parallel to a dashed line. This symbol was created to describe two possible boundary situations: when the doors are closed air does not pass through the boundary (supposing that the doors have an airtight seal) creating a definite boundary (solid line portion of door symbol), but when the doors are open air passes though the boundary creating an indefinite boundary (dashed line portion of door symbol). This boundary symbol was used to give the map reader the impression that the boundary has definite and indefinite (when doors are open) segments creating a perforated boundary. The boundary is also a bona fide and medial boundary.

Map 5.6 is compilation boundary map consisting of the exterior glass wall boundary symbols used in the map series **5.1** to **5.5**. Five boundary symbols representing the exterior glass wall are included on this map to demonstrate how this symbology can be assembled to provide the map reader with a detailed view of the ecological boundary. Each symbol used to map the exterior glass walls on this map represents how each mode of interest interacts with the boundary (see explanations for the symbology described for **Map 5.1** to **5.5**). For example, the gradient colour symbol used in **Map 5.3** to represent the wall-temperature boundary-mode set can be seen on **Map 5.6**. The wall-vegetation boundary-mode set is symbolized as a solid grey line, the wall-soil boundary is symbolized as a solid grey line and is the same symbol used for the wall-vegetation boundary, the wall-light boundary-mode set is represented as a dashed yellow line, and the wall-air boundary-mode set is symbolized as a solid black line with dashed lines parallel to the solid line used to depicting a door. A single symbol was used to represent the wall-vegetation boundary-mode set and the wall-soil boundary-mode set because they are similar enough (definite, bona fide, and medial boundaries) to map using one symbol. This map also includes vegetation (represented in green), the walkways, the bridge, pond, the waterfalls, and an approximate scale.

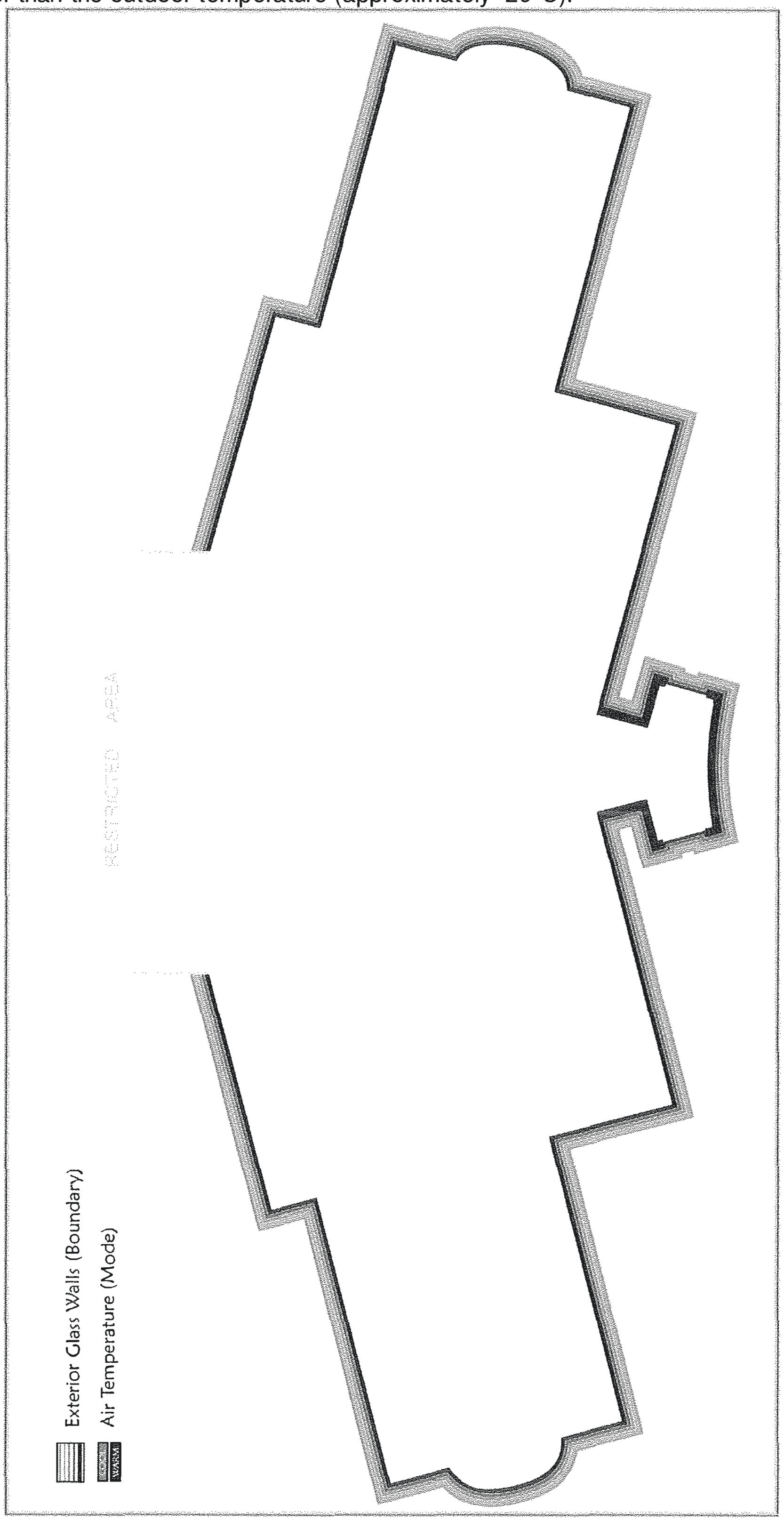
Map 5.1. A map of the Centennial Botanical Conservatory. The ecological boundary of interest is the exterior glass wall and the mode is vegetation inside the Conservatory.



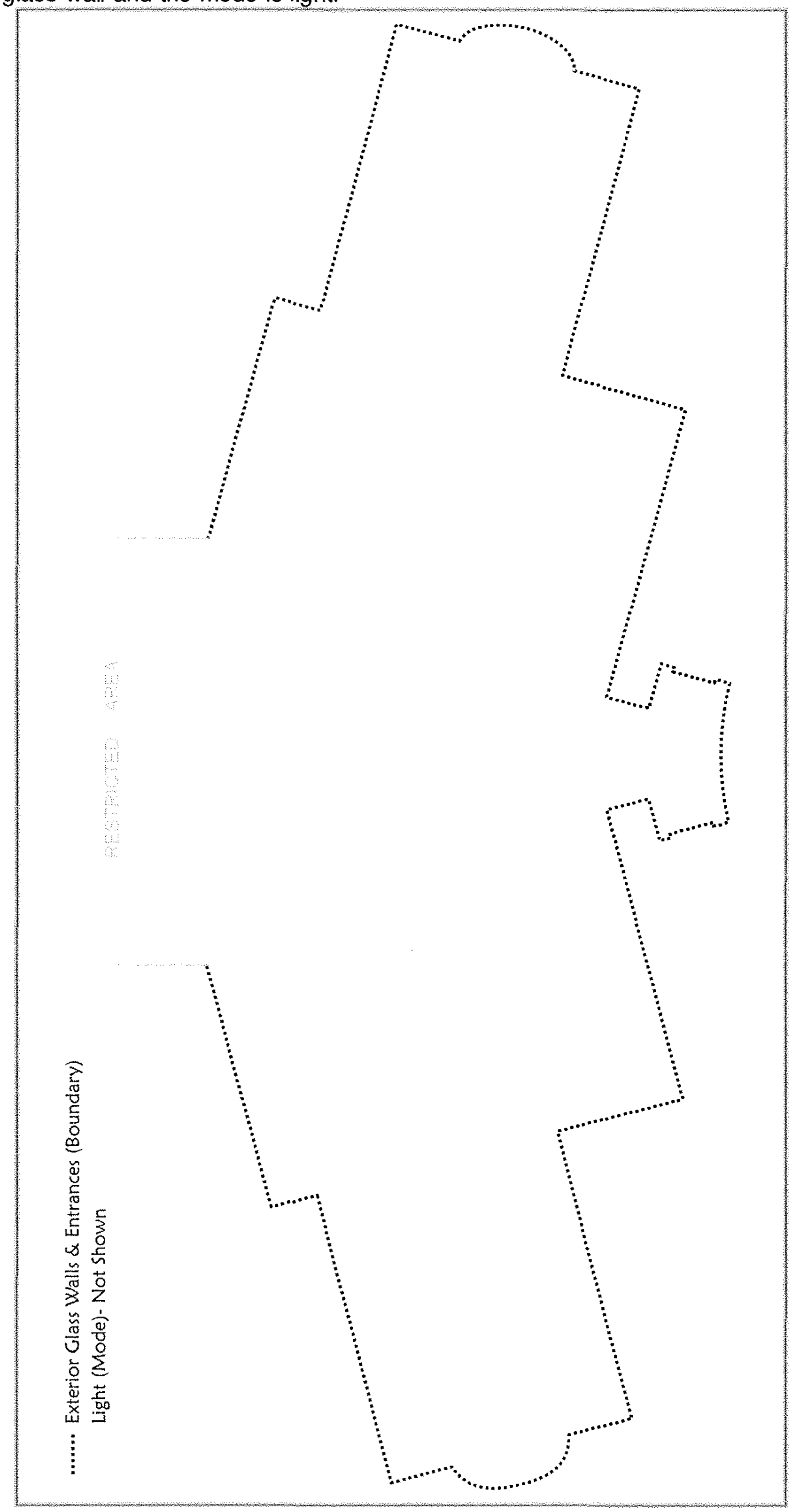
Map 5.2. A map of the Centennial Botanical Conservatory. The ecological boundary of interest is the exterior glass wall and the mode is soil nutrients inside the Conservatory.



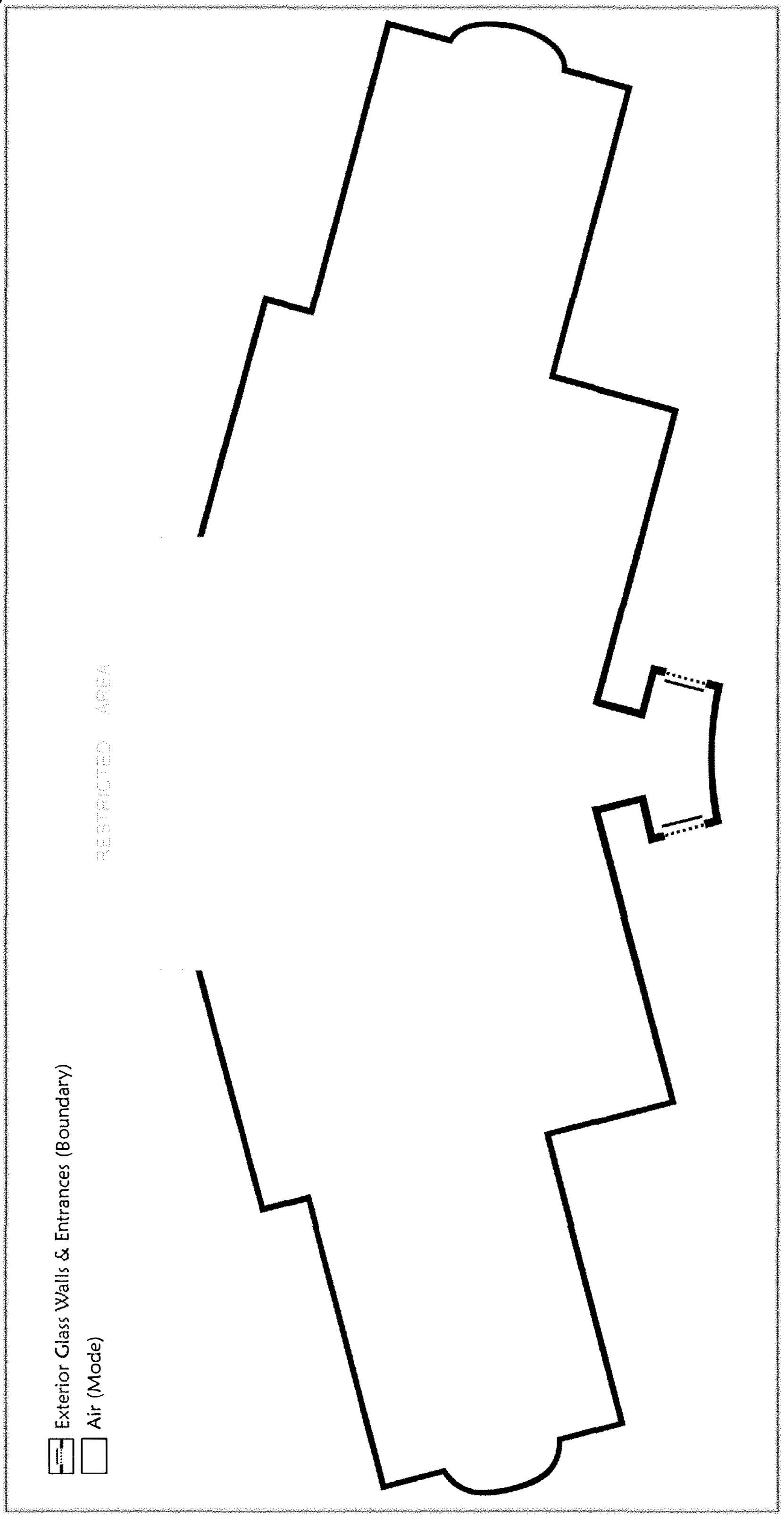
Map 5.3. A map of the Centennial Botanical Conservatory. The ecological boundary of interest is the exterior glass wall and the mode is temperature. Fieldwork observations were conducted in December and January, the air temperature inside (approximately 23℃) the Conservatory was much warmer than the outdoor temperature (approximately -20℃).



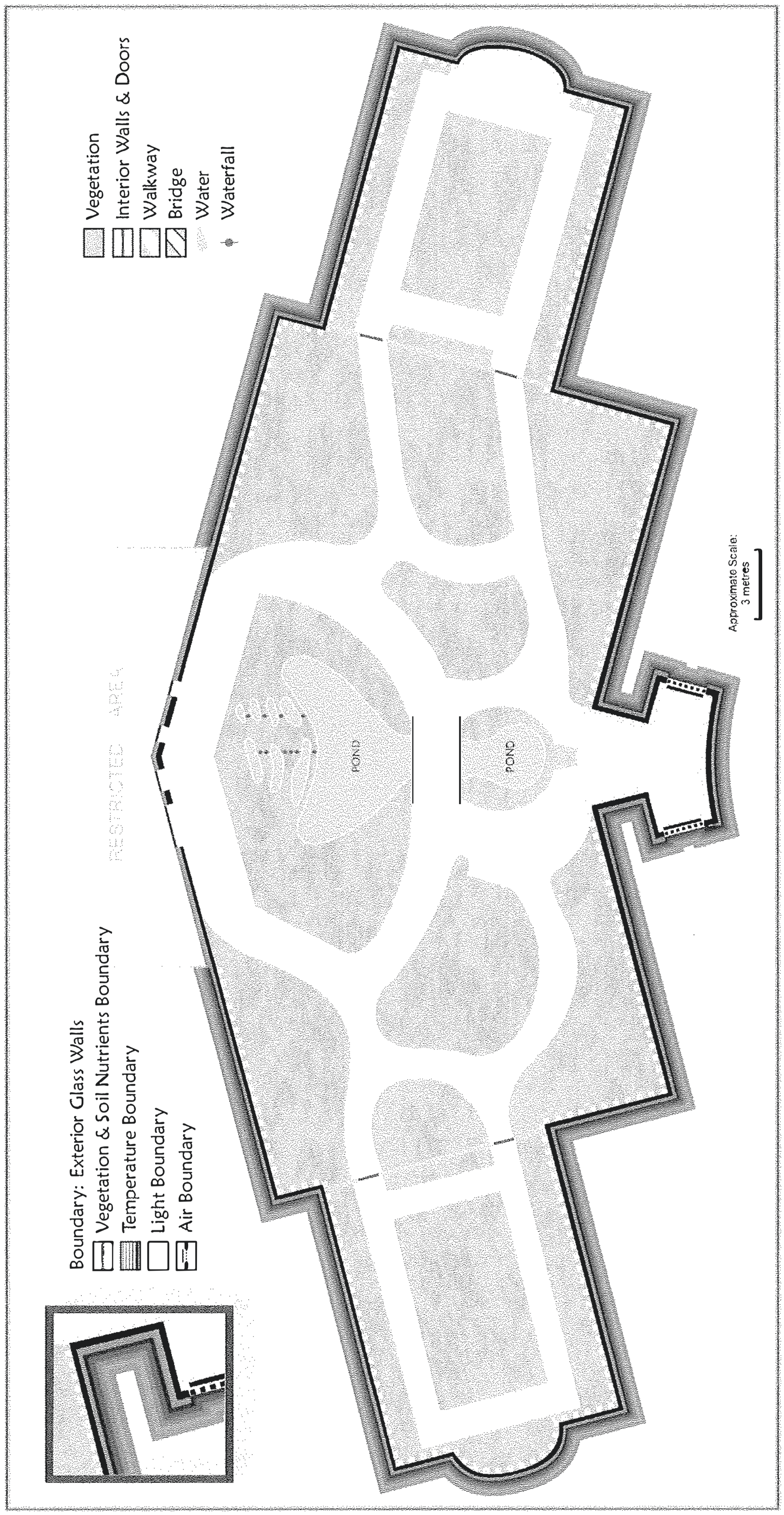
Map 5.4. A map of the Centennial Botanical Conservatory. The ecological boundary of interest is the exterior glass wall and the mode is light.



Map 5.5. Map of the Centennial Botanical Conservatory. The ecological boundary of interest is the exterior glass wall and the mode is air.



Map 5.6. A map depicting all five ecological boundary symbols presented on Maps 5.1 through 5.5.



5.4.2 Symbology on a Landscape Map

Symbology described in this chapter was applied to a map from Manseau et al., 2001 (see **Figure 4.5**) to illustrate how effective symbology can improve the readability of a map and interpretation of the map data. The map by Manseau et al. conveyed two main aspects: a proposed National Park boundary of the Long Point component of the proposed Manitoba Lowlands National Park, Conservation Target Areas (CTAs) that are considered when determining national park boundaries. Overall, the map supports Manseau et al.'s argument that the proposed park boundaries for the Long Point component was inadequate and does not cover five important CTAs.

The CTA boundaries on the Manseau et al. map are symbolized as dashed lines of the same thickness in similar grey tones. The dashed line symbol used for the CTA boundaries is an appropriate symbol choice because it gives the map reader the impression that these boundaries are indefinite boundaries on the landscape (which is the impression a solid line symbol would create). However, the repetitive symbology (i.e. the same dashed line, same thickness, and grey tones, as seen on **Figure 4.5**) decreases map readability if the map reader wishes to identify one CTA boundary from another.

I remapped the Manseau et al. map (**Figure 4.5**) using data provided on the original map as well as the symbology I constructed, described earlier in this chapter (see **Map 5.7** and **5.8**). The CTA boundaries can be considered boundary-mode combinations because there are modes (e.g. caribou) and boundaries (e.g. the CTA limit of the caribou). Some of the CTA boundaries on this map are considered indefinite because they are primarily situated on an undeveloped landscape and are considered natural boundaries. Some boundaries are perforated because there are portions along the boundary where the mode does not pass through the boundary and other portions where the mode can cross the boundary. Some boundaries are bona fide and some are fiat, although, it is difficult to determine for certain whether the boundaries are fiat or bona fide due to a lack of detailed data about the boundaries (e.g. detailed field observations of the boundaries), so I have made some assumptions about the boundaries based on information described by Manseau et al. (2000).

The aquatic CTA boundary is depicted as a thin, dark blue, dashed line. The marks that make up the dashes are short and widely spaced. This boundary is considered a fiat, indefinite, and interface boundary. This boundary is fiat because Manseau et al. (2000) describe the aquatic CTA limit as encompassing a number of medium-sized lakes, wetlands, shorelines, and artisan springs. From the description, it does not appear that there is specific boundary delineation by physical features for the aquatic CTA and it is therefore a human-demarcated fiat boundary. This also lends to defining the boundary as indefinite because the water within the aquatic CTA is not limited by a definitive physical boundary as is assumed to belong to the broader hydrological system of the landscape. This boundary is an interface boundary because no suggestion of a medial boundary is described by Manseau et al. (2000).

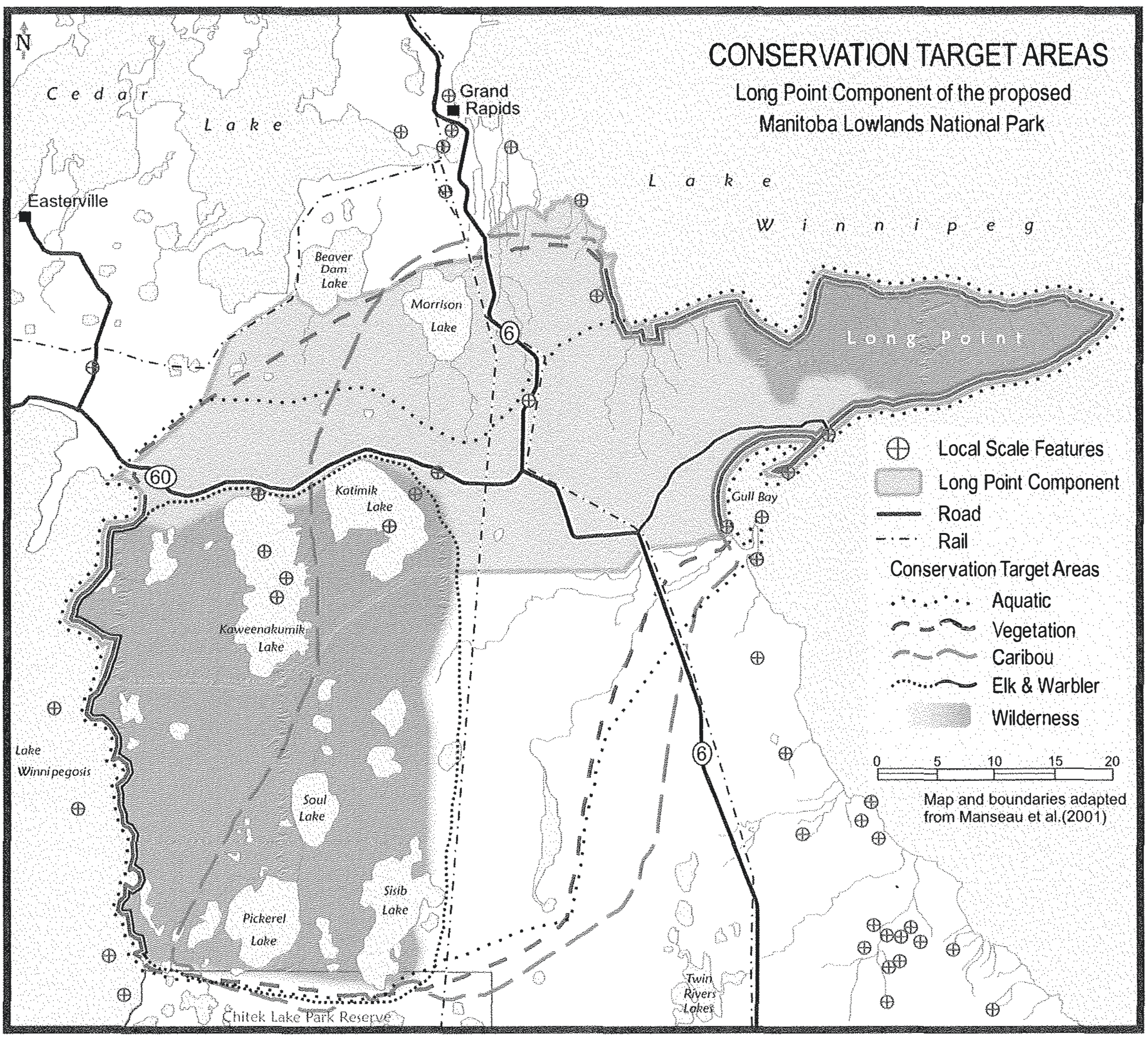
The vegetation CTA boundary is represented as a thicker green dashed line in areas on the map where vegetation is not greatly restricted by the CTA boundary, and as a solid line along the shoreline of Lake Winnipeg and Lake Winnipegosis where rooted vegetation does not cross the CTA boundary into the lake. This boundary is considered a perforated, interface boundary with fiat and bona fide sections. The boundary is perforated because sections of this vegetation boundary are definite (along the shorelines of the two major lakes) and indefinite where the boundary exists on land. It is indefinite on land because the vegetation CTA is not described by Manseau et al. (2000) as having explicit physical limits on land, only that the boundary is intended to preserve plant community biodiversity. For these same reasons, the boundary has bona fide (along the shoreline of the two major lakes) and fiat (the rest of the boundary) sections. This is also an interface boundary along the shorelines and across the land as there is no medial boundary described by Manseau et al. (2000) in between the vegetation (or water) on either side of the boundary.

The caribou and elk/warbler CTA boundaries have similar symbology to the vegetation CTA boundary but are differentiated in colour (orange and fuchsia), dash size (long dashes and short dashes), and symbol width (thicker dashed line for caribou; thinner dashed line for elk/warbler). These boundaries are considered perforated, interface with medial sections, and bona fide and fiat sections. Reasons for labelling this boundary as such are similar to reasons for the vegetation CTA (see **Map 5.7**). There is a potential that physical boundaries for the elk and warbler are created by a highway to the north of the CTA (see **Map 5.7**), and a transmission line to the east of the CTA, as anthropogenic habitat fragmentation often creates new boundaries for many species (Fischer & Lindenmayer, 2007).

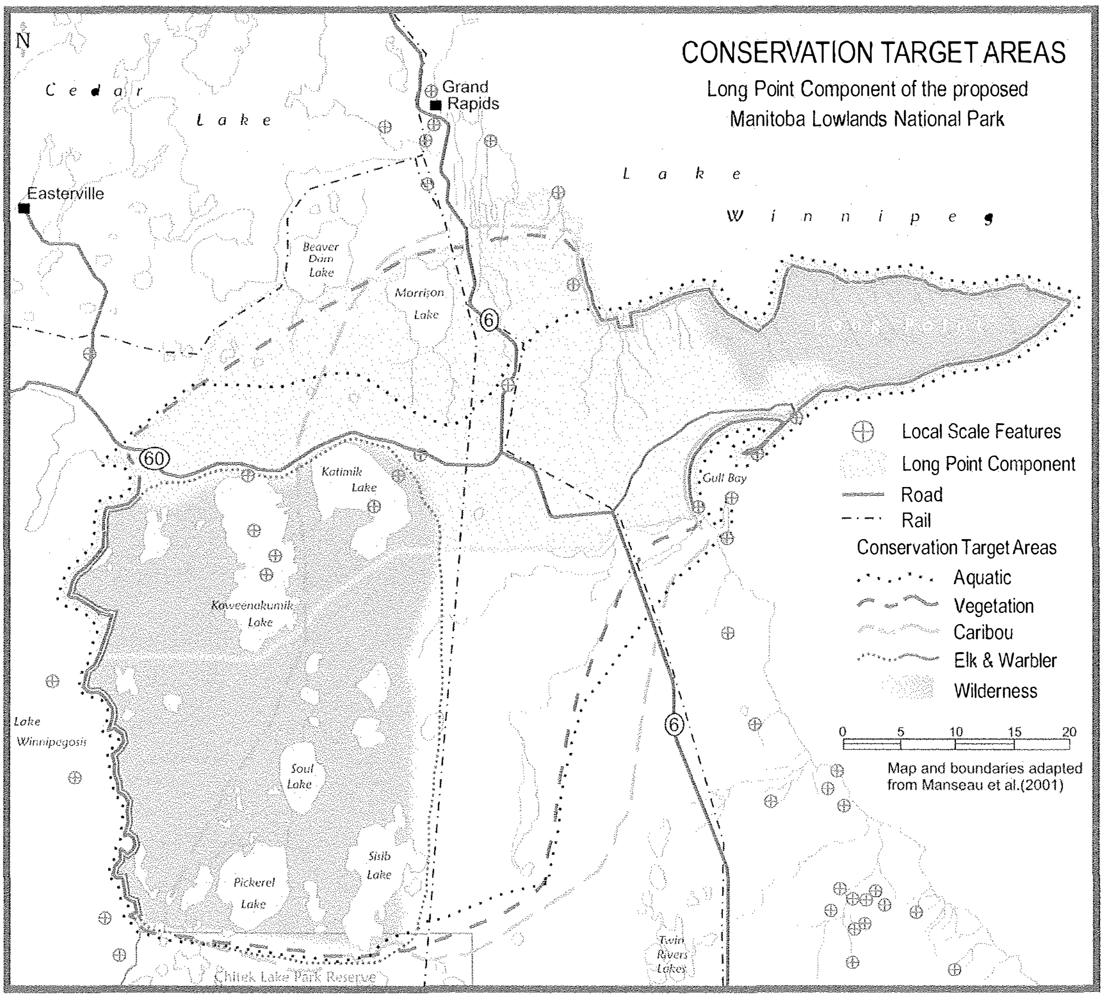
There are two wilderness CTAs on the map and they are depicted as green areas with gradient boundaries that gradually fade into the background of neighbouring colours. The gradient boundaries are intended to give the map reader an impression that the wilderness boundaries are natural and indefinite. Manseau et al. (2000) describes the wilderness CTAs as being areas that are relatively inaccessible (to humans) and unfragmented. The boundaries are considered perforated, interface, with bona fide and indefinite sections. The boundaries are considered perforated but primarily indefinite because there are no clear limits of the wilderness areas except along the shorelines of Lake Winnipeg, Lake Winnipegosis, Kaweenakumik Lake, and Katimik Lake (although they are also loosely based on physical features such as transmission lines, highways, and other park reserve boundaries). The boundaries are considered interface boundaries because no medial boundary objects are described by Manseau et al. (2000). The boundaries are bona fide along shoreline sections of the boundaries and fiat across the land.

The map is also presented in grey tones to illustrate how aspects of symbol choices such as line thickness and dash width can be translated to a black and white map even if the map was originally in colour (see **Map 5.8**). This is important because colour maps are often reproduced in black and white using photocopiers. Map symbology can become unreadable when changing the map scheme from colour to grey tone because many colours often take on similar grey tones. For example, a map consisting of light blue lakes and light green vegetation is converted to a greyscale map; this results in the two colours taking on the same light grey appearance on the grey tone map and the distinction between the waterbodies and the vegetation becomes undetectable. For these reasons, it is important to ensure symbols have other distinguishing aspects such as varying dash size, line width, symbol size, masking, and so on.

Map 5.7. Coloured map based on Manseau et al. (2001) depicting ecological conservation target area (CTAs) associated with the creation of the proposed Manitoba Lowlands National Park, specifically the Long Point component of the proposed National Park.



Map 5.8. Grey tone map based on Manseau et al. (2001) depicting ecological conservation target area (CTAs) associated with the creation of the proposed Manitoba Lowlands National Park, specifically the Long Point component of the proposed National Park.



5.4.3 Boundary Symbology Guidelines

This section describes the steps that I have determined a map maker should follow when mapping ecological boundaries (see **Table 5.6)**. It is most important when these ecological boundaries are a key focus of the map theme. These steps are not independent of one another, instead there is some overlap as one step lends itself to the next or to a further understanding of a previous step. Creating these guidelines was necessary to provide mappers with a cartographic-ecological perspective of mapping ecological boundaries. This was intended to make the mapper cognisant of how symbol construction may be influenced by real world boundary-mode characteristics.

Table 5.6

Guidelines for ecological boundary symbology on maps

1. Observe the boundary: Throughout this thesis, I have stressed the importance of understanding the fundamental nature of the boundary under investigation before mapping it. This means observing ecological and spatial boundary characteristics. It also means carefully considering what modes are associated with the boundary and how these mode characteristics interact with the boundary.
2. Define "boundary" in the context of the research: I have demonstrated in earlier chapters that the term "boundary", despite initially appearing to be straightforward concept, is rather ambiguous when not defined within the context of how it is being used. I argue this is because the general thought on what constitutes a boundary is the same: a boundary is something that limits something else. But beyond this general and vague description, definitions and stipulations diverge greatly from one study to another. For an example of the fundamental differences between boundary definitions, see "boundary" as defined by McCoy et al. 1986, versus work by Cadenasso et al. (2003b) or Strayer et al. (2003). Thus I suggest that it is necessary to explicitly identify the kind of boundary under investigation and define how the term "boundary" is used as it applies to the research and/or map. This includes defining the boundary as bona fide/tangible or fiat/investigative.
3. Determine what is limited by the boundary: Boundaries in the real world, across landscapes, are much more complicated than just "something that limits something else"; many act like semi-permeable membranes through which some phenomena can flow, given the right conditions, while others cannot. Therefore, the physical make-up of the boundary can influence what phenomena flow through. Perhaps variations in spatial and temporal scale also affect what or how much phenomena flow through. Also, the physical characteristics of the phenomena (the modes) in contact or affected by the boundary must be considered. It is important for the researcher to determine the boundary-mode combinations for the ecological boundary they are studying.
4. Determine relevant boundary-mode combinations: It may not be necessary to understand the nature of every boundary-mode combination, of a particular ecological boundary. However, it is important for researchers to determine which boundary-mode sets are relevant to their research and these should receive special consideration during the mapping process. Once this is determined, the terms describing the types of boundaries provided in **Table 5.1** can be applied. Applying the terms can give some direction into how to cartographically portray the boundary.

5. Determine ecological boundary symbology: Very little ecological research at any scale goes without some amount of map analysis. When ecological boundaries are investigated and mapped, it is important that they are represented according to their characteristics, the characteristics of the modes limited or affected by the boundary, and the interactions that result from the boundary-mode set. This means planning symbols carefully based on the characteristics of the boundary-mode set. If more than one boundary-mode combination is under investigation, it may be difficult to depict them on a single map. This is because the symbology of one boundary-mode set may visually interfere with the symbology of other. A possible solution to this scenario is creating overlays (digitally or using transparencies) so that each boundary-mode pair can be mapped and viewed individually, but can also be "layered" with other boundary-mode pairs to generate a robust view of the boundary and its multiple modes.

5.5 Summary

This chapter presented the reader with the results of my cartographic and ecological boundary research. As demonstrated, I found it necessary to create new terms and definitions as well as expand on existing terms and definitions in order to accurately convey the nature of ecological boundaries I studied in the Thunder Bay Centennial Botanical Conservatory. These boundaries were analyzed using the cartographic matrix from Slocum et al. (2005) and the developed Ecological Boundary Symbology Matrix. Boundary symbology was designed based on boundary-mode pairs and applied to maps of the Conservatory as well as an ecological study by Manseau et al. (2001) concerned with multiple ecological boundaries associated with the boundaries of a proposed National Park. Finally, guidelines based on my research, were presented in an attempt to guide future mappers through matters to consider when mapping ecological boundaries.

The next chapter will discuss limitations of this study, as well as describe the significance of the new terms and definitions, symbols, and guidelines. I will also suggest areas of future research.

Chapter Six: Discussion and Conclusions

6.1 Introduction

The last chapter presented the results of my cartographic analysis of ecological boundaries. Here in Chapter 6, I discuss why the results pertain to my research objectives concerned with devising and constructing symbols that effectively portray ecological boundaries on maps. I also discuss the advantages and disadvantages to my methodology. Finally, this chapter presents suggestions for future research and my concluding thoughts.

6.2 Ecological Boundaries and Modes

This section summarizes the concepts of ecological boundaries based on my review of the literature and through my research of ecological boundaries.

From a landscape ecology perspective, ecological boundaries are complex. They have a functional role on the landscape, facilitating or limiting the flow of phenomena (Fortin et al., 2000; Yarrow & Marin, 2007); they are almost never static, and are more likely to be in a state of constant change (Martin et al., 2006); no scale is considered the 'right' scale to conduct research of map ecological boundaries (Christensen et al., 1996). Based on the wide variety of variables, it is difficult to compartmentalize ecological boundaries, and so it is not likely that a single boundary concept can be applied (Yarrow & Marin, 2007).

Furthermore, the term 'boundary' within the field of ecology is an ambiguous word. It has had different meanings in the background literature, depending on the study. Future researchers should define what it means and how they use it in the context of their research (Strayer et al., 2003).

Observing ecological boundaries within the Thunder Bay Centennial Botanical Conservatory was beneficial because it was a simplified and closed environment. For this reason, I recommend utilizing the Conservatory environment for future ecological boundary research. However, more complex studies of ecological boundaries should be carried out on the landscape. After all, the Conservatory is only meant as a simplified analogue for ecological boundaries in the real world.

6.2.1 New terms and Extended Definitions

New definitions and thesis-specific definition extensions in **Table 5.1** demonstrate the need to define and understand ecological boundary properties and characteristics before mapping them. This heightens the map maker's awareness of the boundary and its characteristics, how phenomena interact with it, and how it should be cartographically portrayed.

A notable finding from my research is that a single boundary limits one or many modes in different ways, and the extent to which a boundary limits its modes depends on the spatial characteristics and properties of that boundary as well as the characteristics and properties of the modes. This means the difference between a mode being able to pass through the boundary to some extent, or not at all. This is a significant finding from a cartographic standpoint as it means that mapping ecological boundaries in detail requires more comprehensive symbology and a paradigm shift regarding ways to depict boundaries. However, I have demonstrated that it is possible to achieve this. Therefore, boundaries should not be cartographically depicted based on a single variable, or the most obvious or familiar variable, which is often the case (Omernik, 2004).

6.2.2 Ecological Boundary Symbology Matrix as a Research Tool

From a cartographic perspective, the Ecological Boundary Symbology Matrix demonstrates the cartographic potential of each boundary-mode combination. Every combination presents the opportunity of a unique symbol because each boundary-mode pair possesses unique spatial characteristics and properties that influence the cartographic symbolization in the map design process.

The Ecological Boundary Symbology Matrix was an effective qualitative research tool that adequately met the needs of this thesis. I found it to be an insightful method of exploring the many complexities of symbolizing ecological boundaries on maps. The matrix was low-tech and offered flexibility – it was easy to modify to meet the user requirements. A disadvantage of the matrix was that it included only the information entered into it by the user. Therefore, it may not cover the full range of ecological boundaries and associated modes unless the user included them. However, I still recommend employing matrices in future cartographic analyses as it does provide insight into potential cartographic portrayal based on phenomenon characteristics.

6.3 Cartographic Medium

There may be some question as to why I did not employ GIS into my thesis work. My answer to this is that cartography and GIS are not synonymous. I was not looking at how I could symbolize boundary symbols within the GIS environment. As discussed in Chapter 3, GIS restricts the cartographic creativity of the GIS user who must work within the program's limits. Because of this, I chose to work with graphic design software that offered more creative flexibility. For my research graphic design software was a good choice, enabling the cartographic freedom to explore boundary symbology. Unfortunately, there are also disadvantages to using graphic design software alone to construct maps. This software does not offer the data processing and storage, georeferencing, and spatial analysis tools that GIS offers. Furthermore, compared to GIS, mapping using graphic design software is time-consuming and tedious work (similar to drawing maps by hand).

From a cartographic standpoint, the Conservatory was not complicated to map: projection and accurate scale were not concerns because these maps were not used for navigation, scale was very large, spatial analyses were not conducted, there were no additional attribute data to store, and so on. Furthermore, it is unlikely that maps featuring ecological boundaries would be used for navigational purposes. However, spatial analysis is another matter; GIS makes spatial analysis relatively simple and can be very useful when investigating ecological boundaries. For these reasons, complex ecological boundary research would benefit from GIS and graphic design software, such as MAPublisher. Yet, the cost of the additional software may not be justifiable to some users, especially if it will not be used regularly.

6.4 Symbology

My cartographic exploration into boundary symbology revealed interesting challenges and possible solutions when mapping ecological boundaries. Through matrix research, I discovered that ecological boundaries were complex. What I considered to be an ecological boundary limited some phenomena but not all, or limited phenomena to different extents. For example, I observed the Conservatory glass roof and walls as an ecological boundary that physically limited vegetation – plants could not pass through the walls or roof (not including airborne spores, seeds, etc. that may enter or exit the Conservatory through vents, windows, doors, etc.). Yet, the same boundary did not fully limit temperature or light. This shows how one ecological boundary is not necessarily an equal barrier for all its modes. This became my focus – how do I symbolize boundaries that do not limit all associated phenomena in the same way? Therefore, paying close attention to boundary-mode characteristics was key to creating symbology.

I began this research believing I could create a series of original boundary symbols that could best portray ecological boundaries based on boundary characteristics. Through review of the cartographic literature and matrix work, it became clear that creating "new" symbols was not required in order to portray ecological boundaries more accurately than they currently are. Rather, I discovered the need to "go back to cartographic basics". What I mean by this is that symbols already used to represent boundaries can still effectively represent ecological boundaries, so long as the symbols are chosen wisely. I have already discussed in earlier chapters that using unsuitable symbols can negatively affect the usefulness of a map. In order to avoid using symbols inappropriately, it is crucial to recognize and establish when a symbol effectively represents the real world phenomena. To accomplish this task, it is necessary to understand the cartography of symbols. Using the cartographic matrix from Slocum et al. (2005) and my Ecological Boundary Symbology Matrix, I determined which symbols best represented the boundaries I studied in the Conservatory. The symbols I chose were commonly used boundary symbols; I carefully analyzed what symbols could represent boundary-mode phenomenon best, rather than unconsciously or unknowingly choosing less appropriate symbols.

Rather more unique, is that more than one symbol was used for many of the ecological boundaries. This is because I based the symbology on the multiple boundary-mode sets I studied. Similar to the concerns of Maki and Kalliola (2000), I found that incorporating multiple symbols for the same boundary on one map (to accommodate the various boundary-mode sets) could be quite difficult. Taking the advice of Rossum and Lavin (2000), I established that it was necessary to construct multiple maps of the same boundary, each symbolizing one of the boundary-mode pair characteristics (see Map 5.1 to 5.5 as examples). These multiple maps could also be overlaid to achieve a layered effect and appear as one without being too cluttered, as Maki and Kalliola (2000) encountered. I also demonstrated this by remapping an ecological map by Manseau et al. (2001) depicting conservation target areas for the Long Point component of the proposed Manitoba Lowlands National Park. I remapped the CTAs using carefully chosen symbology based on the ecological boundaries and their modes.

The advantage of the symbol analysis was that it showed how existing boundary symbols could be used in this new method of symbolizing ecological boundaries based on their multiple boundary-mode sets. Unfortunately, this method was time-consuming and requires extensive background knowledge in cartography, ecology, and to some extent the philosophy of boundaries. Subjectivity is also an issue, as no standardized symbol set exists for portraying ecological boundary-mode combinations. If another researcher were to conduct a similar study to determine what symbols best represented ecological boundaries, they may not produce the same symbols that I did. However, this may not be an important issue. The point of a map is to clearly and effectively communicate the information and data – it is not necessary to standardize symbology if more than one symbol is effective. Granted, some symbol standardization does exist, for example, water is most often depicted in blue on maps.

6.5 Guidelines

The final component of my cartographic analysis involved offering a series of guidelines, or recommended steps, that could be used during the process of determining appropriate ecological boundary symbology. These guidelines make the mapper aware of the complexities of ecological boundaries, and this awareness can translate to more effect cartographic symbolization. Anyone mapping ecological boundaries, where boundaries are important map subjects, are encouraged to consult the guidelines in the Results chapter (see **Table 5.6**).

6.6 Linkage to Thesis Objectives

In Chapter 1, I introduced the reader to my thesis objectives. This included determining appropriate symbology to depict ecological boundaries on maps. I achieved this by analyzing ecological boundaries in the Thunder Bay Centennial Botanical Conservatory. This required extensive multidisciplinary review of background literature in ecology, cartography, and philosophy. It also required the use of the Slocum et al. (2005) cartographic matrices and the development of the Ecological Boundary Symbology Matrix.

In order to map ecological boundaries effectively, it was necessary to understand how they interact with various phenomena. Unfortunately, I found that very little of the background literature offered specific terms and definitions for different types of boundaries. Fiat and bona fide boundaries were already defined and discussed in the philosophical literature, but these two terms have not been widely applied to ecology (Jacquez et al., 2000) or cartography prior to this thesis. Furthermore, I have developed other boundary or boundary-related terms including definite boundary, indefinite boundary, perforated boundary, interface boundary, medial boundary, and mode, to further researchers ability to identify and define ecological boundaries.

I argued that ecological boundaries limit various phenomena in different ways. I also demonstrated how this information can be incorporated cartographically into maps to provide detailed and improved representation. Incorporating more detail of the ecological boundaries meant that a map could become cluttered with too much information. The solution suggested here was making multiple maps or employing overlays to effectively display multiple boundary-mode sets.

Overall, I have demonstrated how cartographic knowledge can positively impact ecological boundary mapping. Symbology is the vector used by map makers to communicate spatial data to the map reader. It is possible that the map reader will surmise incorrect findings or conclusions for the mapped data if the symbology is not carefully selected and does not accurately represent the data. This is particularly an issue with many maps constructed by GIS map makers: I have also demonstrated that cartographers and GIS map makers are not synonymous and that GIS map makers often construct maps that do not utilize sufficient cartographic knowledge. I analyzed ecological boundary symbols on a number of maps constructed using GIS and established that these symbols often did not accurately reflect the real world phenomena. I remapped one of the aforementioned maps to illustrate how carefully constructed symbology can better represent ecological boundary properties. The symbols I used are not incredibly complex and this makes the symbols practical to a broad user base. However, I used graphic design software to remap the ecological boundary symbols and some map makers may not be able to justify the cost of this software which is likely an additional cost because they have already purchased and use GIS software.

Overall, this approach to mapping ecological boundaries can result in more representative ecological boundary symbols because it exercises a conscious effort to construct symbols that effectively characterize the real world phenomena. This approach can complement existing mapping approaches by bringing the diverging fields of cartography and GIS back together. The powerful analytical tools of GIS which are often used for ecological mapping and analysis should not be overlooked when mapping ecological boundaries; however, the cartography of map making should not be overlooked either because effective cartography can also aid in ecological analysis. The approach I have outlined can be readily incorporated into ecological boundary research by employing the guidelines during map preparation and construction and graphic design software.

6.7 Recommendations in Future Research

The reader is now informed of the lack of multidisciplinary research between the ecology and cartography of ecological boundaries. Cartographic portrayal of ecological boundaries is rarely discussed in the ecological literature, despite the fact that maps are often used in ecological boundary analysis. Likewise, ecological boundaries were rarely discussed in the cartographic literature. There were no studies like this thesis in the background literature to draw from, no methodologies to consult, and no clear link between ecology and cartography. It is my hope that future ecological boundary research will adopt multidisciplinary approaches. I believe that this can contribute to a well-rounded understanding of processes and complicated structures like ecological boundaries. In the case of ecological boundaries, I believe that it is detrimental to focus on some aspects because they fall within a certain research field while ignoring others because it is believed that they belong to another.

The reader is aware that my research used a simplified landscape study of some of the ecological boundaries in the Thunder Bay Centennial Botanical Conservatory and can be considered a limitation of my research. While I do recommend using Conservatories in future research, I also recommend that research should focus on ecological boundaries across other landscapes. This is because there are differences between the controlled boundaries (within the Conservatory) and those of more natural systems. Two of the main differences are the scale at which ecological research is conducted, as well as the potential for more transitional boundaries on landscapes than those observed within the

Conservatory. Scale, or spatial extent, within ecological research has been described in this thesis to be highly dependent on what is specifically being studied. For example, the spatial extent of the ecological boundaries of caribou is likely to be geographically larger than the spatial extent necessary to study ecological boundaries of Aurora Trout (*Salvelinus fontinalis timagamiensis*).

Regarding the second difference, the Conservatory contains a higher proportion of definite boundaries than there may be across more natural landscapes. Transitional or indefinite boundaries are more commonly observed on less anthropogenically disturbed landscapes for modes such as flora, fauna, temperature, and soil. While definite boundaries are present on more natural landscapes (e.g., shorelines), it is speculated that many would be associated with anthropogenic disturbances such as highway corridors, urban infrastructure, and so on. The Conservatory has a large number of definite boundaries because it is an anthropogenic structure made of materials and laid out in such a way that promotes definite boundaries over indefinite ones. This suggested future research of ecological boundaries on other more natural landscapes would be useful for expanding the Ecological Boundary Symbology matrix (which is currently based on boundaries in the Conservatory), so it could be applied to a larger number of indefinite boundary types than were considered here.

Future work may also focus on the relationship between ecological boundary delineation and cartography. Boundaries on a landscape can be determined using an ecological boundary delineation method (via a software product like BoundarySeer), and then a map maker can cartographically interpret the boundary delineation and appoint appropriate map symbols that best represent the boundary. This methodology may improve the readability and interpretation of ecological maps.

Another limitation previously mentioned is the subjective nature of symbology and cartography. Unlike other research fields, like biology or ecology, where objectivity is often critical, it is unlikely that cartography can ever be anything but subjective given that cartography is often considered an "art form" and is therefore based on individual perspectives.

Finally, constructing maps using graphic design software alone (a modern equivalent to hand drawn maps) present problems such as a large time commitment, high software costs, the knowledge required to create map projections, ensuring accurate map scale and projection, and other aspects of accuracy that GIS software can assist with. This limitation could be remedied using a combination of GIS and graphic design software.

Future research should include furthering the development of more sophisticated cartographic tools in computer software and web-based applications. GIS-based cartographic tools are currently difficult to use and sometimes simply cannot achieve the desired output. I suggest incorporating flexible cartographic tools within GIS that afford the map maker the freedom to design symbols and map in the way they want. While some graphic design software can be linked to GIS, it may not be accessible to the average GIS user who will not make maps regularly and cannot justify the additional cost and time expenditure of learning a new and complex program. Mappers should not be forced to settle for less effective cartographic choices simply because the GIS they use cannot accommodate their cartographic needs. In the future, graphic design software should be incorporated into GIS software. Although this still means the user must learn the new tools and likely pay a bit more for the added features, at least it would be more accessible to the map maker.

Future expansion on my research may include a cartographic critique by a group of my peers of the maps and symbols constructed for the Conservatory and for the Long Point component of the proposed Manitoba Lowlands National Park. This critique would enable the completion of the cartographic process described in Chapter 1.

6.8 Concluding Thoughts

Through results of my research and a review of the background cartographic (and geospatial), philosophical, and ecological literature, I find that an important component of ecological boundary analysis is missing: the cartography of ecological boundaries. My study and review of the literature draws attention to the lack of multidisciplinary research across these fields. This, in my opinion, works to the disadvantage of ecological boundary research because maps are often an integral element of ecological analysis. Much of the background literature, with the exception of Kuchler (1988) and Wagner (1957), show no concern with the cartography and symbology of ecological boundaries. The use of maps as a method of boundary analysis may be limited by poor representation of boundary-mode phenomena. These poor symbol choices can mislead a researcher who is looking to interpret the mapped information. This is especially true if the researcher interpreting the map information is not the same person who produced the map; the mapper may have more insight into the boundary phenomena (because he or she worked with the spatial data) than the map implies and what the researcher interprets. My study has shown that compartmentalizing research into single fields or disciplines does not help establish the "bigger picture" about ecological boundaries.

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APPENDIX A:
CONSERVATORY PHOTOGRAPHS

Appendix A contains a collection of photographs I took during fieldwork at the Centennial Botanical Conservatory in the winter of 2008. It includes a photo of the Conservatory, as well as photos of the each of the ecological boundaries analyzed in the Ecological Boundary Symbology Matrix (see Appendix B and C). Boundaries photographed include: glass roof, exterior glass walls, interior glass walls, pond surface, stone retaining wall/cement walkways/soil. No photo was taken of the floor/foundation, as it was not visible to be photographed.

Figure A.1. A photograph of the Thunder Bay Centennial Botanical Conservatory. Located at 1601 Dease Street, Thunder Bay, Ontario, Canada. Taken December 2008.

Figure A.2. A photograph of the glass roof boundary taken inside the Conservatory.

Figure A.3. A photograph of the exterior glass wall boundary taken inside the Conservatory.

Figure A.4. A photograph of the interior glass wall boundary taken inside the Conservatory.

Figure A.5. A photograph of the pond surface boundary taken inside the Conservatory.

Figure A.6. A photograph of the stone retaining walls, cement walkway, and soil taken inside the Conservatory.

APPENDIX B:
ECOLOGICAL BOUNDARY CUE CARDS

Appendix B contains the cue cards constructed during preliminary cartographic analysis of the ecological boundaries studied in the Conservatory. Cue cards are displayed here with the front of the cue card on the left side and the back on to the immediate right; if there was no information on the back of a cue card, an empty space will appear to the right instead. Cue cards format is as follows.

Information on front of cue card:	Information on back:
Top left corner: mode Top right corner: boundary. Bottom left corner: map perspective. Bottom right corner: spatial phenomenon and visual variables, according to Slocum et al. (2005). Centre: supplementary notes.	Sketches

T° **Roof**

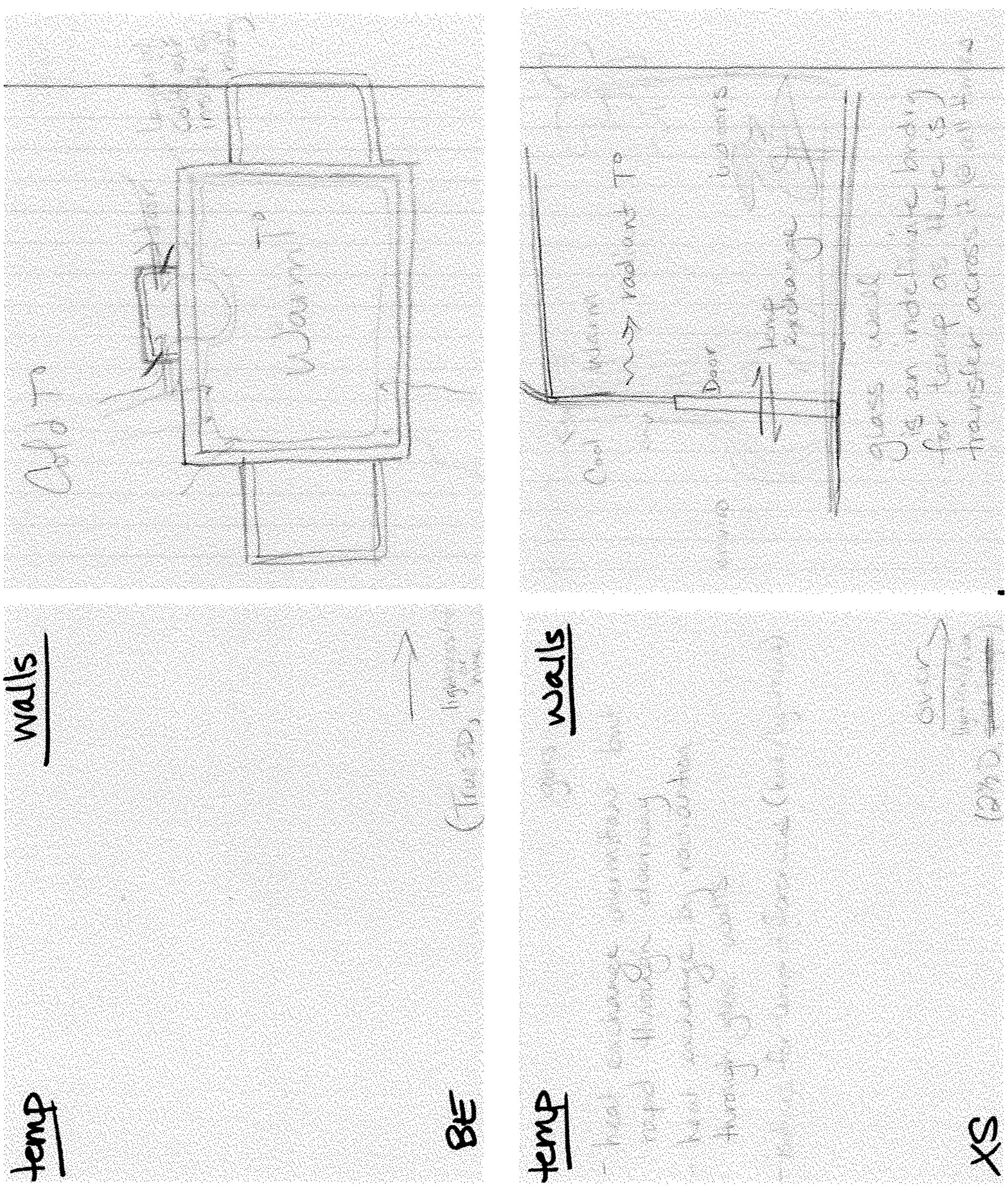
- roof is an indefinite bndry because the roof is glass (poor insulator)
- If roof had been made of a better insulator, the bndry would likely have been definite.

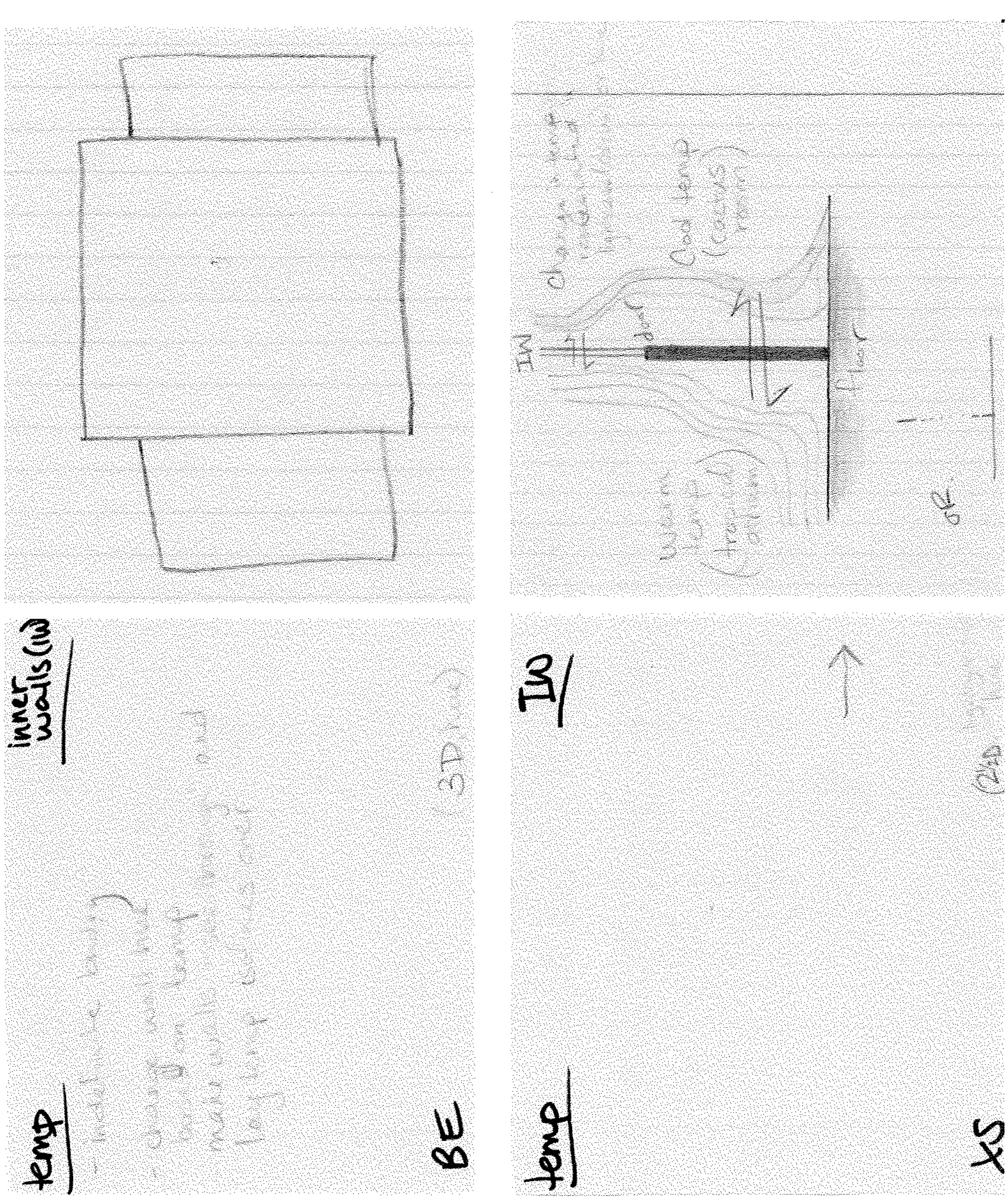
B-E - isolines (x,y,z coords)

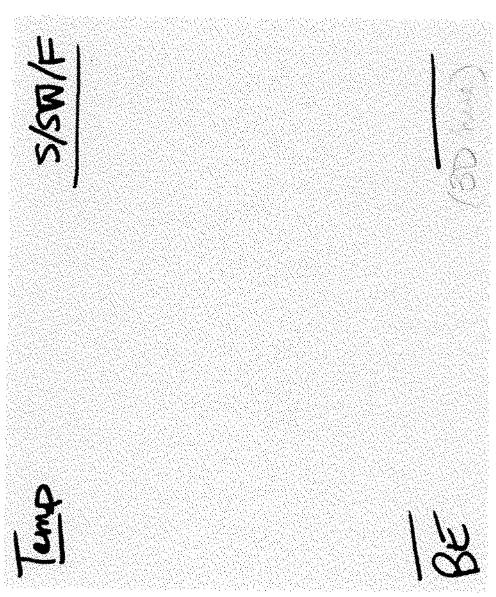
T° **Roof**

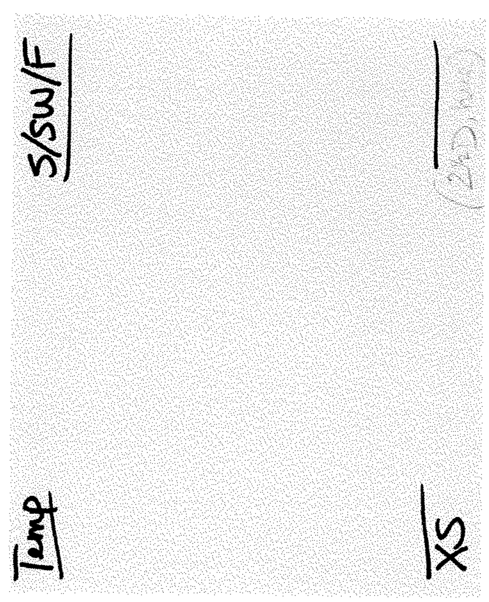
- temp transfer ~~[illegible]~~ across roof bndry via conduction + radiation (sun's rays)
- boundary is indefinite because of heat transfer + sun's radiation across roof bndry.

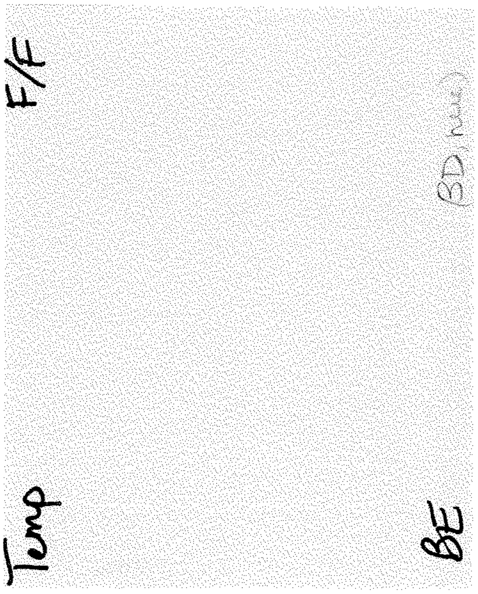
X-S. - isolines (x,y,z coords)

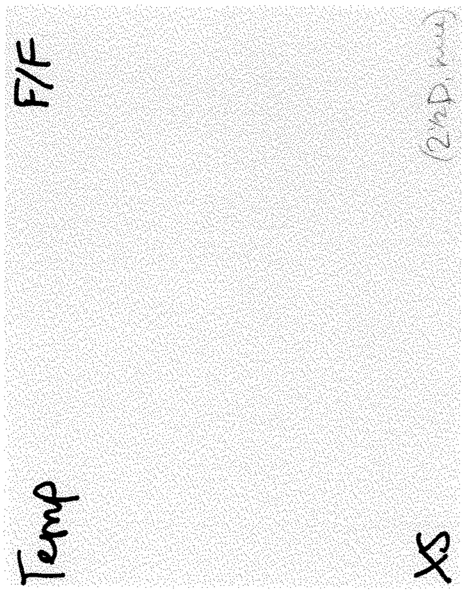

temp
walls
BE
temp
walls
XS

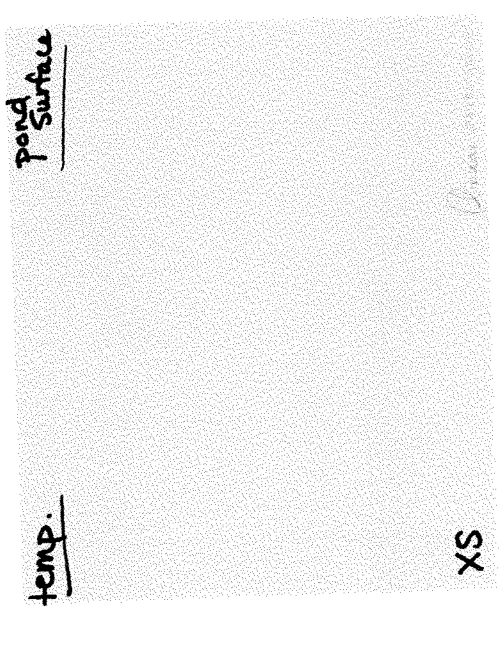

temp
inner walls (IW)
BE
temp
IW
XS
IW
floor

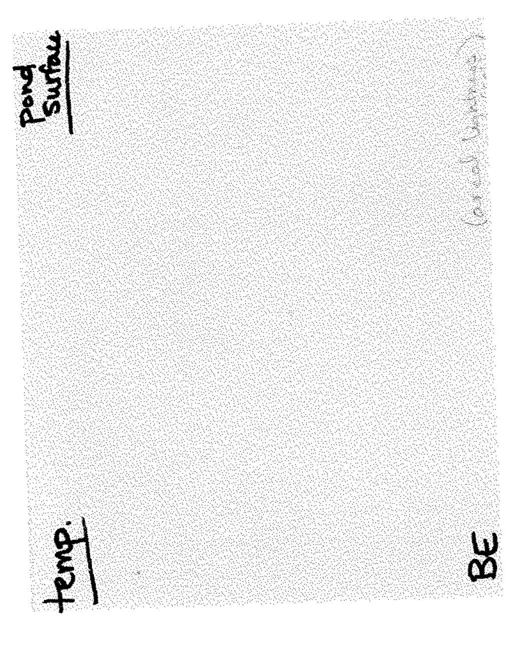

Temp
S/SW/F
BE


Temp
S/SW/F
XS


Temp
F/F
BE


Temp
F/F
XS


pond surface
temp.
XS

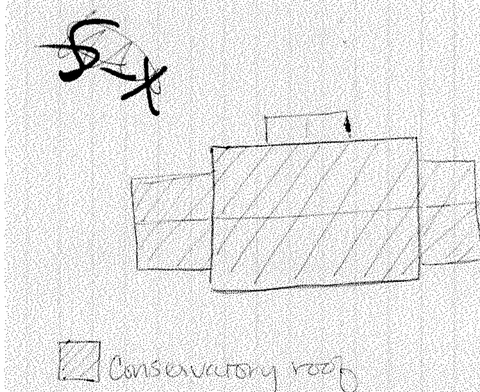

pond surface
temp.
BE

Precip **Roof**

- roof is a definite bndry (curved roof w/sloping side)
- ~~cliffline~~
- precip doesn't cross this bnary so the roof should be portrayed as a barrier
- possible hatching symbol?
- difficult to clearly portray from BEV

[illegible] **Birds eye** (BEV)

(aerial, lightness)



Precip **Roof**

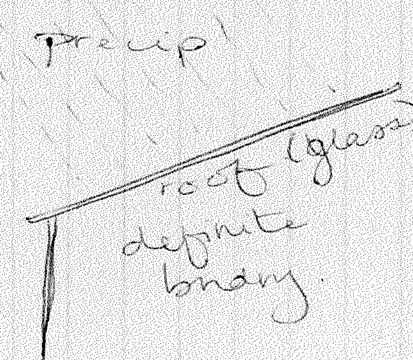
- linear bndry because no precip can get through roof.
- also nutrients (another sub mode)
  - water (sub-mode also)
  - pollutants (s-m)
- roof in discrete definite bndry

View Pt

looking from x-section (X-S)

XS

(linear size)

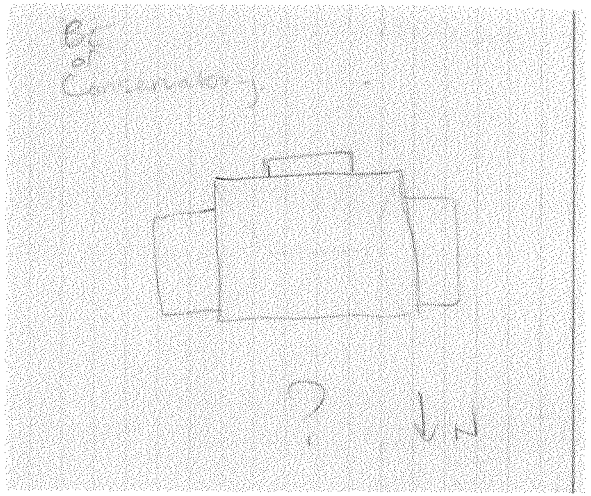


precip-nutrients (sub-mode) **roof**

- see mode: precip

BE

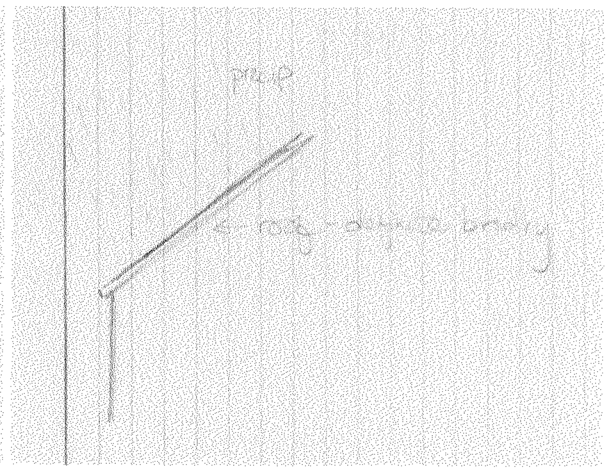
(area, lightness)

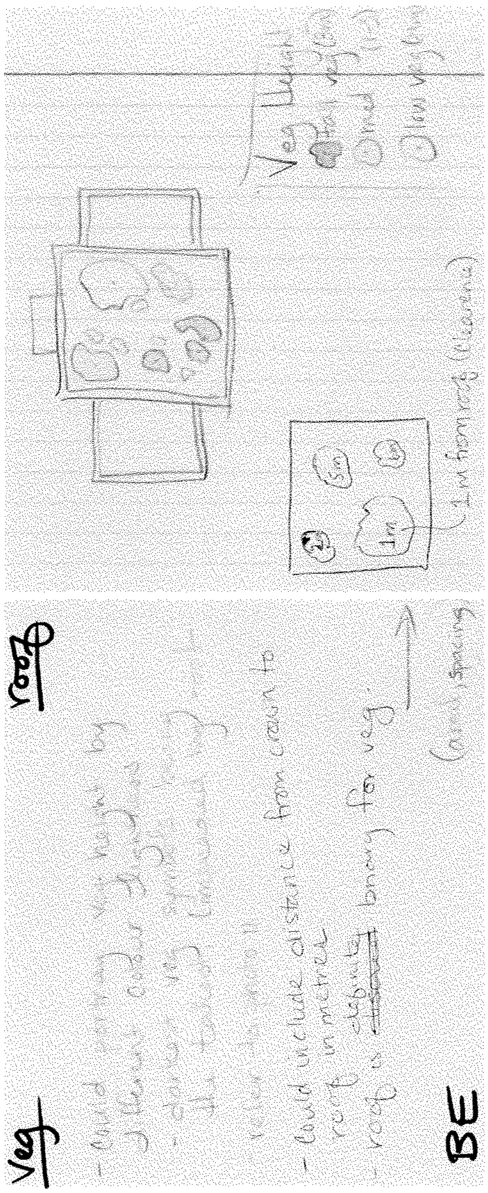


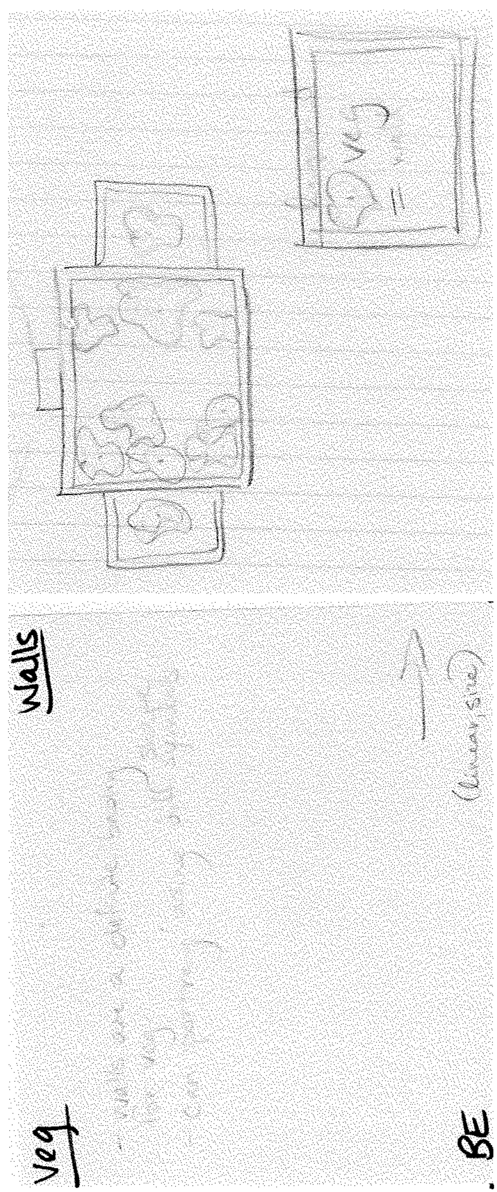
Precip - nutrients Roof

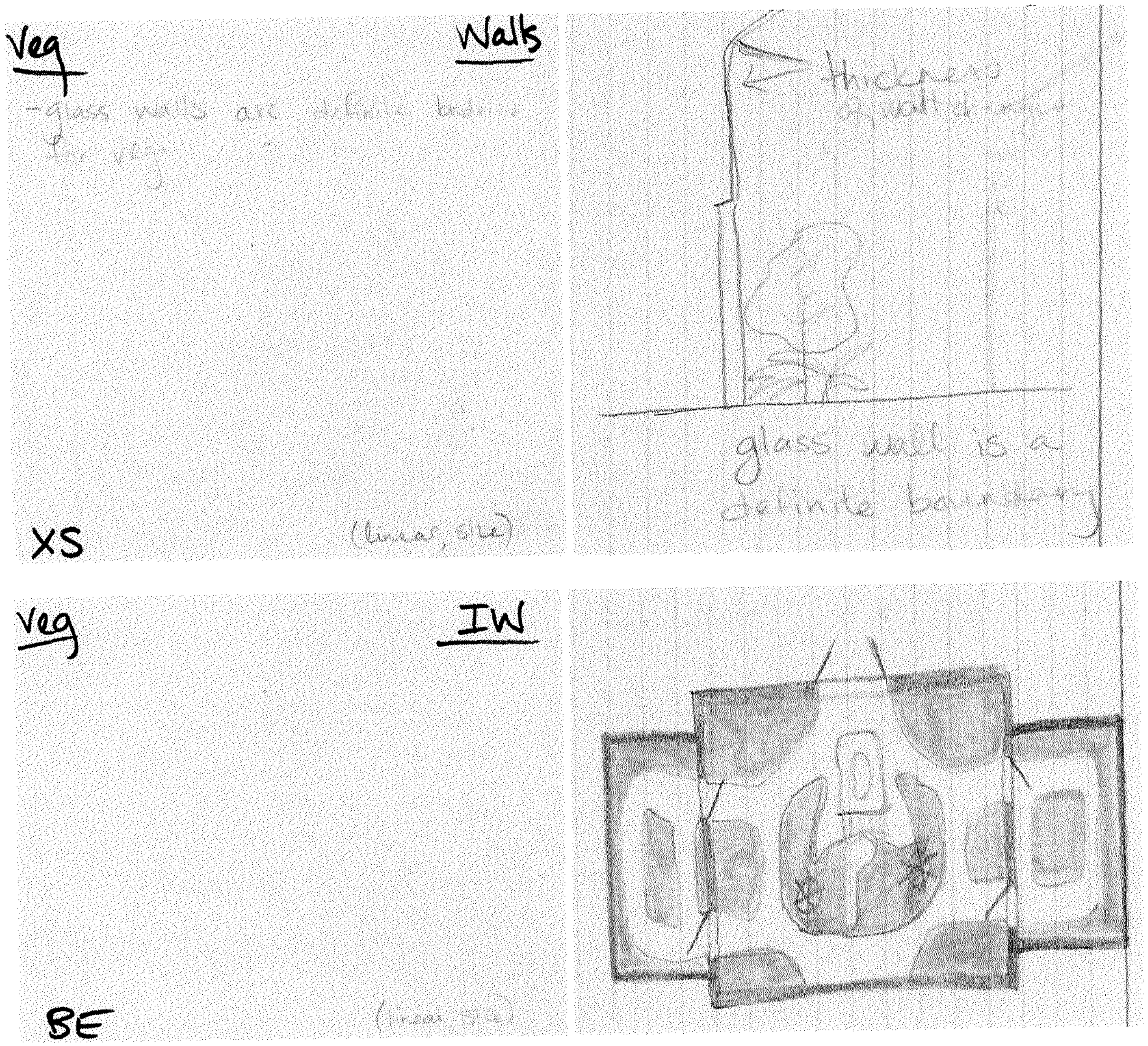
XS

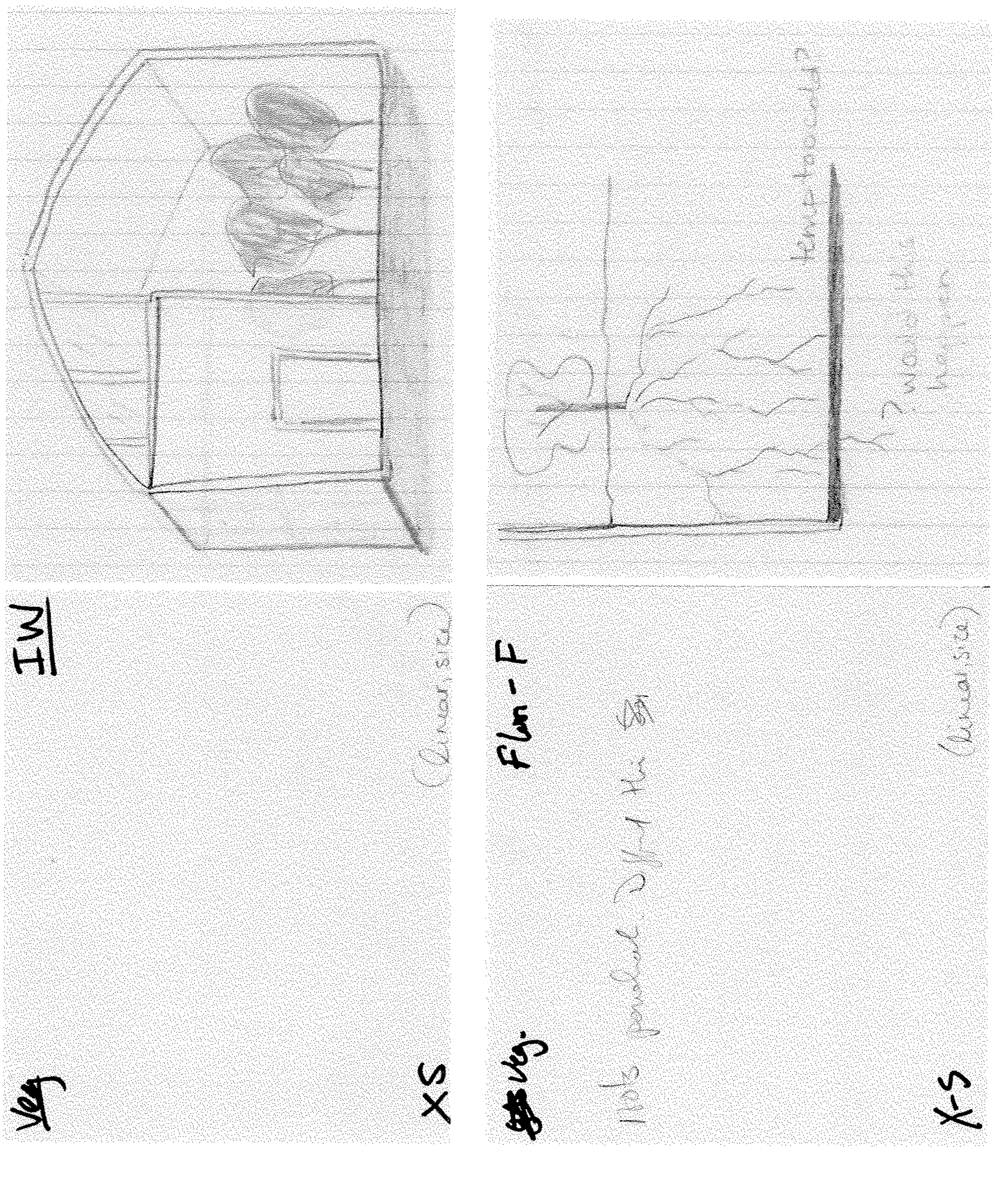
(linear, size)

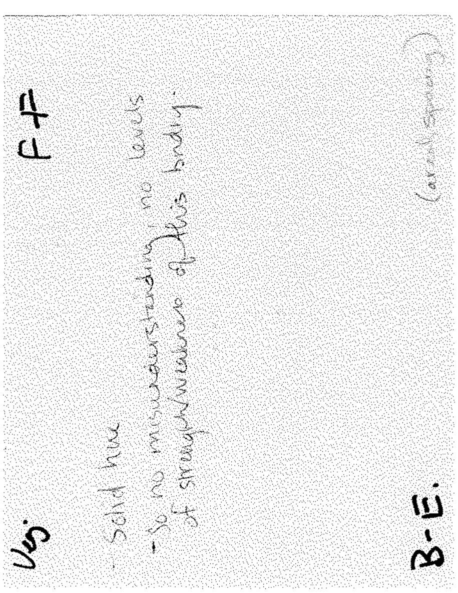


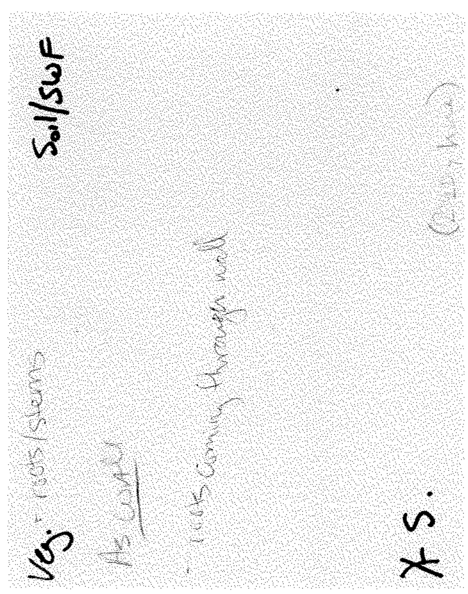

Veg
Roof
BE

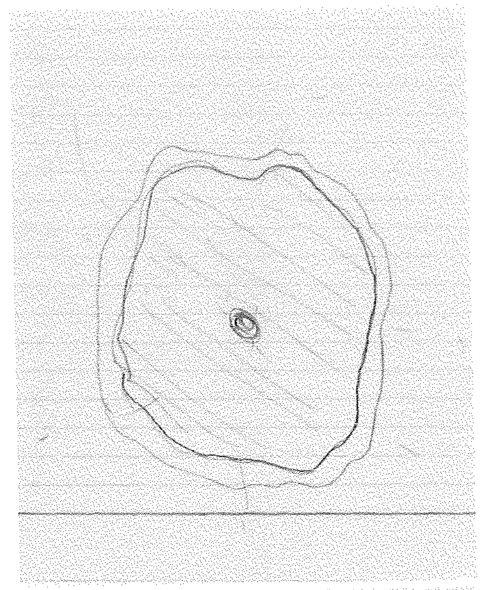

Veg
Walls
BE

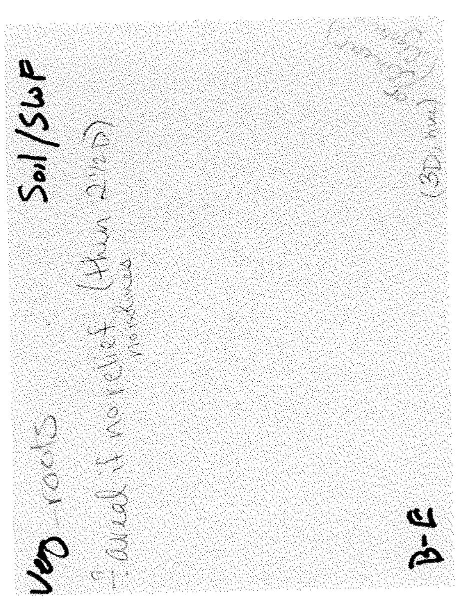

Veg
Walls
XS
(linear, size)
thickness
glass wall is a definite boundary
Veg
IW
BE

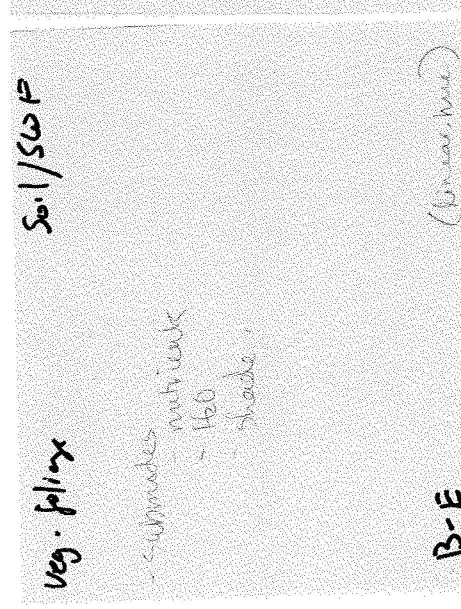

Veg
IW
XS
X-S

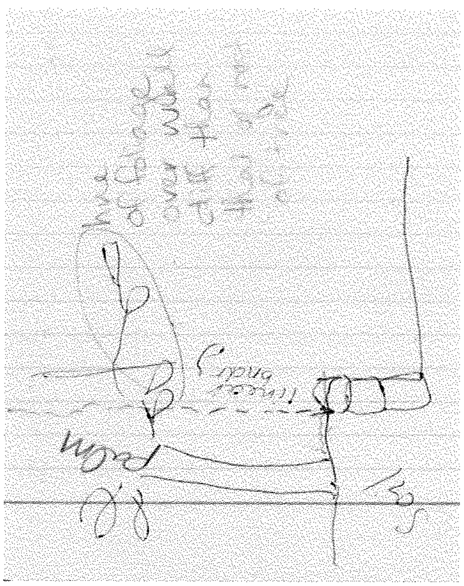

Veg.
F-F
· Solid line
- so no misunderstanding, no levels of strength/weakness of this binding.
B-E.

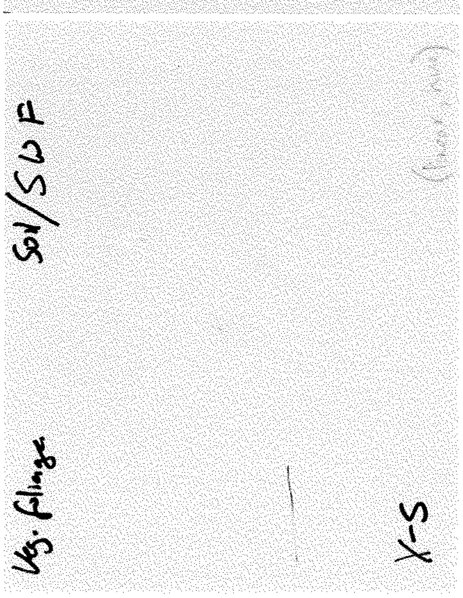

Veg.: roots/stems
Soil/SWF
· roots coming through wall
X S.

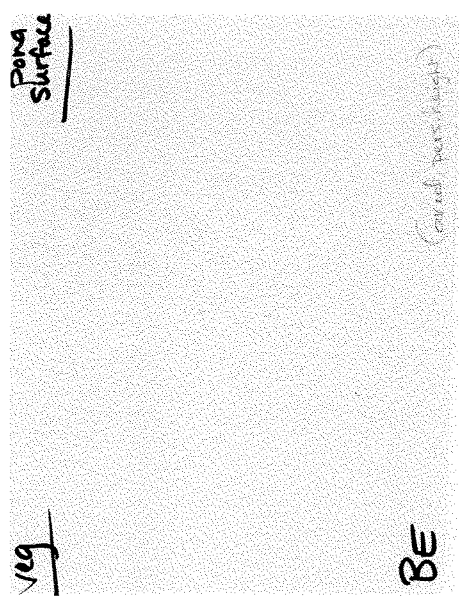


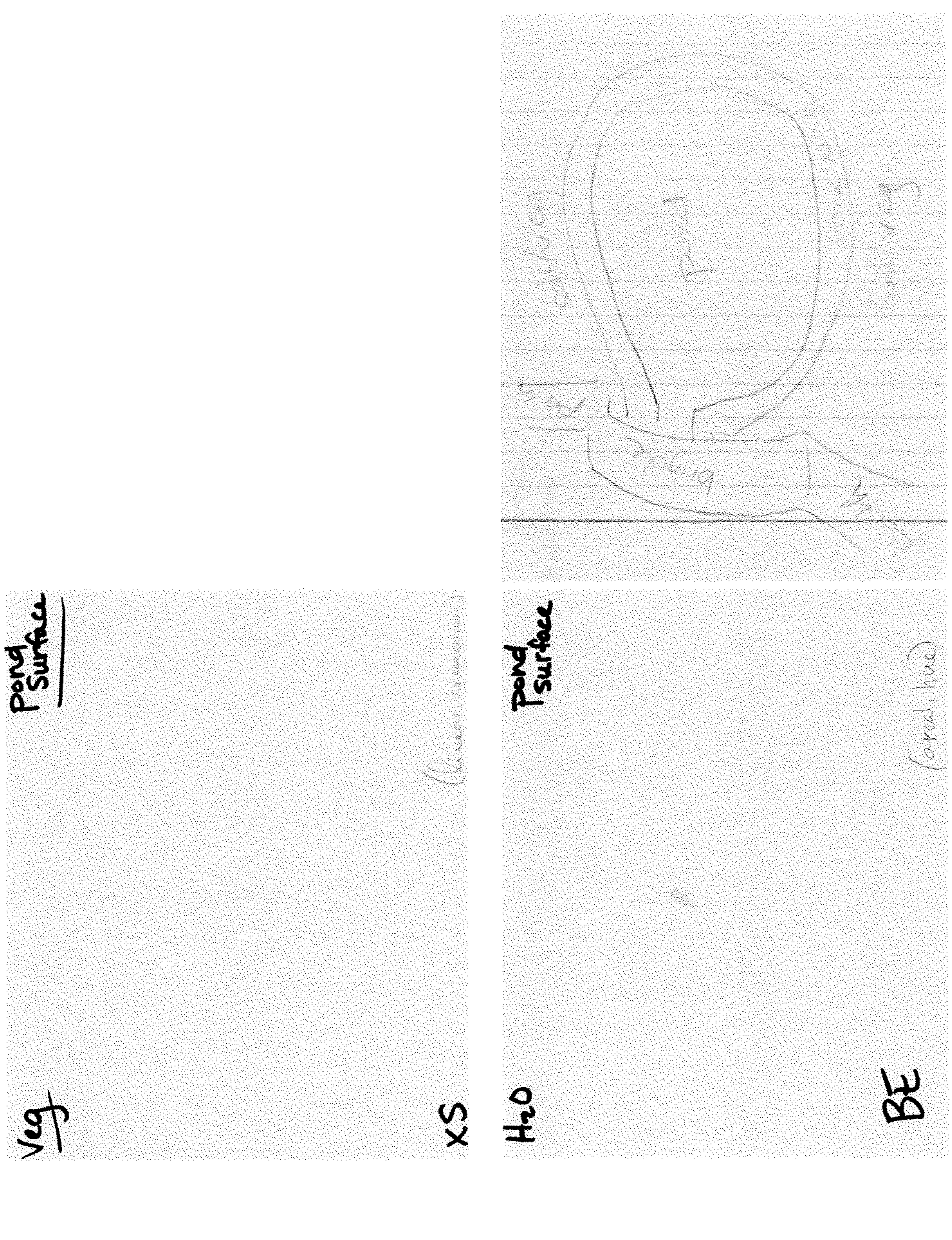

Veg roots
Soil/SWP
(3D, hue)
B-E

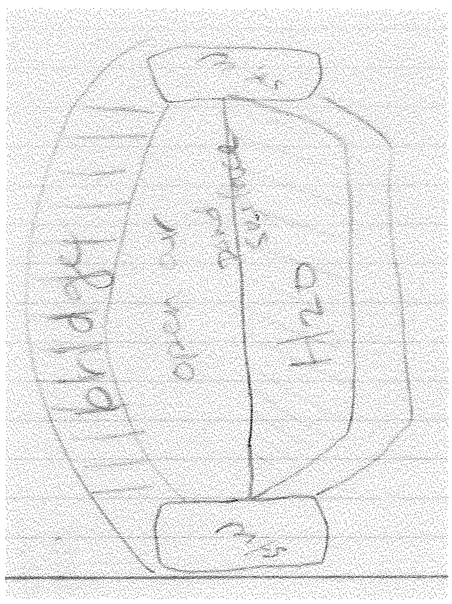

Veg. foliage
Soil/SWP
nutrient
H2O
shade
(linear, hue)
B-E

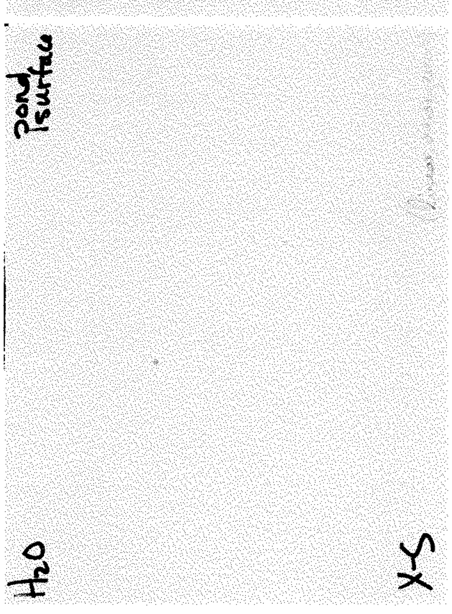


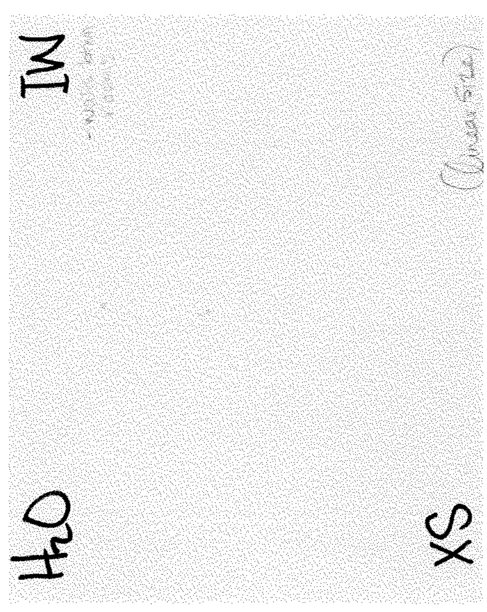

Veg. foliage
Soil/SWF
X-S

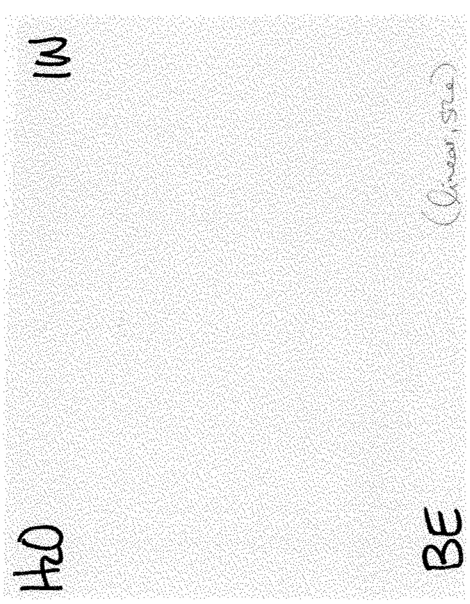

veg
Pond Surface
BE

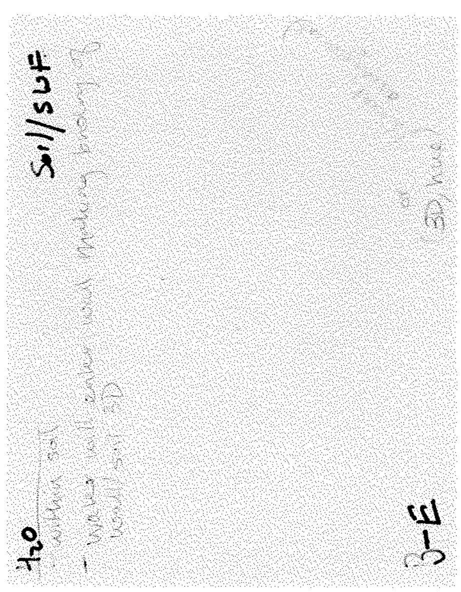

Veg
Pond Surface
XS
H2O
Pond Surface
BE

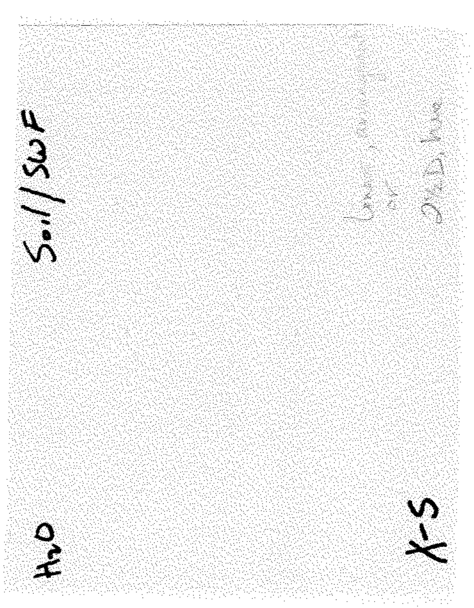

bridge
open air
pond surface
H2O

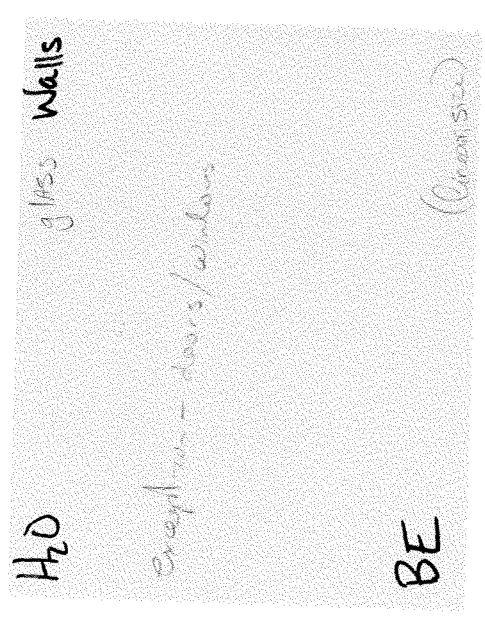

H2O
pond surface
X-S


H2O
IM
XS


H2O
IW
BE


Soil/SWF
3-E


H_2O
Soil/SWF
X-S


H_2O
glass
Walls
BE

Cue card for:

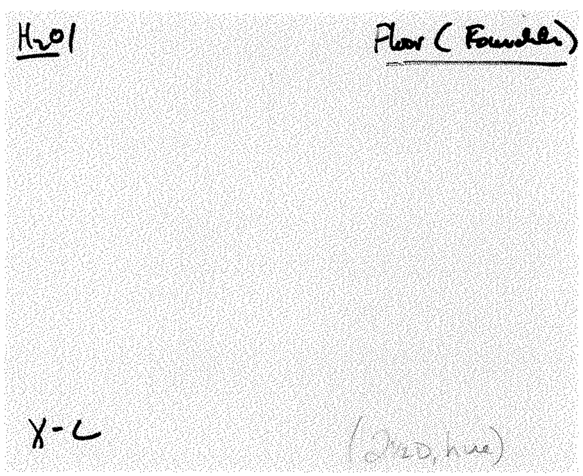
Boundary – Outer Walls

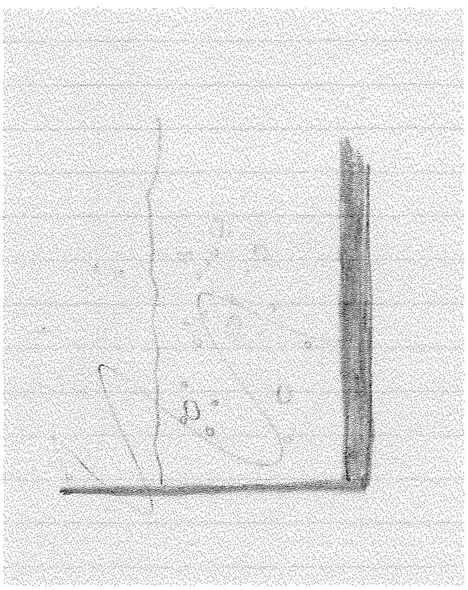
Mode – Water

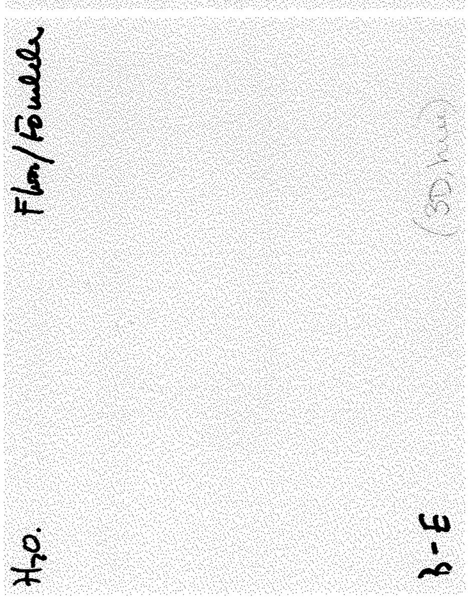
Perspective – BE

Cartographic Representation: Linear,

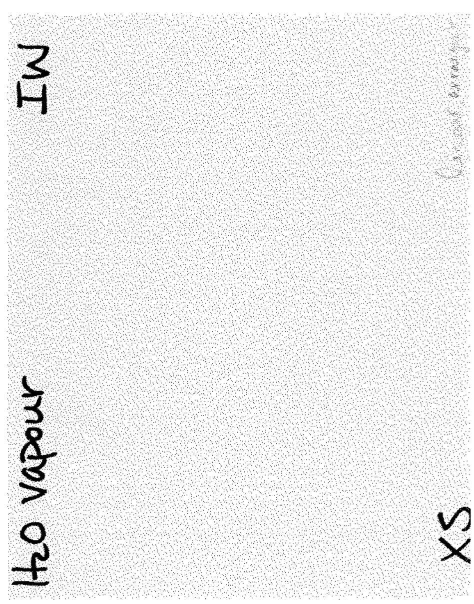
Spacing or Arrangement



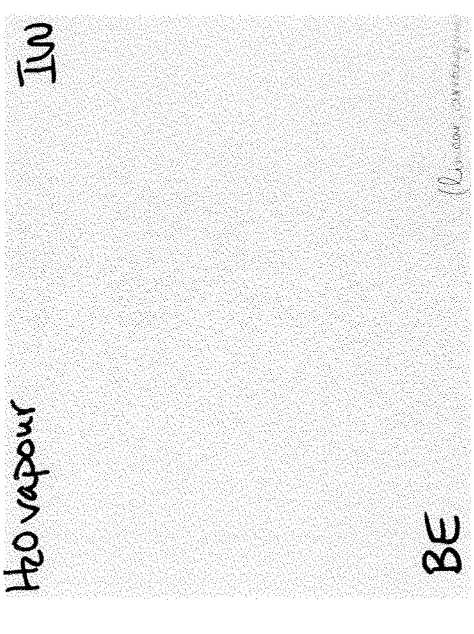


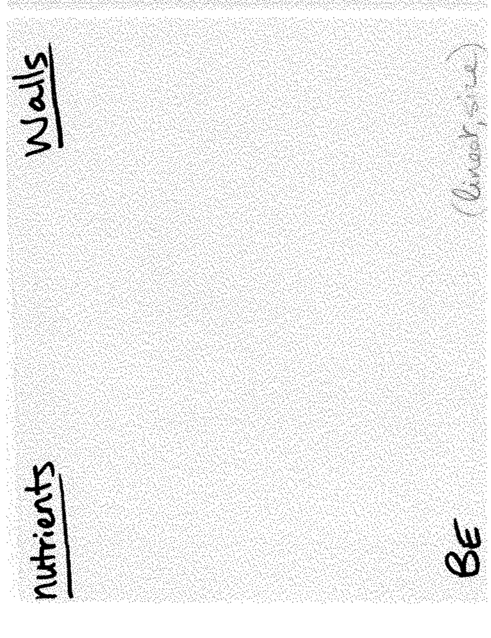


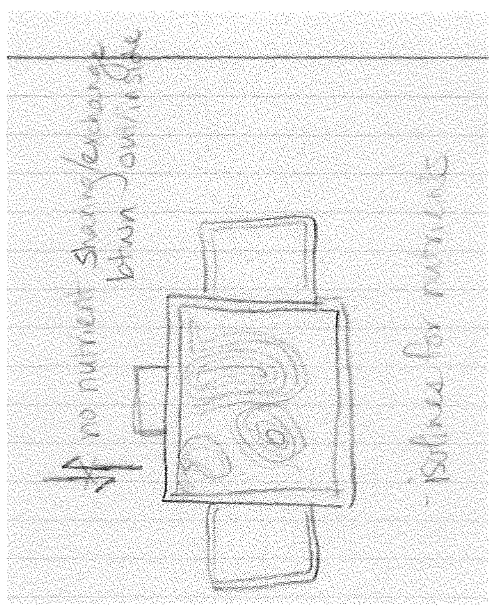
H2O.
Flow/Foundation

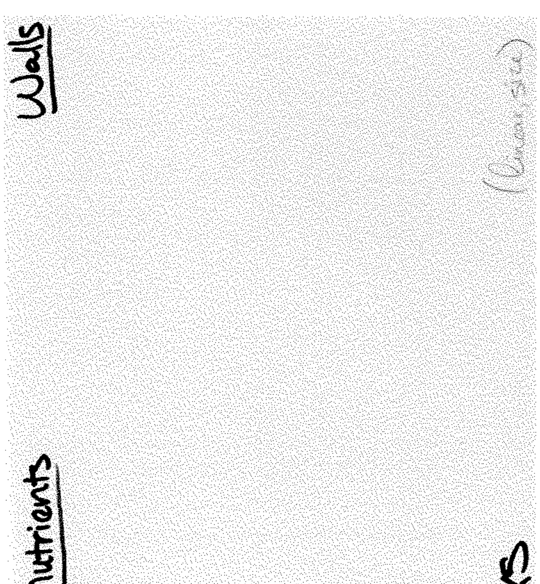


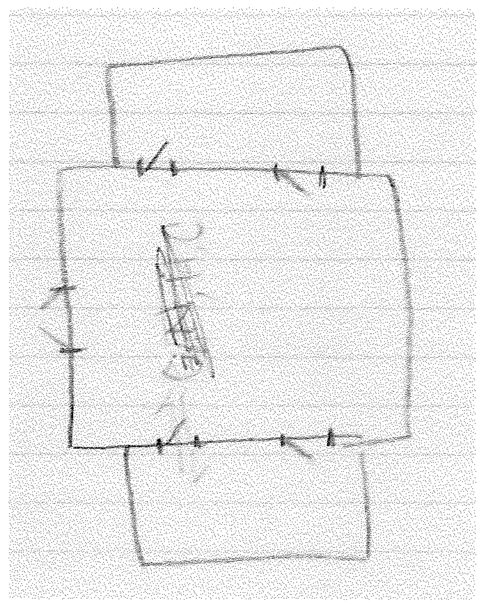
H2O Vapour
IW
XS

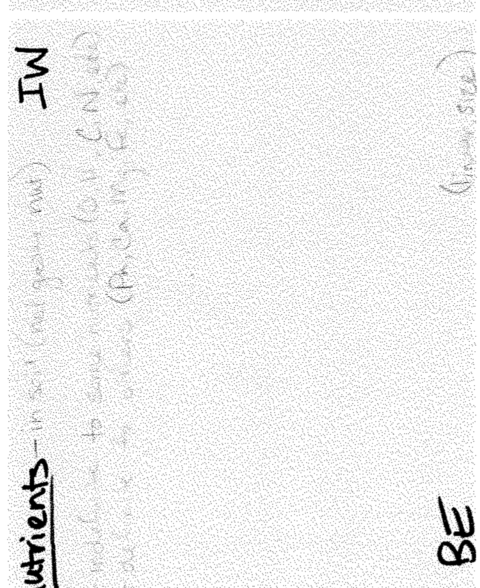

H2O vapour
IW
BE

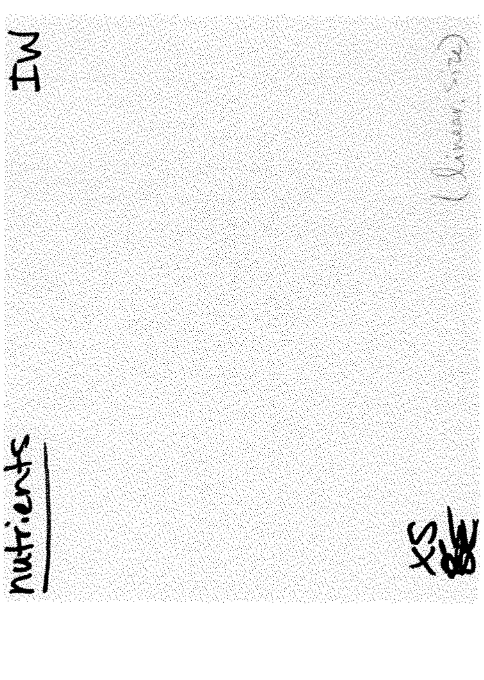

Nutrients
Walls
(linear, size)
BE

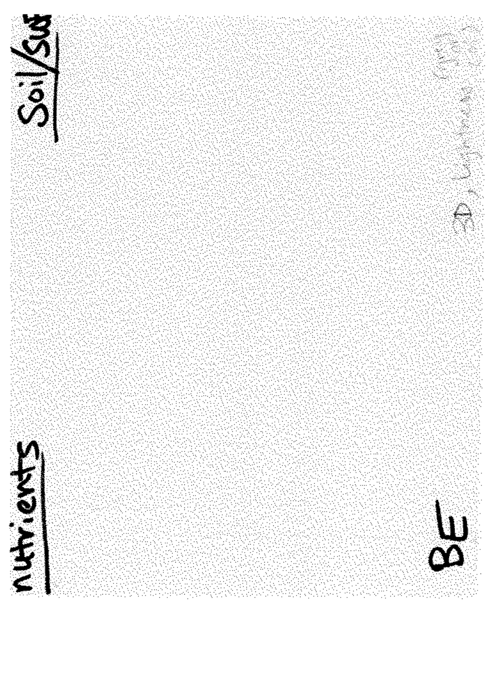


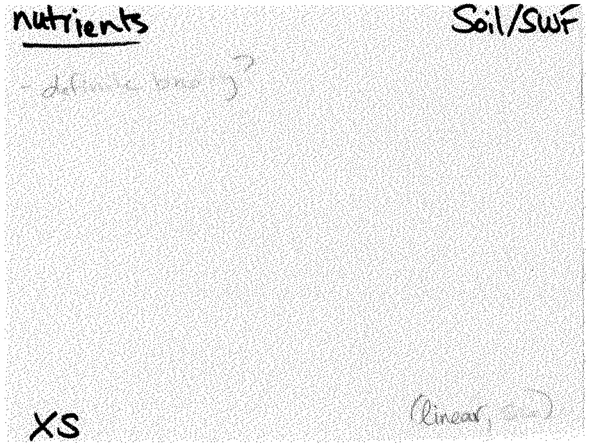

Nutrients
Walls
XS

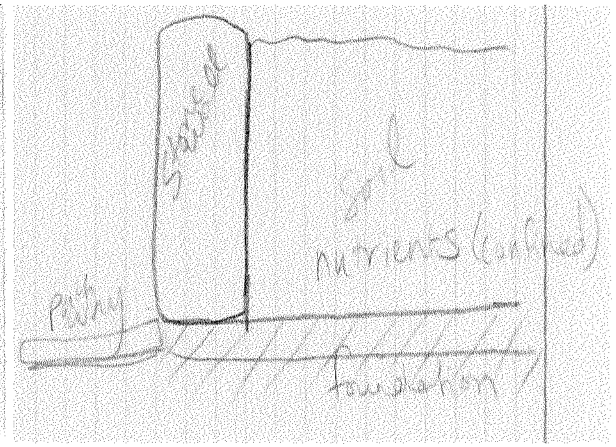


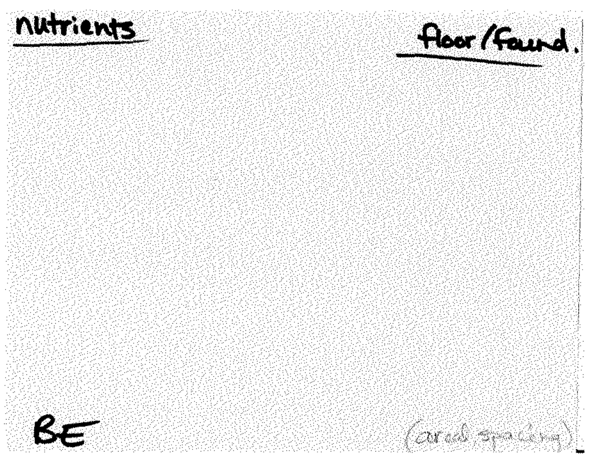

Nutrients
IW
BE

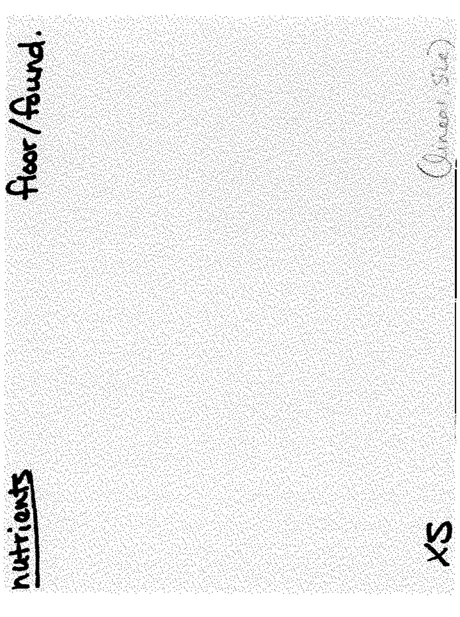

nutrients
IW
XS

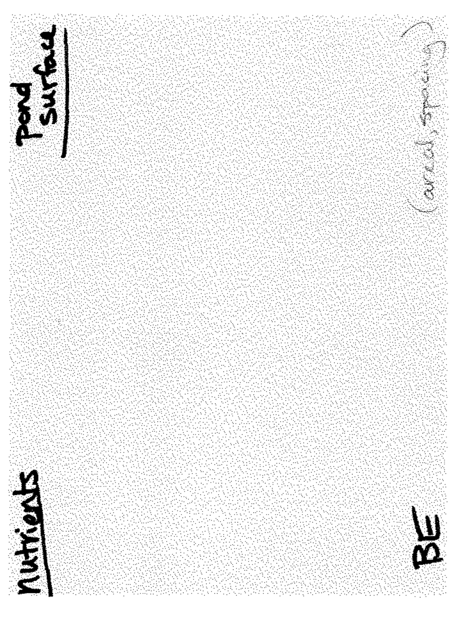

nutrients
BE

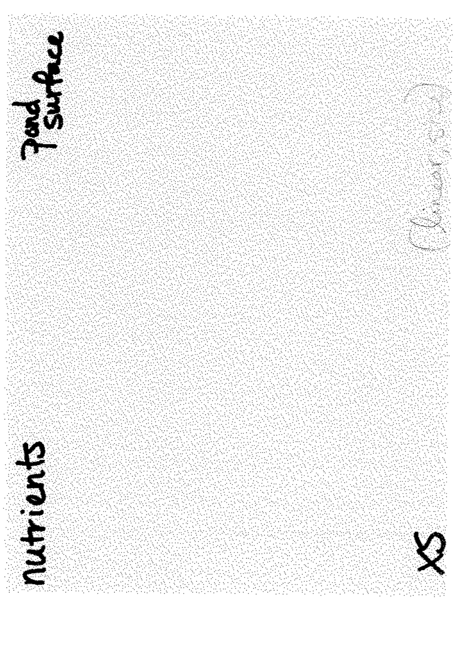

nutrients
Soil/SWF
XS
(linear,

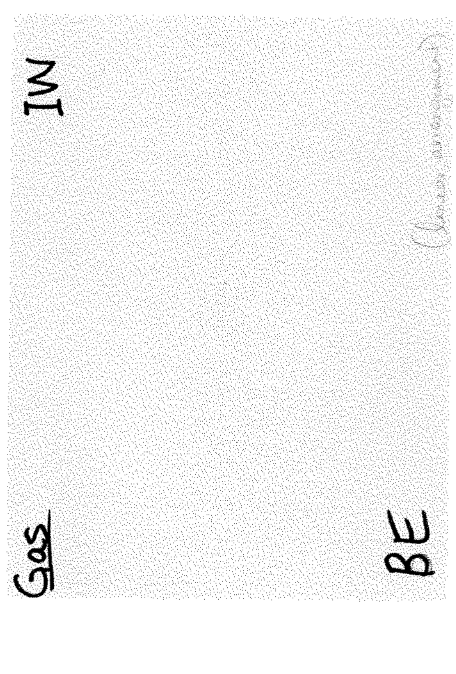

nutrients (confined)
foundation

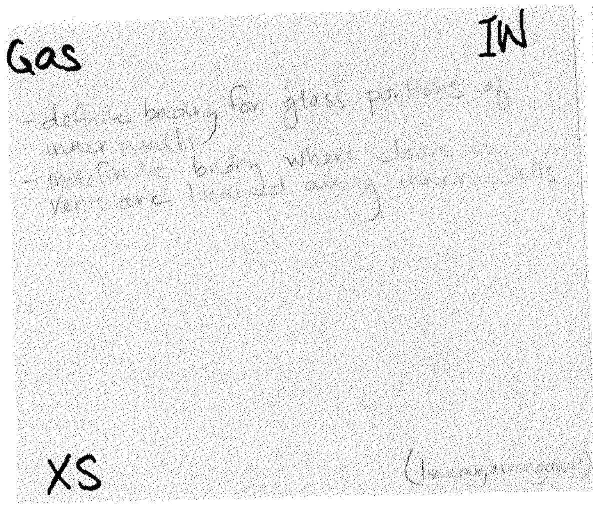

nutrients
floor/found.
BE
(areal spacing)

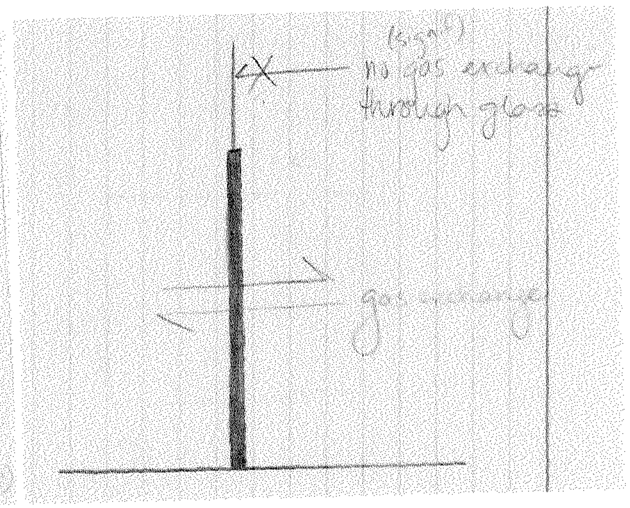

nutrients
floor/found.
XS

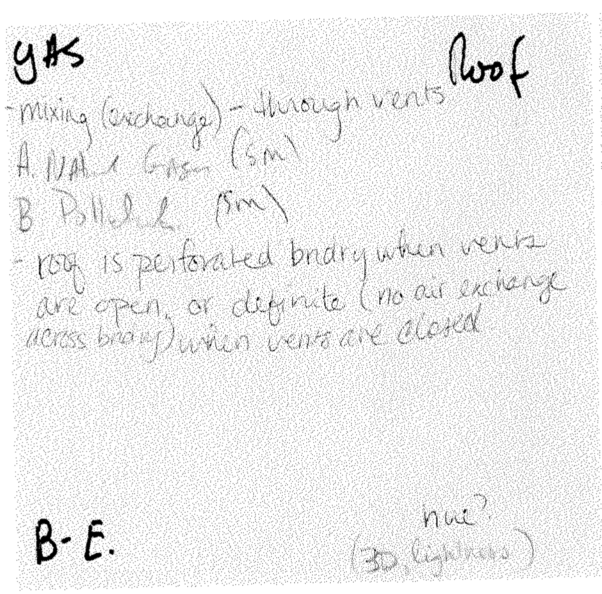

nutrients
pond surface
BE

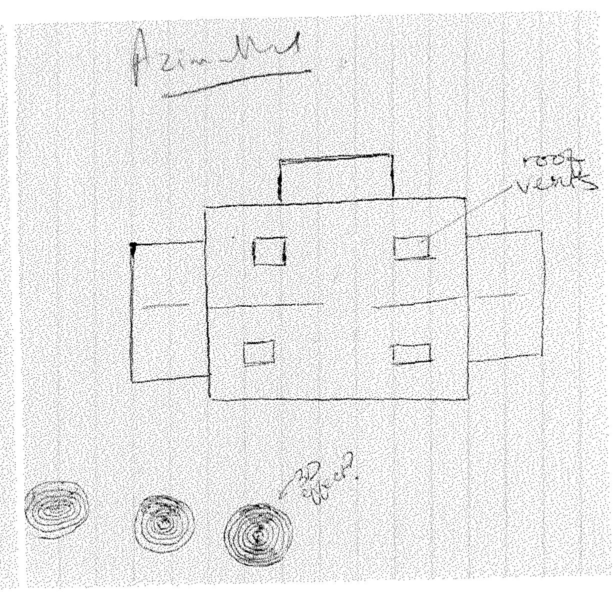

nutrients
food surface
XS

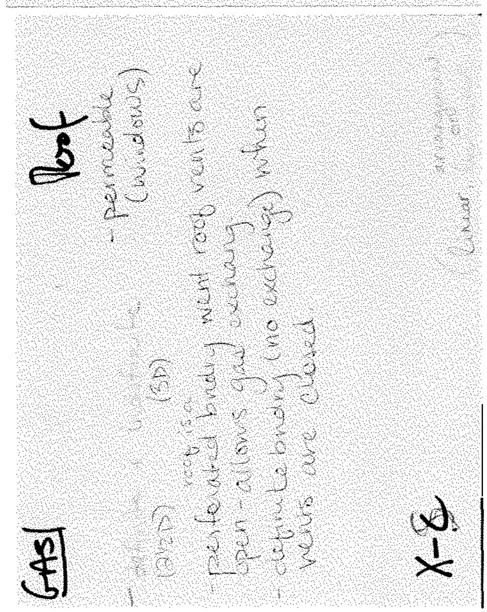

Gas
IW
BE

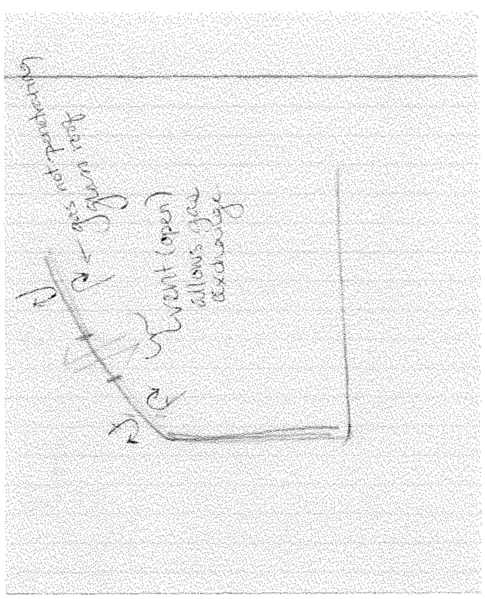

Gas
IW
- definite bndry for glass portions of inner walls)
vents are
XS

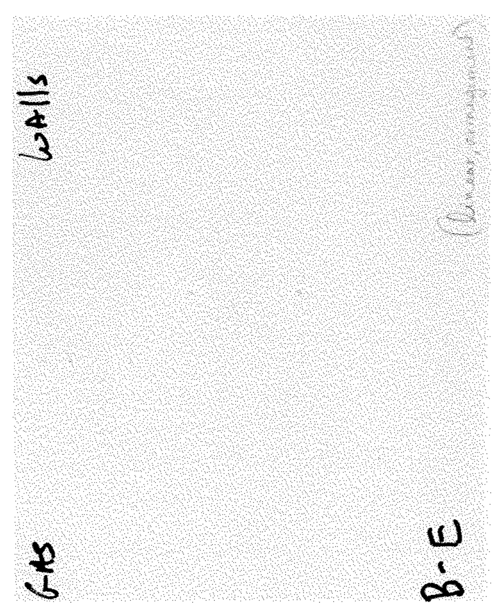

(signif)
no gas exchange through glass
gas exchange

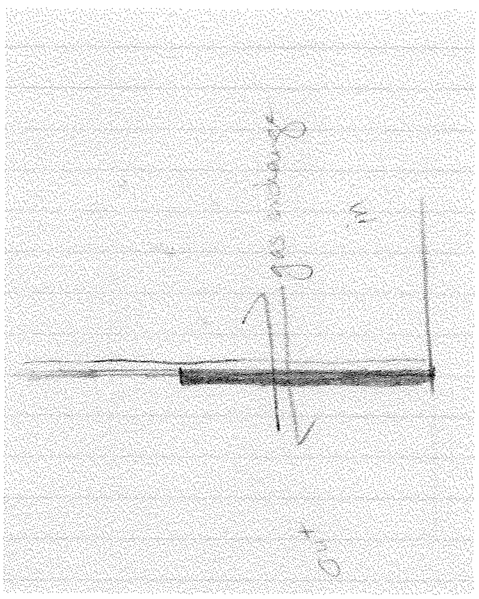

yAs
Roof
- mixing (exchange) - through vents
A. NAtl Gas (5m)
B. Polluted (5m)
- roof is perforated bndry when vents are open, or definite (no air exchange across bndry) when vents are closed
B-E.
hue?
(3D, lightness)

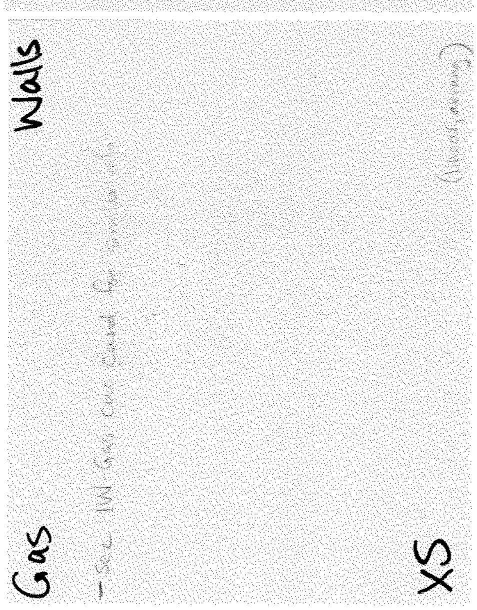

Azimuth
roof vents
3D effect?

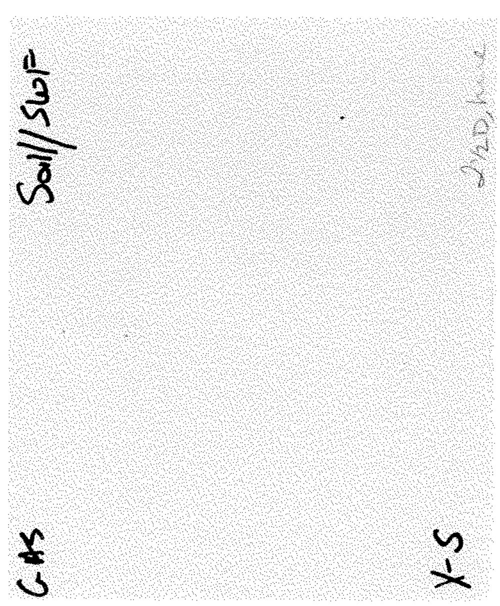

GAS
Roof
- permeable (windows)
(2½D) (3D)
roof is a
- perforated bndry went roof vents are open - allows gas exchang
- definite bndry (no exchange) when vents are closed
X-8
linear


← gas not penetrating glass roof
vent (open) allows gas exchange


GAS
WAlls
B-E


gas exchange
out
in

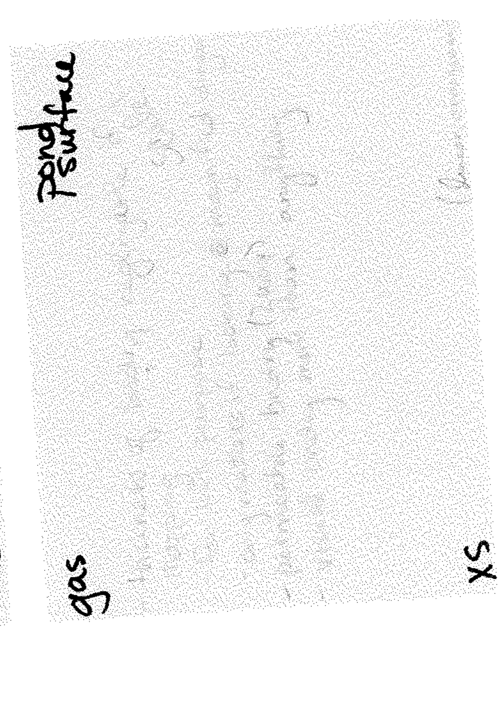

Gas
Walls
XS

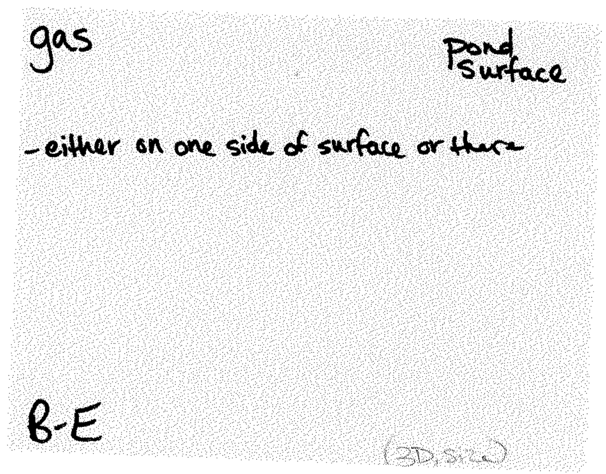

GAS
X-S


Gas
Soil/SWF
B-E


gas
floor/foundation
BE


gas
XS


gas
pond surface
XS



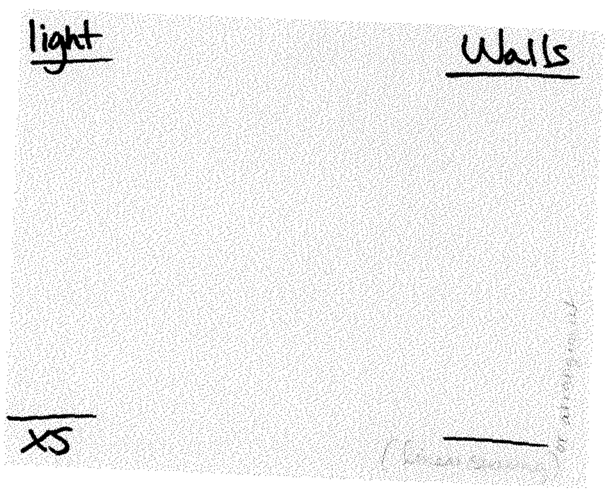
gas

Pond
Surface

- either on one side of surface or there

B-E

(3D, size)



light

Walls

XS

Cue card for:

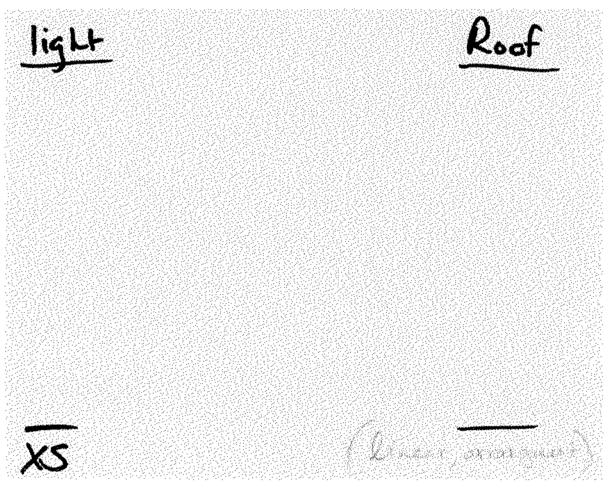
Boundary – Outer Walls

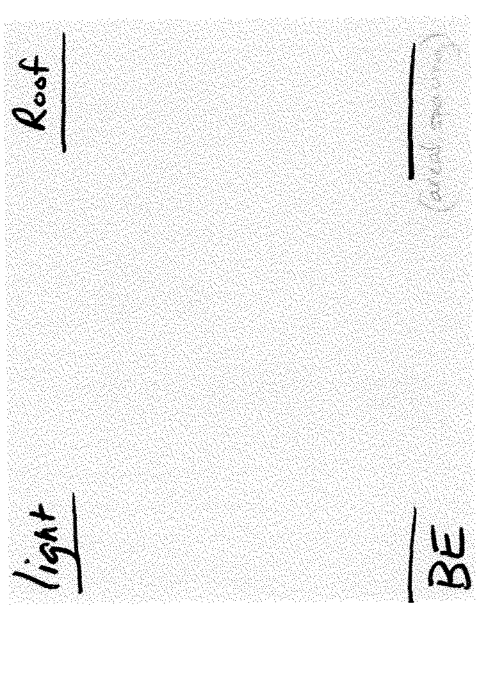
Mode – Light

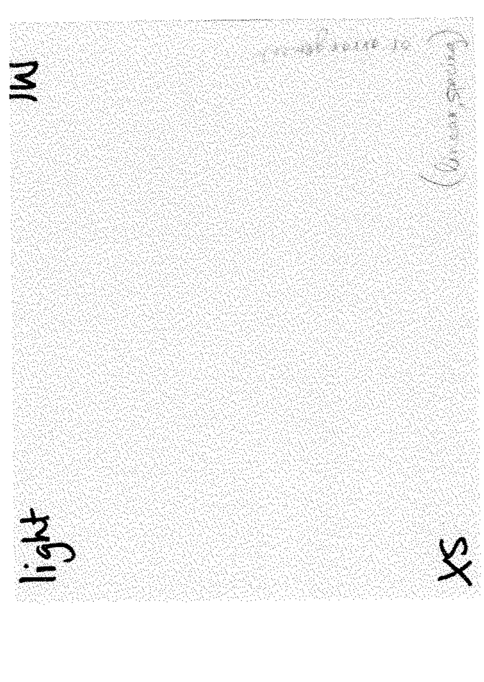
Perspective – BE

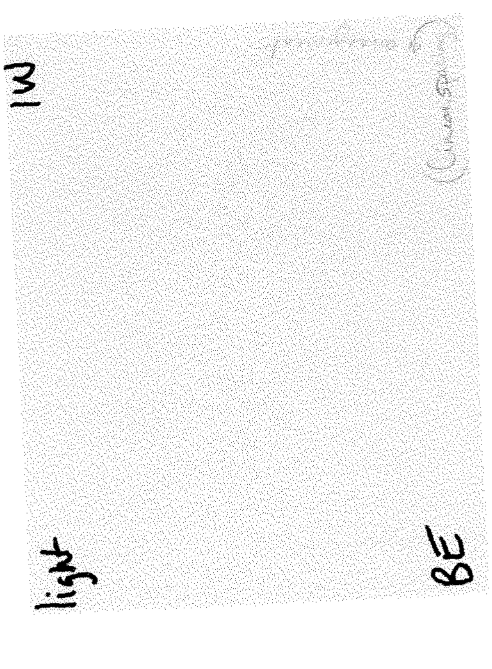
Cartographic Representation: Linear,

Spacing or Arrangement

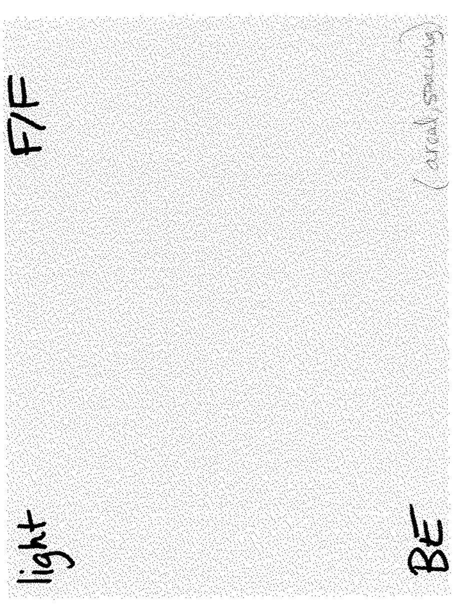


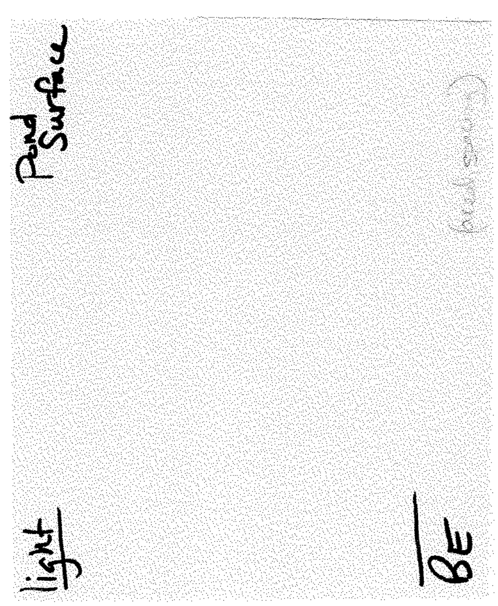

Roof
light
BE


light
XS

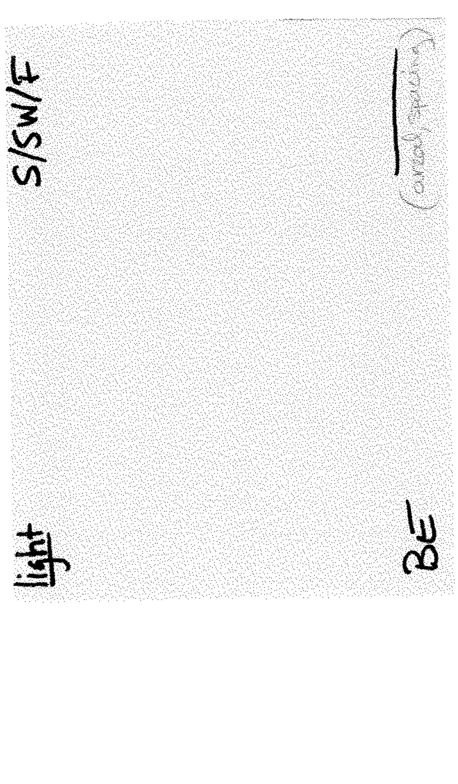

IW
light
BE

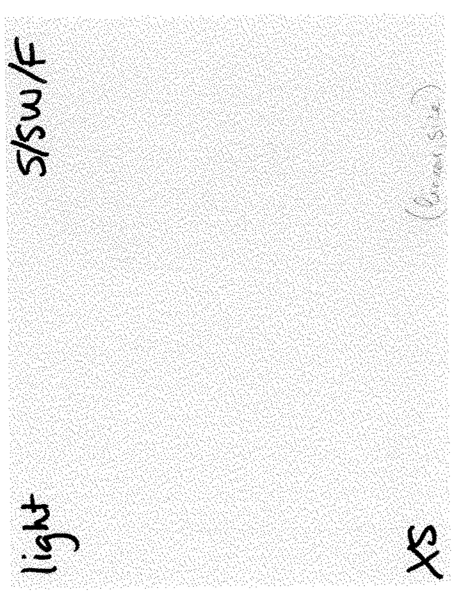

F/F
light
XS


light
F/F
BE


light
Pond Surface
BE


light
Pond Surface
XS


light
S/SW/F
BE
(areal spacing)


S/SW/F
light
XS

APPENDIX C:
ECOLOGICAL BOUNDARY SYMBOLOGY MATRIX

Appendix C allows the reader to view the Ecological Boundary Symbology Matrix in its entirety. It was originally constructed in Microsoft Excel 2003 during my research. It contains 76 entries of the boundary-mode sets studied inside the Thunder Bay Centennial Botanical Conservatory (see Figure A. 1.) during the winter of 2008. The matrix includes the boundaries observed a the Conservatory, boundary classifications, associated modes, the spatial phenomenon of the mode, map perspective, cartographic portrayal of the boundary phenomenon, cartographic visual variables, and supplementary notes.

Boundary	Definite/Indefinite/Perforated Boundary	Fiat or Bona fide Boundary	Interface or Medial Boundary	Mode	Spatial Phenomenon of Mode	Map Perspective	Portrayal of Boundary Phenomenon	Visual Variables	Supplementary Notes
floor/foundation	definite	bona fide	interface	gas	True 3-D	BE	areal	spacing	
floor/foundation	definite	bona fide	interface	gas	2 ½-D	XS	linear	size	
floor/foundation	definite	bona fide	interface	nutrients	True 3-D	BE	areal	spacing	
floor/foundation	definite	bona fide	interface	nutrients	2 ½-D	XS	linear	size	
floor/foundation	definite	bona fide	interface	vegetation	True 3-D	BE	areal	spacing	solid hue, so no misunderstanding, no levels of strength/weakness of this boundary
floor/foundation	definite	bona fide	interface	vegetation	2 ½-D	XS	linear	size	
floor/foundation	definite	bona fide	interface	light	True 3-D	BE	areal	spacing	
floor/foundation	definite	bona fide	interface	light	2 ½-D	XS	linear	size	
floor/foundation	indefinite	bona fide	interface	temperature	True 3-D	BE	True 3-D	hue	
floor/foundation	indefinite	bona fide	interface	temperature	2 ½-D	XS	2 ½-D	hue	
floor/foundation	indefinite	bona fide	interface	water	True 3-D	BE	True 3-D	hue	
floor/foundation	indefinite	bona fide	interface	water	2 ½-D	XS	2 ½-D	hue	
interior walls (IW)	definite	bona fide	medial	nutrients	True 3-D	BE	linear	size	
interior walls (IW)	definite	bona fide	medial	nutrients	2 ½-D	XS	linear	size	
interior walls (IW)	definite	bona fide	medial	vegetation	True 3-D	BE	linear	size	
interior walls (IW)	definite	bona fide	medial	vegetation	2 ½-D	XS	linear	size	
interior walls (IW)	definite	bona fide	medial	water	True 3-D	BE	linear	size	
interior walls (IW)	definite	bona fide	medial	water	2 ½-D	XS	linear	size	

interior walls (IW)	perforated	bona fide	medial	gas	True 3-D	BE	linear	arrangeme nt	
interior walls (IW)	perforated	bona fide	medial	gas	2 ½-D	XS	linear	arrangeme nt	
interior walls (IW)	perforated	bona fide	medial	water - vapour	True 3-D	BE	linear	arrangeme nt	
interior walls (IW)	perforated	bona fide	medial	water - vapour	2 ½-D	XS	linear	arrangeme nt	
interior walls (IW)	indefinite	fiat	medial	temperature	True 3-D	BE	True 3-D	hue	
interior walls (IW)	indefinite	fiat	medial	temperature	2 ½-D	XS	2 ½-D	hue	
interior walls (IW)	indefinite	fiat	medial	light	True 3-D	BE	linear	spacing	
interior walls (IW)	indefinite	fiat	medial	light	2 ½-D	XS	linear	spacing	
exterior walls (glass)	definite	bona fide	medial	soil nutrients	True 3-D	BE	linear	size	
exterior walls (glass)	definite	bona fide	medial	soil nutrients	2 ½-D	XS	linear	size	
exterior walls (glass)	definite	bona fide	medial	vegetation	True 3-D	BE	linear	size	
exterior walls (glass)	definite	bona fide	medial	vegetation	2 ½-D	XS	linear	size	
exterior walls (glass)	definite	bona fide	medial	water	True 3-D	BE	linear	size	exception being the doors and windows
exterior walls (glass)	definite	bona fide	medial	water	2 ½-D	XS	linear	size	
exterior walls (glass)	perforated	bona fide	medial	gas	True 3-D	BE	linear	arrangeme nt	perforated because: definite boundary with doors, windows, vents
exterior walls (glass)	perforated	bona fide	medial	gas	2 ½-D	XS	linear	arrangeme nt	
exterior walls (glass)	indefinite	bona fide	medial	temperature	True 3-D	BE	True 3-D	hue	isolines
exterior walls (glass)	indefinite	bona fide	medial	temperature	2 ½-D	XS	2 ½-D	hue	isolines
exterior walls (glass)	indefinite	fiat	medial	light	True 3-D	BE	linear	spacing	add transparency
exterior walls (glass)	indefinite	fiat	medial	light	2 ½-D	XS	linear	spacing	add transparency

pond surface	indefinite	bona fide	interface	nutrients	True 3-D	BE	areal	spacing	
pond surface	indefinite	bona fide	interface	nutrients	2 ½-D	XS	linear	size	
pond surface	indefinite	bona fide	interface	temperature	True 3-D	BE	areal	lightness (colour)	
pond surface	indefinite	bona fide	interface	temperature	2 ½-D	XS	linear	arrangement	
pond surface	indefinite	bona fide	interface	terrestrial vegetation	True 3-D	BE	areal	perspective height	
pond surface	indefinite	bona fide	interface	terrestrial vegetation	2 ½-D	XS	linear	arrangement	
pond surface	indefinite	bona fide	interface	water	True 3-D	BE	areal	hue	
pond surface	indefinite	bona fide	interface	water	2 ½-D	XS	linear	arrangement	
pond surface	indefinite	fiat	interface	gas	True 3-D	BE	True 3-D	size	either on one side of the surface or the other. will not be inside of the boundary - but will pass through
pond surface	indefinite	fiat	interface	gas	2 ½-D	XS	linear	arrangement	thickness of bndry negligible if mapping and for the purpose of this thesis. Only matters if looking at magnified scale diagram. Permeable bndry (2-way) and a visual bndry more than anything
pond surface	indefinite	fiat	interface	light	True 3-D	BE	areal	spacing	
pond surface	indefinite	fiat	interface	light	2 ½-D	XS	linear	arrangement	
roof	definite	bona fide	medial	precip - nutrients	True 3-D	BE	areal	lightness (grey scale)	
roof	definite	bona fide	medial	precip - nutrients	2 ½-D	XS	linear	size	
roof	perforated	bona fide	medial	gas	True 3-D	BE	True 3-D	lightness (colour)	mixing (exchange). Sub-modes include natural gases and pollutants
roof	perforated	bona fide	medial	gas	2 ½-D	XS	linear	arrangement	permeable windows

roof	definite	bona fide	medial	precipitation	True 3-D	BE	areal	lightness (grey scale)	curved roof with sloping sides
roof	definite	bona fide	medial	precipitation	2 ½-D	XS	linear	size	Linear bndry b/c no precip can get through the roof.
roof	definite	bona fide	medial	vegetation	True 3-D	BE	areal	spacing	
roof	definite	bona fide	medial	vegetation	2 ½-D	XS	linear	size	
roof	indefinite	bona fide	medial	temperature	True 3-D	BE	True 3-D	lightness (colour)	sizing of arrows; isolines
roof	indefinite	bona fide	medial	temperature	2 ½-D	XS	2 ½-D	lightness (colour)	isolines
roof	indefinite	fiat	medial	light	True 3-D	BE	areal	spacing	
roof	indefinite	fiat	medial	light	2 ½-D	XS	linear	arrangeme nt	
soil/stone wall/walkway	definite	bona fide	interface	gas	True 3-D	BE	True 3-D	hue	
soil/stone wall/walkway	definite	bona fide	interface	gas	2 ½-D	XS	2 ½-D	hue	
soil/stone wall/walkway	definite	bona fide	interface	soil nutrients	True 3-D	BE	True 3-D	lightness (grey scale)	
soil/stone wall/walkway	definite	bona fide	interface	soil nutrients	2 ½-D	XS	linear	size	
soil/stone wall/walkway	definite	bona fide	interface	vegetation - foliage	True 3-D	BE	linear	hue	submodes: nutrients, H20, shade
soil/stone wall/walkway	definite	bona fide	interface	vegetation - foliage	2 ½-D	XS	linear	hue	
soil/stone wall/walkway	definite	bona fide	interface	light	True 3-D	BE	areal	spacing	
soil/stone wall/walkway	definite	bona fide	interface	light	2 ½-D	XS	linear	size	
soil/stone wall/walkway	perforated	bona fide	interface	temperature	True 3-D	BE	True 3-D	hue	
soil/stone wall/walkway	perforated	bona fide	interface	temperature	2 ½-D	XS	2 ½-D	hue	
soil/stone wall/walkway	perforated	bona fide	interface	vegetation - roots	True 3-D	BE	True 3-D	hue	areal if no relief (then it'd be 2 ½-D), no isolines

soil/stone wall/walkway	perforated	bona fide	interface	vegetation - roots	2 ½-D	XS	2 ½-D	hue	boundary as floor. photo showing roots protruding through wall into open air
soil/stone wall/walkway	perforated	bona fide	interface	water	True 3-D	BE	True 3-D	hue	refers to water w/n soil, water enters wall making bndry of wall/soil 3D
soil/stone wall/walkway	perforated	bona fide	interface	water	2 ½-D	XS	2 ½-D	hue	