VISUALIZING LANDSCAPE SYSTEMS WITH PARAMETRIC MODELING

by

STUART MACKENZIE JONES

(Under the Direction of Douglas Pardue)

ABSTRACT

Parametric tools are a way of defining design constraints in order to visualize design opportunities. Digital parametric tools allow landscape architects a greater ability to visualize how landscape systems change over space and time. Landscape systems, which are the interconnected pieces and processes of a landscape, are integral to the long term function of designed spaces. This thesis gives an overview of parametric tools and parametric thinking, and describes how parametric tools are being applied to the design of the built environment and landscape systems. The thesis argues that parametric tools can incorporate the theories of Complexity Science, Emergence, and Resilience as a method of visualizing how landscape systems change over time. The argument is tested by using parametric tools to visualize and enhance an adaptive and resilient planting strategy.

INDEX WORDS: Parametric Modeling, Grasshopper, Landscape Systems, Complexity Science, Emergence, Resilience, MaryCarol Hunter

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B.A., Williams College, 2008

A Dissertation Submitted to the Graduate Faculty of The University of Georgia in Partial Fulfillment of the Requirements for the Degree

MASTER OF LANDSCAPE ARCHITECTURE

ATHENS, GEORGIA

2012

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ACKNOWLEDGEMENTS

The development of this thesis has had near constant support from Doug Pardue. I am very grateful for his commitment and dedication in helping me through the thesis writing process. Thank you very much to my thesis committee for reviewing my work and sharing their thoughts and opinions. Many other members of the UGA community as well as outside faculty and friends have supported me in writing this thesis. I am grateful for all of their support.

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CHAPTER 1 INTRODUCTION

The recognition of landscapes as a set of complex and interrelated elements and the need to manage these and the goals of sustainability has lead landscape architects to design with landscape processes that change over time. Traditional analog tools such as pencil sketching and plan and section drawings are limited in their capacity to compute and thereby visualize a complex landscape system. Parametric tools have the potential to help landscape architects visualize complex landscape systems in space and time. Parametric tools, a way of defining design constraints in order to visualize design opportunities, offer landscape architects a way to relate landscape variables into a complex system in order to visualize how designs will change over space and time.

Two subquestions addressed in the introduction of this thesis are, “How can parametric tools help landscape architects visualize landscape systems in space and time?”, and “What are the variables that landscape architects must understand to visualize and manage landscape systems?”

This thesis explores ideas that are both at the edge and the heart of the profession of landscape architecture. Landscape architects have long focused on how humans can benefit from dynamic natural systems (Zaitzevsky, 1982). The idea that nature is a changing system that landscape architects play a role in managing is at the heart of landscape architecture (McHarg, 1969). Meanwhile this thesis is on the edge of landscape architecture because many of the tools and techniques that can be used to design with dynamic systems that are discussed in this thesis are relatively new and are still being developed (Rutten, 2012). These new tools, which can be combined with scientific theory, are at the edge of our ability to visualize and understand how dynamic systems will respond and adapt to change over time (Weinstock, 2010).

At the core of this thesis is an exploration of the powerful new tools, specifically the program Grasshopper, that are available to landscape architects. The 21st Century may well be defined by the ability of search engines like google to allow access to vast amounts of data and information. Not only is there increased access to data but there are also incredible new abilities to create data as well. The digital tools that are typical of landscape architectural practice have only begun to access the full potential of the 21st Century. The steady flow of information that comes from our phones is being used to describe in real time large human systems such as traffic patterns. The data from thousands of individual users is able to visualize how the system of traffic functions as a whole (Figure 1-1). This visualization of traffic has lead to the ability to more efficiently navigate our complex environment. These changes are possible only through the direct influence of digital technology. Digital technology offers the same potential revolutionary impact for the discipline of landscape architecture.

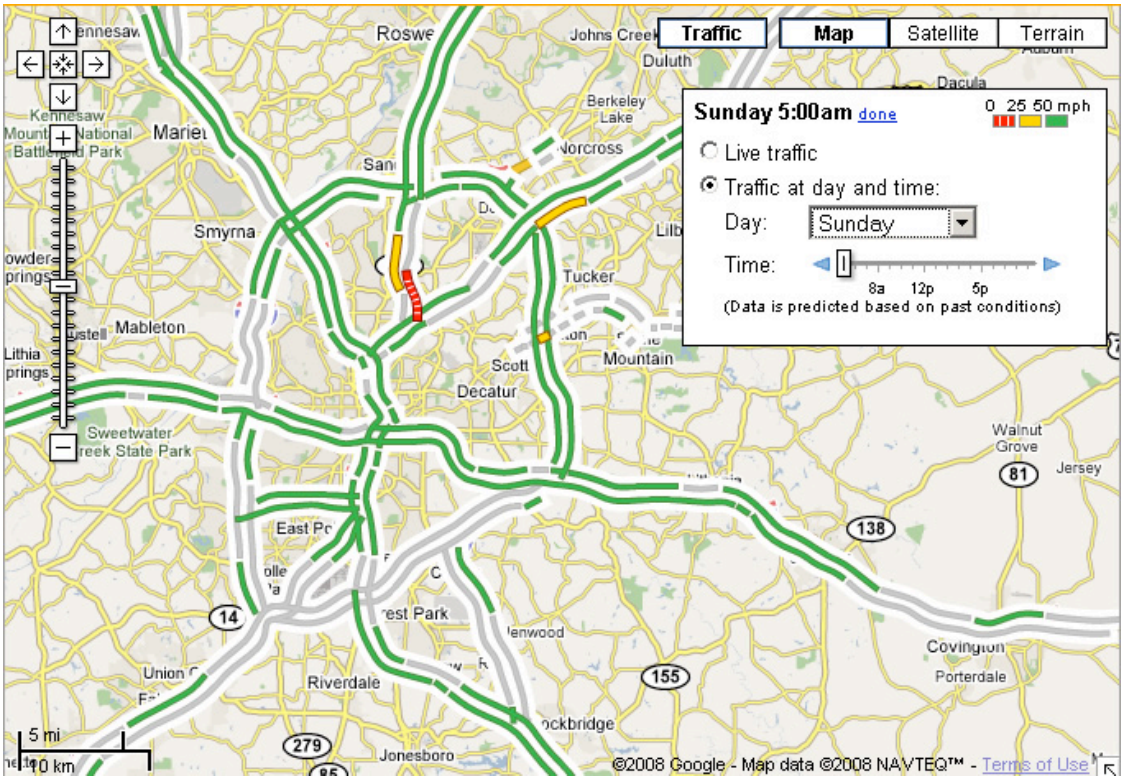


Figure 1-1 - Google Traffic - Location data from many individual cell phones are used to create real time traffic information.

At the moment, architects are far ahead of landscape architects in their embrace of digital technologies (Burry, 2010; Ceccato, 2010; Hensel, 2010; Liaropoulos-Legendre, 2011). Through the direct use of advances in digital technology architects are able to construct extremely complicated structures that seem to perform aerial acrobatics as they twist into the sky.

Figure 1-2 - Foster - Parametric Structure (Partners, 1997-2004)

Figure 1-3 - CCA Media Lab - (Architecture/MEDIAlab, 2008 – 2009)

Parametric tools can be used in a variety of different ways. Increasingly architects are looking to create buildings that are able to respond to change in real time (Hensel, 2010; Schumacher, 2010; Weinstock, 2010). Digital sensors are being combined with parametric tools to test how buildings will function in response to rapidly changing environmental conditions. While architects are exploring dynamic structures, landscape architects are being asked to design landscapes which can evolve and adapt to changing conditions over time. The interest in designing with natural systems is not new to landscape architecture. Design with changing systems has been a core principal in landscape architecture since Frederick Law Olmsted first created spaces to act as the lungs of the city (McHarg, 1969; Zaitzevsky, 1982). What is new for landscape architecture is both the understanding of how landscape systems interact as well as availability of powerful parametric tools.

This thesis argues that landscape architectural design would benefit from using digital technology to visualize how designs might change over time. While visualization often refers to creating images to convey the experience of a design, this thesis focuses primarily on visualization as a method of conveying how design decisions impact the function of a landscape in space and time. The primary difference between the two types of visualization is that visualizations that are used as a tool for describing and understanding the functional aspects of landscapes tend to be more mathematical and focused on various possible outcomes and less on pictorially representing the experience of a landscape.

There are many reasons why landscape architects should be concerned with how their designs function in space and time. First, clients are requesting that landscapes be built with a greater awareness of their impact on environmental systems. Clients are also asking that designs be created with funding methods to exist with the design over the life of the space. Second, the rapid growth of cities combined with a rapidly changing climate require a greater sensitivity be given to the complexity of the built environment.

Parametric tools do not alter the qualities of a successful design, but instead change the way a successful design is developed and conceptualized (Moussavi, 2011). Landscape architects should use parametric tools because they offer the ability to visualize complex systems which is fundamental to understanding how landscapes change over time. The ability to visualize a system can help landscape architects maximize the function of their designs. While there are other methods of visualizing systems, parametric tools are powerful, but relatively unexplored for landscape architecture.

Methods

A parametric model was created for this thesis to test how parametric tools can visualize landscape systems in space and time. The model was based on an existing design strategy that visualizes landscape systems in space and time. In order to develop the parametric model the thesis relied on a literature review of how parametric tools work, the parametric tools that are available to landscape architects, the way parametric tools are being used in the built environment, the way landscape architects have visualized landscape systems, as well as a review of systems theory which included Complexity Science, Emergence, and Resilience. A comparison of parametric tools led to the selection of Grasshopper as the specific parametric tool to be used to create the parametric model. The literature review of how parametric tools work was used to select an existing design strategy which would be replicable with parametric tools. Case studies on the variety of parametric tools available to landscape architects and how landscape architects have designed and visualized landscape systems over time, are used to reinforce the information from the literature review.

Overview

The second chapter of the thesis focuses on parametric tools, how they are currently being used in contemporary practice, and their potential to allow landscape architects to visualize dynamic systems. The chapter answers, “what are parametric tools?" and "How are designers currently using parametric tools in the design of the built environment?". The chapter distinguishes parametric thought from parametric modeling and gives a basic definition of parametric tools, their origin, as well as provides a brief overview of the various tools that are available to designers. The chapter also explores a range of case studies of designs that have used parametric tools, as well as a discussion on the some of the criticism as well as the praise for how parametric tools can be used to visualize landscape systems.

The third chapter gives the background of how landscape architects have understood, designed, and visualized landscape systems. The chapter argues that landscape architects have always had an interest in understanding and designing with natural systems and that as our understanding of systems, both ecological as well social, increases so too has our ability to manipulate these systems. The chapter answers, "What are landscape systems?", "Why are landscape systems important to landscape architecture?", "How have landscape architects visualized how landscape systems change in space and time?", "How do parametric tools expand the way landscape systems are visualized?", "How are designers using parametric tools to visualize the design of the built environment over space and time?", and "What is needed to visualize a landscape system with parametric tools?"

Case studies on Olmsted's Emerald Necklace, McHarg's design strategies, Steinitz's framework for Camp Pendleton, Corner's Freshkills Park, Khoolhaas's Downsview Park, and Bradley Cantrell's study of erosion in the Gulf Coast are used to highlight how, as our knowledge of natural systems increased so too has our ability to manipulate these systems. The case studies are also used to highlight not only the value of creating systems that change over time but also the types of change landscape architects seek to manipulate.

The chapter links with the previous chapter by discussing how parametric tools can be used as a way of increasing our knowledge of natural systems because of their ability to help landscape architects visualize how designs interact with complex systems. The city of New Orleans is highlighted as an example of how the potential negative impacts of ignoring some of the larger overall climactic systems in favor of the shorter term social and political systems. The chapter uses the exploration of digital as well as analog techniques by landscape architecture professor Bradley Cantrell as way to highlight how parametric tools are helping landscape architects understand how the human systems of the Gulf Coast could positively interact with the geological systems of the Gulf Coast.

The fourth chapter discusses the scientific study of complex systems and how that research can be incorporated into landscape architecture through parametric tools. The chapter answers, “What are the theories that landscape architects are using to guide how landscapes change over time?”, “Why is Complexity Science a useful framework to understand landscape systems in space and time?”, “Are parametric tools capable of incorporating the theories of Complexity Science into the visualization of landscape systems?”, and “How are landscape architects visualizing Resilience?” Expanding from a foundation of Complexity Science, the theories of Emergence and Resilience are two examples of scientific theories that can be applied to landscape architecture through the use of parametric tools. The chapter describes some of the basic principles of Complexity Science and why they are applicable to landscape architecture. It then goes into a more detailed analysis of the subset theories of Emergence and Resilience and how digital technologies are being used to visualize the complex systems that landscape architects design on a regular basis.

The chapter ends by describing how some of the digital techniques that scientists use to study Emergence and Resilience can be translated into the digital tools used by landscape architects.

The fifth chapter goes into a detailed example of how landscape architects are using Complexity Science in designs and the ways that parametric tools can enhance those designs. the chapter answers, "What is needed in order to parameterize MaryCarol Hunter's resilient design strategy?", "What are the benefits and limitations of using parametric tools to visualize MaryCarol Hunter's design strategy?", "What are the more general benefits and limitations of parametric tools that can be extrapolated from the modeling of MaryCarol Hunter's design strategy?" An adaptive design strategy developed by the landscape architect MaryCarol Hunter is an example of a design that can be enhanced by the ability of parametric tools to visualize complex systems. The example describes how the existing strategy would need to be modified in order to be incorporated into a parametric tool and also explores how parametric tools can expand and enhance Hunter's research.

The final chapter summarizes the challenges and benefits of incorporating parametric tools into landscape architecture, describes potential future applications, as well as areas for future research. The paper determines that parametric tools are powerful, but can difficult and potentially dangerous to implement.

A Cautionary Tale

While this thesis argues for a greater incorporation of science and technology into design, it is advisable to take a step back and acknowledge some of the fundamental challenges to human knowledge. We should always be skeptical of what we think we know. The digital technology about to be presented can be particularly dangerous because there can be a false certainty that creeps into the use of computer models. It is important to remember that models are never a perfect description of the real world. There is an allegory that was shared with me by a professor when I was an undergraduate in environmental studies which is worth sharing as a cautionary tale before discussing the potential of digital technology to advance landscape architecture.

A group of scientists that were studying the effects of deforestation through aerial photography in Africa came across a village that was burning their nearby forests. The forests surrounding the village were in patches along a great swath of Savanna. The scientists were very concerned about the damage that the village was causing to the sensitive forest habitat. They were particularly concerned because edge habitats like the forest surrounding the village were known to have much larger amounts of bio diversity than other ecosystems. The burning of the forests was likely to be causing untold amounts of damage to local ecosystems.

The scientists met with the villagers and told them that what they were doing to forests was bad for the environment. The villagers responded that they needed the wood of the forest for cooking and their own survival. The scientists told the villagers that there would be no wood left when they had burned down the few remaining patches of forest that existed. It was then that the villagers were able to explain to the scientists that the forest patches that were surrounding the village were not remnants of a great forest that was being destroyed, but the beginning of a forest that was being created from the village. The village fence posts were living trees and every few years the village would move, leaving their living fence posts behind to create a forest that would soon attract abundant wildlife.

It wasn't until the scientists talked with the villagers that the changes of the larger time scale of the human and ecological system became apparent. The villagers were managers of their natural resources.

This allegory, true or not, speaks not only to the ability of humans to manipulate their environments for the benefit of many different systems, but also importance of understanding how systems function over different time scales. The scientists' time scale was short and incomplete and as a result only saw the consumption of valuable resources. Meanwhile the villagers were able to appreciate and understand the longer time scale of their local savanna ecosystem and had created a forest ecosystem system that balanced their immediate needs with the needs of future generations. Scientists relied on theories, logic, and models to develop a false understanding of the forest ecosystem, while the village relied on tradition, intuition, and observation of the ecosystem functioning over time. The ruthless logic of the parametric models can entice designers into the sense that solutions can be developed remotely with computer visualizations. Designers should be careful to resist being spell bound and uncritical of parametric modeling. Parametric models are only an approximation of the real world and should always be tempered with real world observation combined with a well cultivated design intuition.

CHAPTER 2 PARAMETRIC TOOLS

Introduction

The chapter is intended to illuminate the current use of parametric tools as well as the potential of the tools to visualize landscape systems in both space and time. This chapter answers the questions, “What are parametric tools?”, “How are designers using parametric tools in the design of the built environment?”, and “What is needed in order to be able to visualize a landscape system with parametric tools?”

What are Parametric Tools?

Parametric tools are a method of defining design constraints in order to visualize design opportunities. In other words, parametric tools link one aspect of a design to another. A very simplistic example can be found in the relationship between a road and a sidewalk that runs parallel to that road. In parametric modeling, the relationship between the road and sidewalk can be explicitly described as, “the sidewalk should be parallel to the road”. The curve of the road is linked to the curve of the sidewalk through the explicit relationship of being parallel. If the curve of the road changes, the curve of the sidewalk will also change, in order to adhere to the rule of being parallel to the road. The form of the sidewalk only exists as an output of the rule of being parallel to the road. The advantage of this particular function is that it allows a computer to carry out the pre existing explicit relationship as opposed to implicitly creating the relationship by hand every time a road is drawn.

There are also aspects of design which are intuitively understood by designers, but that are explicitly understood by other disciplines such as property assessment. Parametric tools offer a bridge between disciplines because of their ability to connect explicit but abstract relationships to 3-D design environments that are typical of landscape architecture. Real estate developers attempt to asses the value of a store based on certain explicit and measurable criteria (Figure 2-1). Property assessments are not an exact science, but they are also not completely arbitrary either. The rules for property assessment such as floorspace and location can be attached to the footprint of buildings in order to allow designers to understand how different designs impact the potential retail value of the spaces created. The designer is able to go beyond their intuitive understanding of economically desirable space and use the detailed understanding of property assessment to directly and explicitly impact the form the design.

Cost Assumptions	
Purchase Price	$400,000
Land Value (25%)	$100,000
Building Value (75%)	$300,000
Improvements	$10,000
Closing Costs	$8,000
Total Cost	**$418,000**
Selling Costs	7%

Financing Assumptions	
Downpayment	20%
Finance Amt	$320,000
Downpayment Amt	$80,000
Interest Rate	7.0%
Mortgage (Years)	30
Mortgage Payment	$2,129
Cash Outlay	**$98,000**

Revenue Assumptions	
# of Units	8
Total Rent/Month	$4,500
Other Rev/Month	$200
Gross Rev / Month	**$4,700**
Gross Rev / Year	**$56,400**
Vacancy Rate	12%

Key Values	
Cost/Unit	$52,250
Capitalization Rate	8.89%
GRM	7.41
Cash ROI	11.86%
Total ROI	23.71%
DSCR	145.49%
Annual Cash Flow	$11,621

		Monthly	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11
Annual Revenue Increase		3%	0.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%
Annual Operating Expense Increase		3%	0.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%
Annual Appreciation		2%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%
Revenues													
Rental Income		4,500	54,000	55,620	57,289	59,007	60,777	62,601	64,479	66,413	68,406	70,458	72,571
Vacancy Rate	12.0%	(540)	(6,480)	(6,674)	(6,875)	(7,081)	(7,293)	(7,512)	(7,737)	(7,970)	(8,209)	(8,455)	(8,709)
Net Rental Income		3,960	47,520	48,946	50,414	51,926	53,484	55,089	56,741	58,444	60,197	62,003	63,863
Other Income		200	2,400	2,472	2,546	2,623	2,701	2,782	2,866	2,952	3,040	3,131	3,225
Gross Income		4,160	**49,920**	**51,418**	**52,960**	**54,549**	**56,185**	**57,871**	**59,607**	**61,395**	**63,237**	**65,134**	**67,088**
Expenses													
Property Taxes	Annual	4,000	4,000	4,120	4,244	4,371	4,502	4,637	4,776	4,919	5,067	5,219	5,376
Insurance	Annual	600	600	618	637	656	675	696	716	738	760	783	806
Property Mgmt	(% Rent)	6%	2,851	2,937	3,025	3,116	3,209	3,305	3,404	3,507	3,612	3,720	3,832
Maintenance & Repairs	Annual	3,000	3,000	3,090	3,183	3,278	3,377	3,478	3,582	3,690	3,800	3,914	4,032
Advertising	Annual	300	300	309	318	328	338	348	358	369	380	391	403
Utilities	Annual	2,000	2,000	2,060	2,122	2,185	2,251	2,319	2,388	2,460	2,534	2,610	2,688
Other 1	Annual	0	0	0	0	0	0	0	0	0	0	0	0
Other 2	Monthly	0	0	0	0	0	0	0	0	0	0	0	0
Other 3	Monthly	0	0	0	0	0	0	0	0	0	0	0	0
Total Expenses			**12,751**	**13,134**	**13,528**	**13,934**	**14,352**	**14,782**	**15,226**	**15,682**	**16,153**	**16,637**	**17,137**
Net Operating Income (NOI)			**37,169**	**38,284**	**39,432**	**40,615**	**41,834**	**43,089**	**44,381**	**45,713**	**47,084**	**48,497**	**49,952**
Cash Flow													
NOI (Cash Available)		3,097	37,169	38,284	39,432	40,615	41,834	43,089	44,381	45,713	47,084	48,497	49,952
Mortgage		2,129	25,548	25,548	25,548	25,548	25,548	25,548	25,548	25,548	25,548	25,548	25,548
Total Cash Flow		**968**	**11,621**	**12,736**	**13,885**	**15,068**	**16,286**	**17,541**	**18,834**	**20,165**	**21,537**	**22,949**	**24,404**
Cash ROI			**11.86%**	**13.00%**	**14.17%**	**15.38%**	**16.62%**	**17.90%**	**19.22%**	**20.58%**	**21.98%**	**23.42%**	**24.90%**
Equity Accrued			3,251	3,486	3,738	4,008	4,297	4,608	4,941	5,298	5,681	6,092	6,533
Appreciation			8,360	8,527	8,698	8,872	9,049	9,230	9,415	9,603	9,795	9,991	10,191
Total Return			**23,232**	**24,749**	**26,320**	**27,947**	**29,633**	**31,379**	**33,190**	**35,067**	**37,013**	**39,032**	**41,128**
Total ROI			**23.71%**	**25.25%**	**26.86%**	**28.52%**	**30.24%**	**32.02%**	**33.87%**	**35.78%**	**37.77%**	**39.83%**	**41.97%**

Figure 2-1 - A spread sheet can be considered a form of parametric modeling.

Another example of a parametric tool is the online color selection tool “Kuler” created by Adobe (Figure 2-2). Color theory has very specific rules such as, triads, monochromatic, or complementary. In Adobe’s parametric tool, the individual color is a variable that can be changed; other colors based on a chosen relationship will then be output. The explicitly defined rule of the triad remains fixed, while the colors change based on a single and adjustable initial color variable.

Figure 2-2 - Adobe Kuler is a parametric tool which encodes color theory (Abode, 2012)

This tool allows designers to use color theory in an intuitive and exploratory way instead of having to focus on the mechanics of color theory. This illustrates how using parametric tools to describe explicit rules can make the design experience more intuitive for the designer.

This thesis proposes that parametric tools can be a visual aid in the testing of complex site dynamics which would otherwise be only roughly conceptualized through mental models. Every design project faces a variety of constraints, from client requests to physical limitations. Parametric tools help to find variation within the constraints of a well-defined problem. The difficulty then lies in defining the design problem. Once the problem has been defined, the designer can spend more time thinking about the range of possibilities (Menges, 2011). While the problem of defining a design problem and exploring a design solution is not new, the way that designers define the problem and come to conclusions about the best alternatives is altered by parametric tools (Woodbury, 2010).

What Makes Parametric Tools Different?

Parametric tools are fundamentally different from typical digital design tools (Menges, 2011). Unlike traditional design software, which essentially mimics the hand-drawing process in digital form, parametric design tools are a radical departure from the hand-drawing process in their use of explicit relationships between specific design elements. In traditional design, the rules that determine the design are implied and the form of the design is explicit. In other words, the final design has been created with rules, but the rules are embedded in the intuition of the designer and are expressed only in the shapes of the design. With parametric design, the rules need to be explicit or described in complete detail; the form emerges from these rules. Embedding rules into design can be beneficial when they help to utilize existing relationships but poorly understood relationships in the design such as the amount of sunlight and absorptive material needed to increase ambient evening temperatures.

Parametric Tools in the Built Environment

Parametric tools are increasingly being used in architecture but are underutilized in landscape architecture. This statement has been determined by the abundant writings and parametric designs of architects compared to the lack of discussion by landscape architects. A search of scholarly articles on The University of Georgia's library website for, "parametric and "architecture"" produced 4027 results, whereas a search on the same site for, "parametric and "landscape architecture"" produced 10 results. There are a variety of potential reasons for such a disparity such as the relative size of both professions, but in general, the information and discussion of parametric tools has been focused on architectural uses (Schumacher, 2011).

While architects have been creating complicated constructions with parametric tools for over a decade (Burry, 2010), landscape architecture has been slow to embrace and utilize the technology. However, as the landscape architecture professionals continue to explore dynamic landscapes (Corner, 1999), the ability of parametric tools to visualize and test dynamic processes will become a more valued design tool because of the ability to relate significant rules between design elements.

One example of the use of parametric tools to extend typical designs is Sir Norman Foster's glass roof at the British Museum's Great Court. Foster used parametric tools to create a glass ceiling in which every pane of glass has a unique size and shape, and meets its surrounding panes at a distinct angle. While such a task would have been impossible by hand, parametric technology allowed for the intricate and mathematically complex design to be created. (Figure 2-3).

Figure 2-3 - Queen Elizabeth II Great Court, (Partners, 1994-2000)

Parametric tools allow the designer to set up properties that are to be repeated through a series of different variables. For example, a bolt length might be set to be the distance between two pieces of wood. That distance may change depending on the angle of the joint. Even if every joint is unique, the calculation for the bolt length remains constant. As a result, the software can automatically compute the length of the bolt. Any calculation that is simply a matter of repeating a series of steps can be repeated and expressed simply.

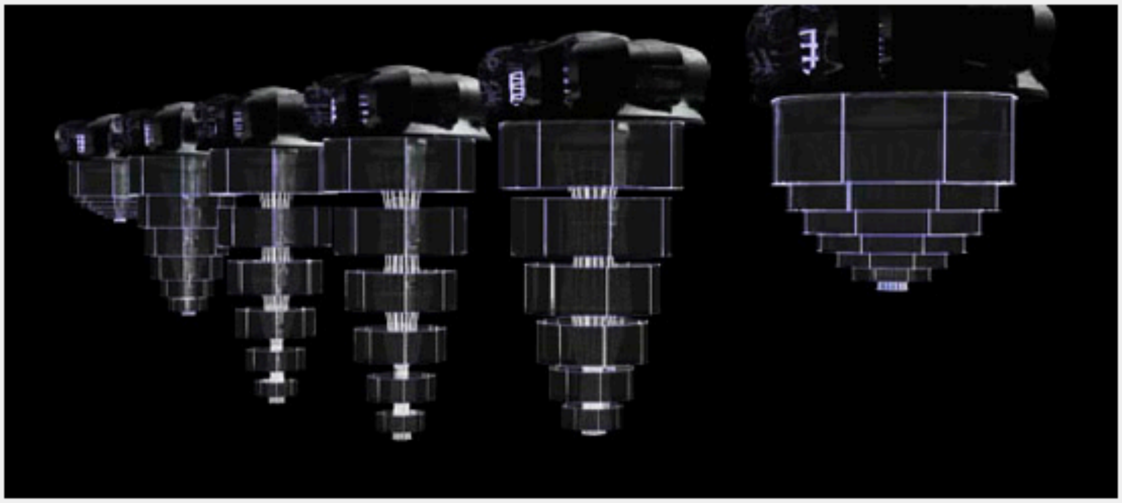
The same ability to reduce complex designs into something that can be physically constructed can be seen in West 8's series of Wave Decks. The Wave Decks are able to thriftily enliven the industrial Toronto waterfront through a dramatic undulation in the boardwalk in the rough shape of a wave (Figure 2-4). The thriftiness of the design is embodied in the single, but dramatic, change in typical boardwalks from flat to undulating. Other than the undulation, the wave decks are the exact same as a typical

Figure 2-4 - Wave Deck, West 8, Toronto, 2006 (Geuze, 2008) board walk, wooden planks along the edge of a body of water. By undulating the surface the typical boardwalk is able to serve as a play space for kids, seating for people to watch, as well as a novelty to draw people down to the Toronto waterfront. Thrift is defined as the ability to achieve many outcomes with a single gesture. West 8 is an example of a landscape architectural firm working with parametric tools to extend the ability of typical architectural construction in order to create exciting results. While there is a lack of literature on the tools used by West 8 to develop the wave decks, parametric tools could have enabled the exploration of form as well as the the efficient production of complicated construction documents.

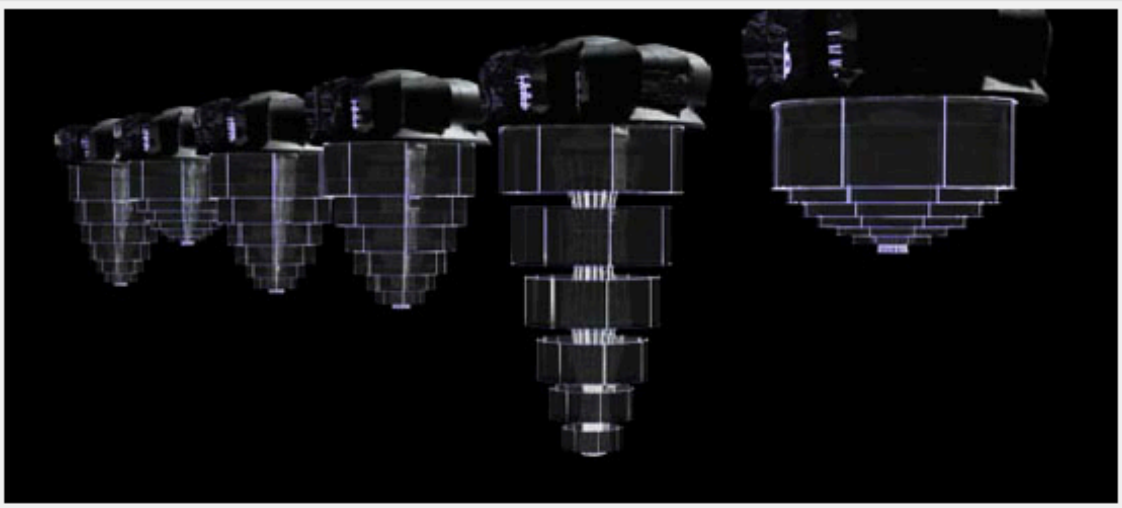
Another example of parametric architecture / landscape architecture is Diller and Scofidio's Blur Building (Figure 2-5). The structure was a temporary construction for a Swiss exposition in 2002. The "building" looks like a cloud that is floating on a lake. The structure is titled blur building but it is physically more of a landscape due to the lack of walls and a roof. The structure is a platform that is built on a lake and creates a physical cloud of mist from 37,000 spray nozzles that spray water directly from the surrounding lake (Diller, 2002). The misters are controlled by a computer that can read the weather and control the misters so that the cloud of mist hangs around the structure. The relationship between the computers and the nozzles is an explicit parametric relationship. In order for the computer to control the spray nozzles, very specific rules need to be created for the computer to follow. The exact movement of the wind and other climactic conditions could never be fully predicted, instead sensors collect information about the local climate and feed that information to the computer. Through a fixed set of rules, the computer adjusts the nozzles based on the climate to maintain the cloud.

Figure 2-5 - Blur Building, Diller and Scofidio, Switzerland, 2002 (Diller, 1999)

Bradley Cantrell, a landscape architecture professor at Louisiana State University, uses parametric tools in a similarly responsive way as Diller and Scofidio. Cantrell describes his work as exploring, “the device or infrastructure that responds to environmental phenomena” (Cantrell, 2012). Cantrell uses parametric relationships to create lighting prototypes that respond to changes in their environment (Figure 2-6). Like Diller and Scofidio, the exact actions of the space do not need to be predicted, instead responses to potential changes in the space are programmed into the function of the lighting fixture. Because the function of the light is entirely dependent on the moment to moment changes in the space, no two experiences would ever be the exact same. This is not a built work, but the function of the light has been modeled in a computer environment.



Device Array Configuration 1



Device Array Configuration 2

Figure 2-6 - Ambient Space, Cantrell (Cantrell)

Cantrell has also run studios where students have used responsive parametric relationships similar to the responsive relationship created in Cantrell's light prototype to develop landforms that are created through responses of mechanical systems to the flow and movement of river systems (Moser, 2012).

Both of the last two example are unbuilt, but the ideas and technologies rely on parametric thinking and are quite similar to the built work of Diller and Scofidio. It is worth noting that the smaller scale prototypes of responsive lighting systems are increasingly feasible to build and test with the help of low cost programmable electronics such as the Arduino micro controller and fabrication machines such as laser cutters and CNC routers. The more experimental ideas may seem like something out a futuristic science fiction novel, the development of these prototypes can progress beyond the confines of the imagination and into the real world as they have in the example of the Blur Building.

These examples are used to highlight the ability of the computer to extend typical designs. Parametric tools are also being used by other professions to explore dynamic processes such as the movement of forest fires (Robert et al., 2007). While the software being used by other disciplines may be different, for example landscape ecologists use a program called R, many of the computational techniques and thought processes are similar because of the shared language of the computer (Lazowska, 2011).

Components of Parametric Tools

In order to understand how landscape systems can be visualized with parametric tools it is necessary to understand how parametric tools function. The rest of the chapter details the thought processes and information that are needed to visualize systems as well as the range of parametric tools that are available to landscape architects.

The concept of parametric tools is quite old. While computer technology makes parametric modeling more powerful, the thinking behind this technology has existed for centuries. For instance, the proportions of the classical columns are based on a set of rules or parameters. To create a perfectly proportioned classical column, all that needs to be done is to multiply the diameter of the column to other values to get the precise length of specific elements (Figure 2-7).

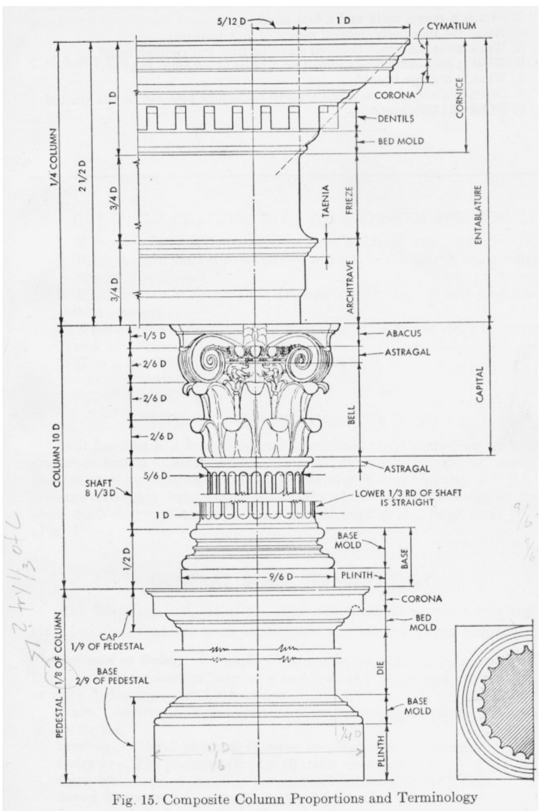


Figure 2-7 - Proportions of a composite Column ("Column,")

Digital parametric tools, distinct from parametric thinking, are both old and new. They are old in the sense that they were part of some of the original CAD programs (Sakamoto, 2008), but were pushed aside for more traditional interaction methods.

Instead of embracing the elements that make design with a computer different than designing with traditional tools of pencil and paper, computer programs were made to mimic traditional techniques (Menges, 2011). Digital parametric tools are new in that they have recently been “rediscovered.” This is partly due to the increased power of computers as well as the increased understanding of computers.

Computers are what make parametric design powerful (Liaropoulos-Legendre, 2011). Designers could always use parametric thought and craft explicit rules by hand, but without the computational ability of the computer to run variables through the rules millions of times over, it would be next to impossible to collect and analyze the results. After a relationship or set of rules is programmed into the computer, the designer is able to adjust variables and observe the range of relationship outcomes instantly, allowing rapid exploration of infinite design variations.

Variety of Parametric Tools

“Parametric” is a broad term which can be applied to many different types of design tools. For example, Autodesks’ Autocad program has a parametric tool set that allows designers to create specific relationships between geometry. The relationships are limited to a specific set that consist mainly of geometrical relationships such as angle, offset distance, and start point.

Autodesk has developed a program that has more robust parametric tools called Vasari. The tool is still in a development stage, but the relationships that can be created between objects has a wider range of possibilities than Autocad. While Autocad was initially designed as a drafting tool and has recently added parametric thinking as an design option, Vasari has been created with parametric thinking as an integrated part of the program, “Project Vasari is focused on conceptual building design using both geometric and parametric modeling.” (Autodesk, 2012).

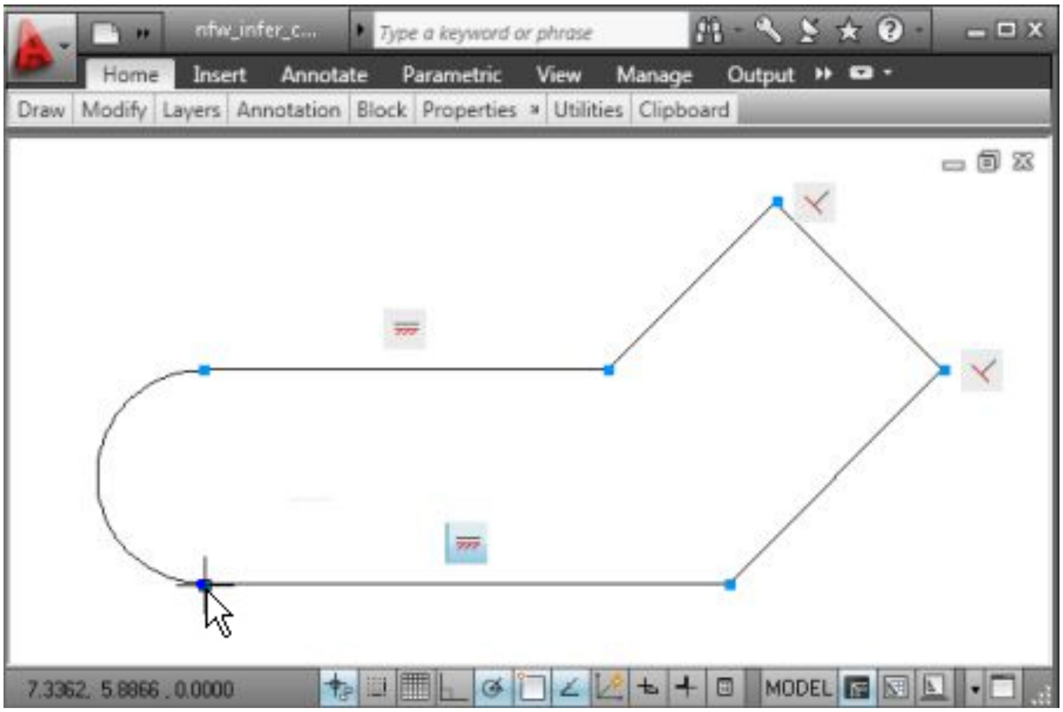


Figure 2-8 - Autocad Parametric Toolset

One way that Vasari has a wider range of possibilities than Autocad is the ability to attach solar information to the positioning of geometric elements. The ability to attach different kinds of data to geometry other than just geometric relationships greatly expands the range of meaning that can be created with parametric tools.

Autodesk has another program that is also a parametric tool, but different from the parametric tool Vasarai, called DesignScript. In an online video an Autodesk instructor compares DesignScript directly with Bently’s Generative Components and RhinoMcNeel’s Grasshopper.

```
def calc(firstnumber, operator, secondnumber):


        if (operator=='+'):
                result = firstnumber + secondnumber

        elif (operator=='-'):
                result = firstnumber - secondnumber

        elif (operator=='*'):
                result = firstnumber * secondnumber

        elif (operator=='/'):
                if (secondnumber==0):
                        result = "Can't divide by zero"
                else:
                        result = firstnumber / secondnumber
        elif (operator <>'+' or operator<>'-' or operator<> '*' or operator<>'/'):
                result = " I'm sorry, I do not recognize the operator you entered. Please try another."

        return result

def main():
        firstnumber= float(raw_input("1st number: "))
        operator= raw_input("operator: ")
        secondnumber= float(raw_input("2nd num: "))

        result = calculator(firstnumber, operator, secondnumber)
        print result


        '''userinput = raw_input("Enter first number, operator, and second number: ")
        prob = str(userinput).split()
        try:
                firstnumber = float(prob[0])
                operator = prob[1]
                secondnumber = float(prob[2])
                result = calculator(firstnumber, operator, secondnumber)
                print "Answer: ", result
        except:
                print "Invalid input."
```

Figure 2-9 - Typical scripting languages are able to utilize the computational ability of a computer but can be less accessible to the visual thought processes of designers.

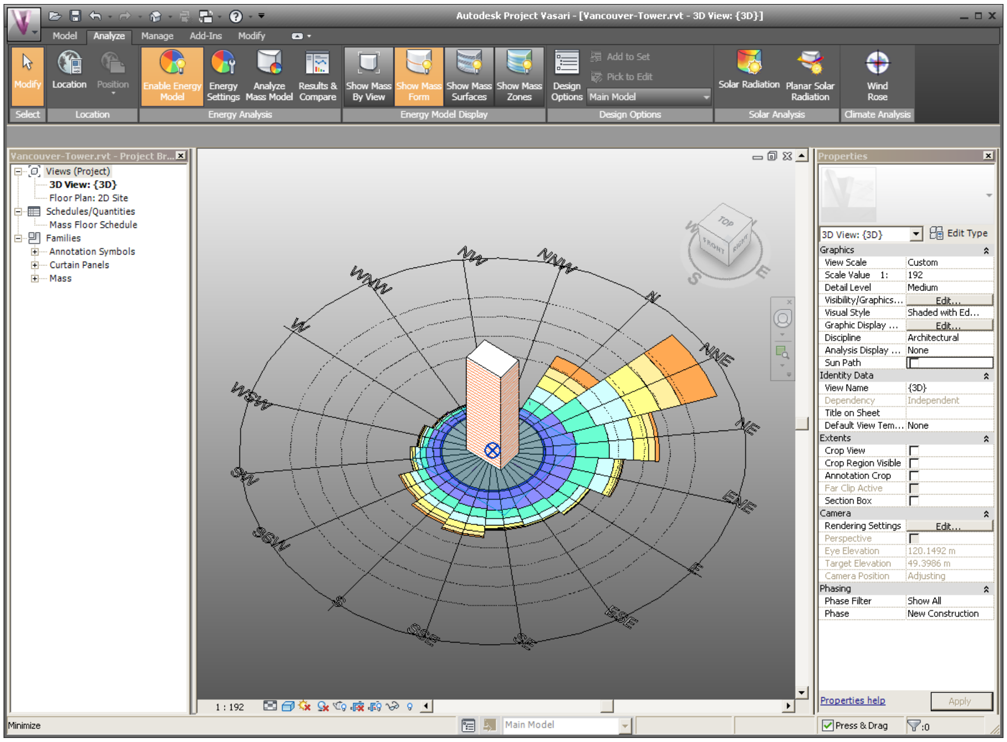


Figure 2-10 - Vasari - Climactic data is used to analyze 3-D Designs (Autodesk, 2012)

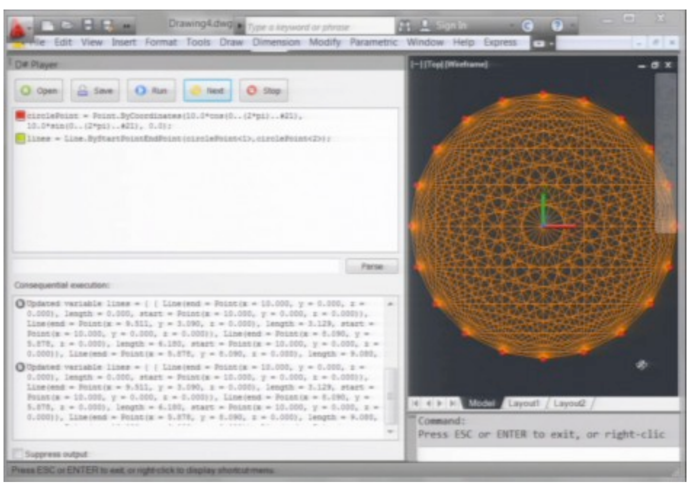


Figure 2-11 - Autodesk DesignScript (Aish, 2012)

Bently's Generative Components, often referred to as GC, is a dedicated parametric modeling tool. GC has been described as a powerful parametric tool but one that has a steep learning curve. The program relies on a text based scripting language which is a form of computer interaction which is not typical for some of the more common design programs such as Autocad.

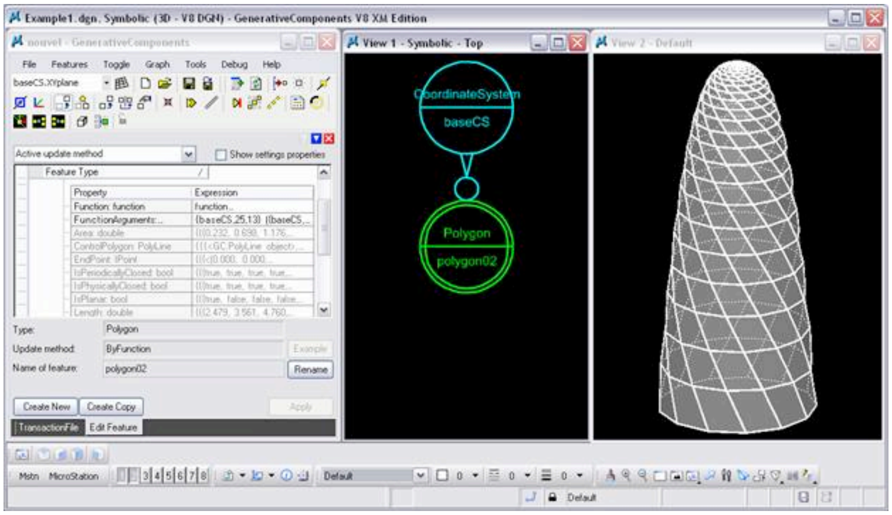


Figure 2-12 - Generative Components (Bently, 2012)

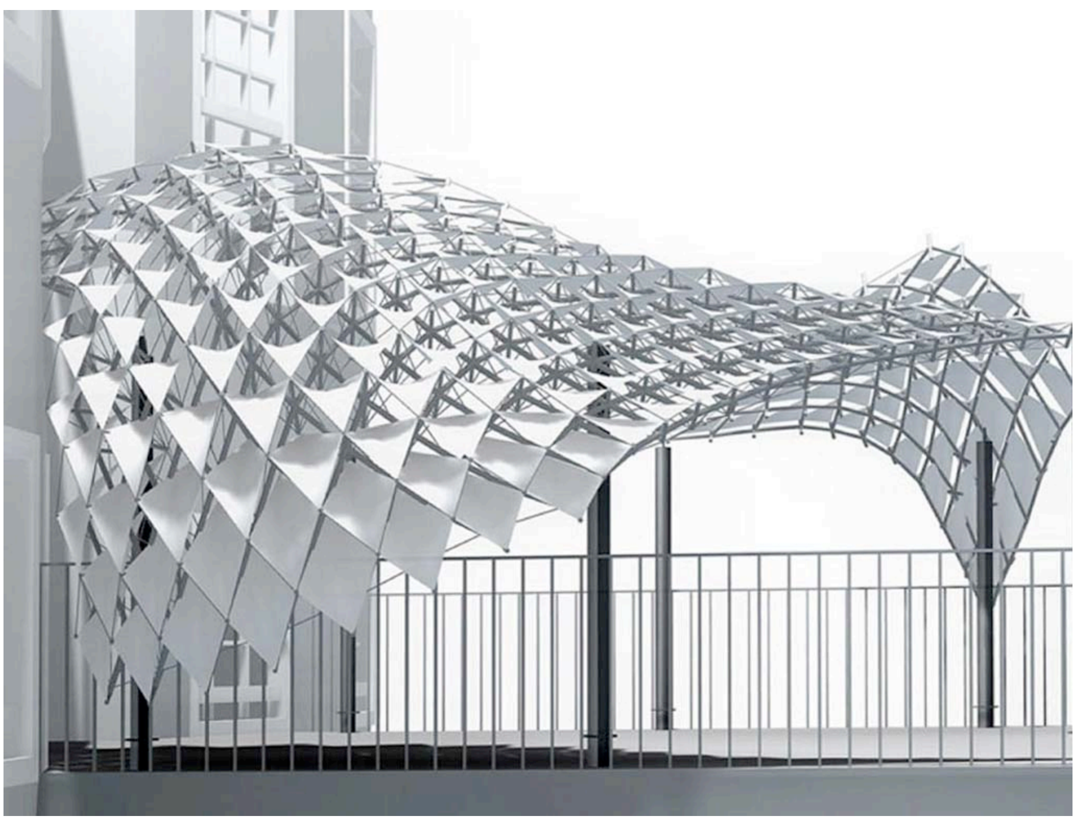


Figure 2-13 - A Shade Screen Modeled with Generative Components (Bently, 2012)

Figure 2-14 - Generative Components - Built (Bently, 2007)

Grasshopper is another parametric tool similar in parametric ability as DesignScript and Generative Components. Grasshopper is self described as, “for designers who are exploring new shapes using generative algorithms […] a graphical algorithm editor tightly integrated with Rhino’s 3-D modeling tools. Unlike RhinoScript, Grasshopper requires no knowledge of programming or scripting, but still allows designers to build form generators from the simple to the awe-inspiring.” (Grasshopper 3-D, 2012)

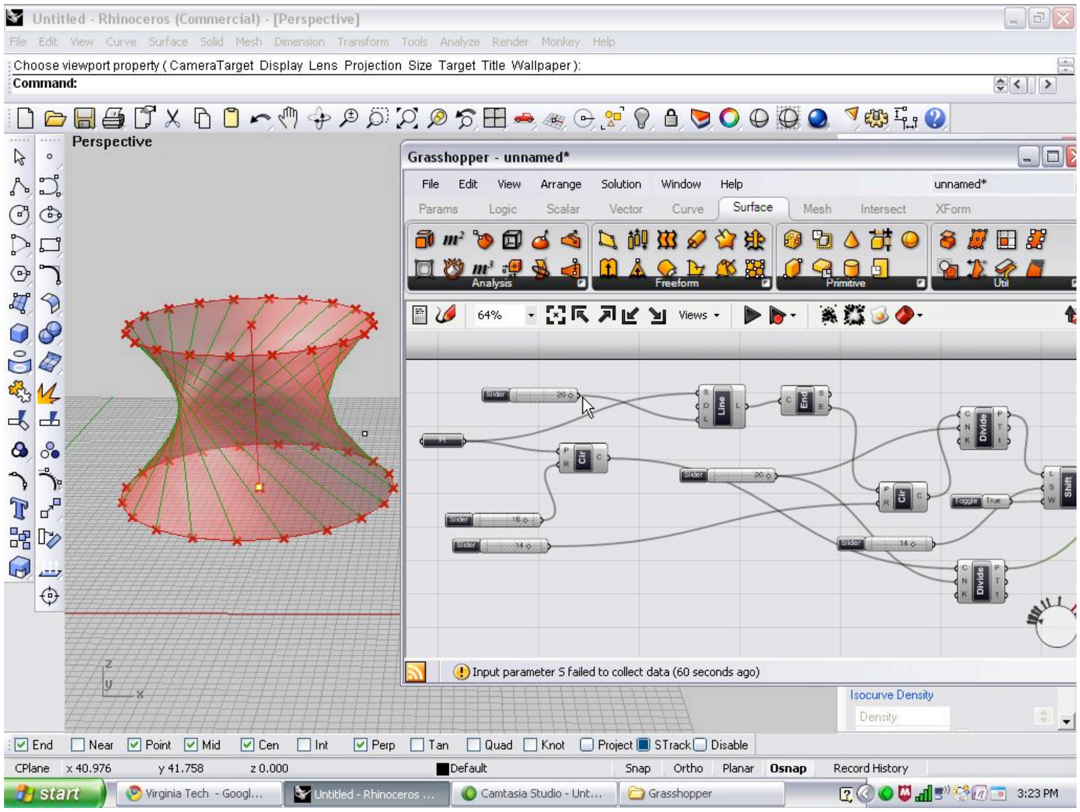


Figure 2-15 - Grasshopper (Rutten, 2012)

The computational power provided by Grasshopper shares a similarity to programming languages such as Java or C++ in terms of process, abstraction, and capabilities (Woodbury, 2010). Both text based programming languages and Grasshopper rely on creating explicit relationships between design elements. Unlike text-based programming languages, Grasshopper relies on visual icons for the programming interface. The advantage to using icons is that the relationships between various components can be more intuitively and visually understood than textual relationships.

Another important difference is that Grasshopper works very closely with the 3-D modeling program Rhino. The close connection between the two programs greatly enhances the visual feedback between the abstract algorithms and the effect of the algorithm on the modeled form. This feedback helps the user connect their abstract process with a visual design.

Some other programs which are not covered here are GEM paracloud modeler which works with Google Sketchup, Digital Project developed by Frank Ghery, as well as SolidWorks. This list of existing parametric software presented here is not exhaustive, but it does help to show the range of parametric modeling tools. There are some tools like Autocad where parametric rules are available but not integral to program, or Vasari where there is a mixture of parametric modeling and traditional modeling, or programs like GC that are dedicated to parametric modeling. All of these programs are directly linked through a shared connection of parametric thought and graphical feedback.

ESRI the maker of ArcMap, has recently added a design tool to their suite of analysis tools intended to rely on parametric modeling. The tool is called CityEngine, and is part of the many parametric tools that are becoming available for designers. All these tools share commonalities in thought processes and techniques. As this is a relatively new field there is more growth in programs than consolidation.

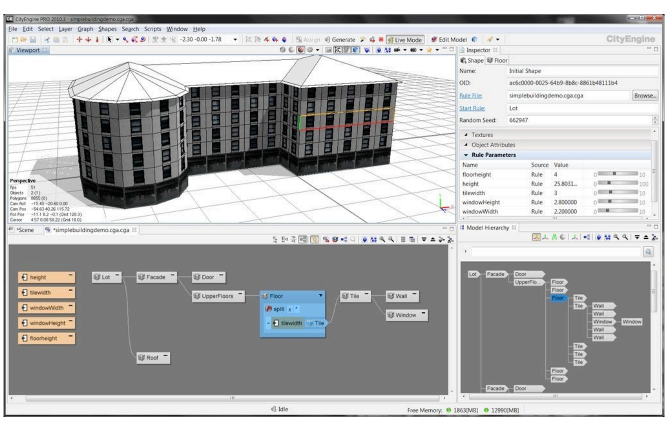


Figure 2-16 - ESRI CityEngine (ESRI, 2012)

There are a host of animation programs which are also have similar visual and scripting capabilities. Animation tools were not considered as part of this thesis One example to show similarity between programs is called Fugu. On the left of the image is the scripting panel where instructions are typed to the computer. The right side of the image has a visual output of the instructions.

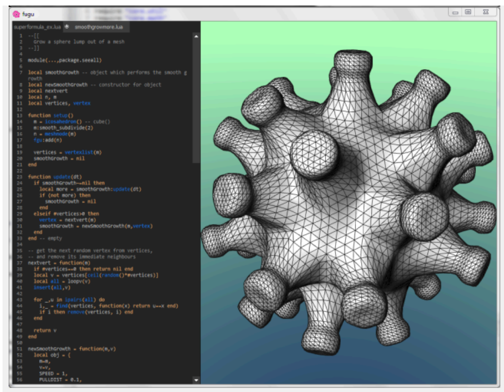
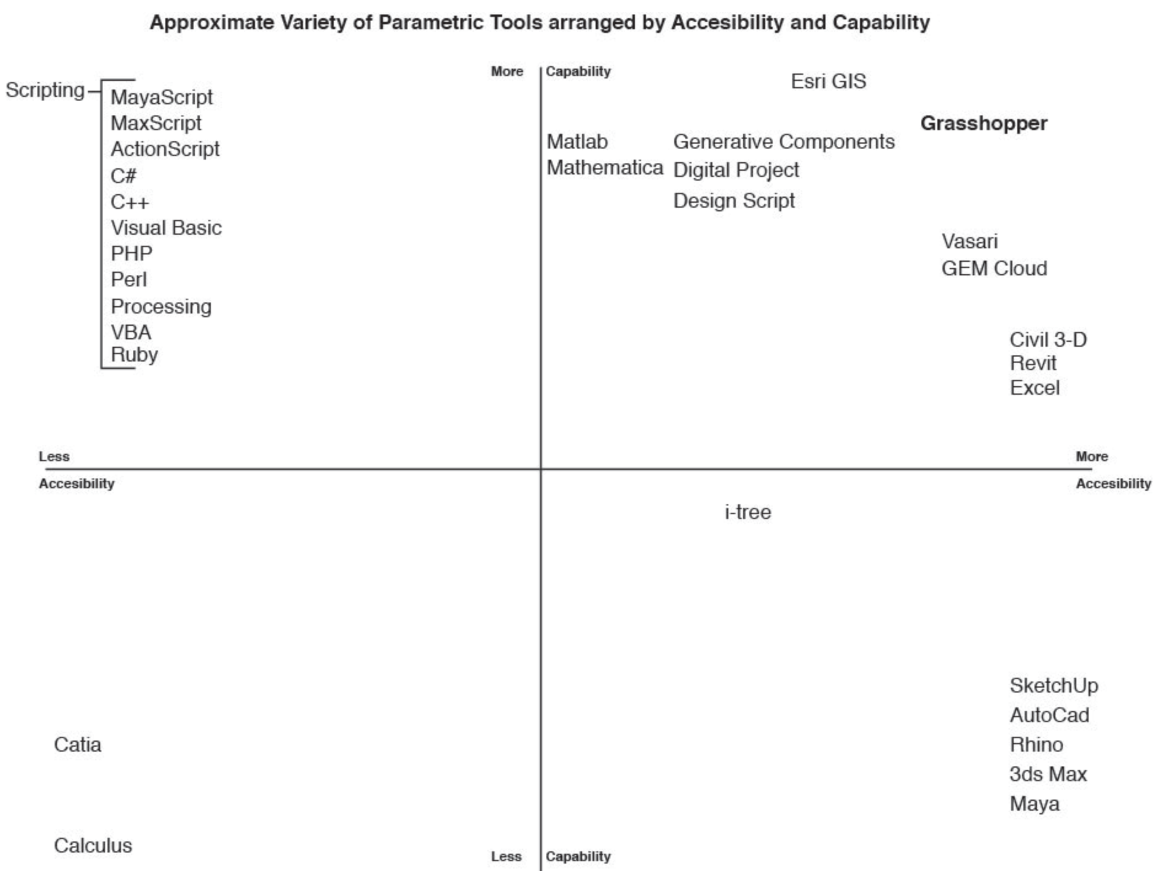


Figure 2-17 - Fugu (Ben Porter, 2012)

There are many different parametric tools that are available to landscape architects. While landscape architects are typically seen as synthesizers with diverse backgrounds, computer science is not likely to be one of the larger common denominators. Certain computer programs are more accessible to landscape architects than others. A chart has been developed to roughly describe how these different tools relate to each other. The chart is divided into accessibility and capability. Accessibility is based on a variety of factors including cost, educational materials (instructor led classes, online tutorials, etc), peer use/prevalence, and visual feedback/user interface. Capability is a rough approximation. Even the most capable tool in the hands of someone unskilled is of little value while a skilled expert can make the simplest tools very capable. In this case capability is framed for landscape architects in terms of the ability to perform different computational tasks. The 3-D modeling program Sketchup would rank higher in accessibility than the 3-D modeling program Rhino because it is a free program with many online tutorials as well as instructor led classes. Rhino however is slightly more capable than Sketchup because it uses a more extensive computational method of drawing curves. In general both Sketchup and Rhino are more similar than the typical programming languages such as Python, and parametric modeling tools such as Grasshopper. Parametric modeling tools are more accessible than traditional scripting languages because they are visually linked to typical design software such as Rhino, but are more capable than digital drafting tools such as Autocad because of their greater computational ability.

Table 2-1 - Capability vs. Accessibility



Grasshopper, DesignScript, Generative Components

Though there are many different forms of parametric tools appearing in a variety of design programs, this paper will focus on the parametric tool Grasshopper.

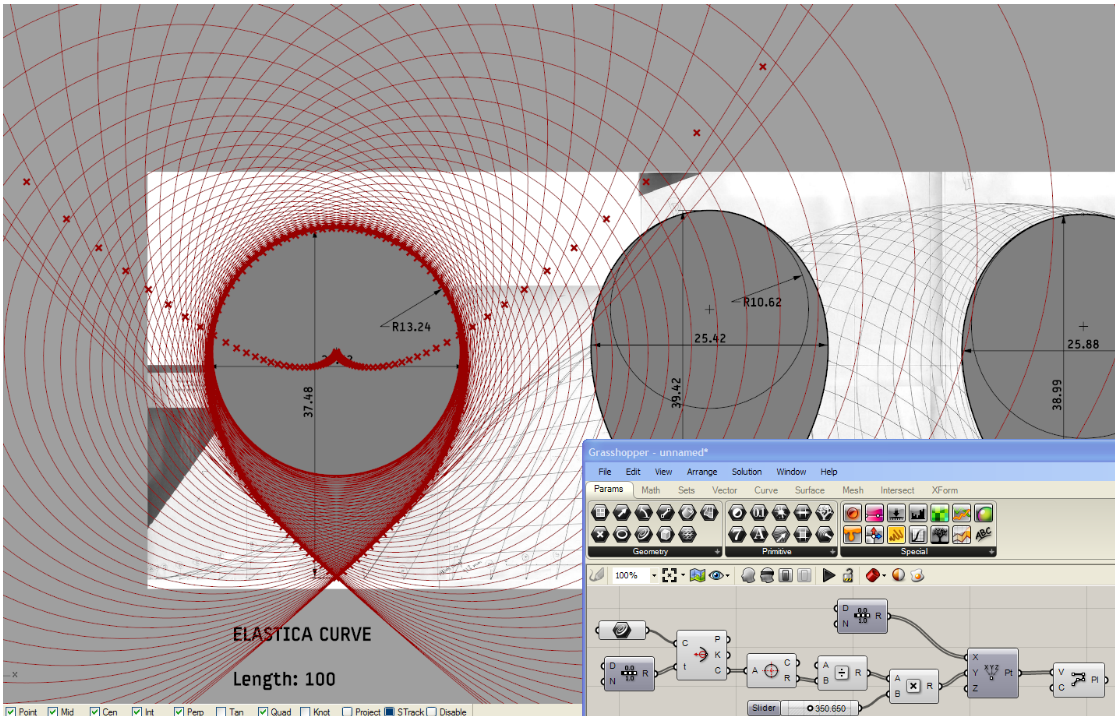


Figure 2-18 - Grasshopper and Rhino (Rutten, 2012)

There are a number of reasons for choosing Grasshopper over other parametric platforms. The primary reason being that Grasshopper was highly accessible in terms of online tutorials as well as instructor lead workshops. Many of these programs offer similar abilities, thought processes, and skill sets. Grasshopper was chosen primarily because of a background knowledge of the program before the writing of this thesis. Digital tools change rapidly and will certainly date this thesis. The ideas and thought processes however should have a longer relevancy because while individual softwares change, the fundamental computational processes remain the same.

The are certain benefits that are particular to Grasshopper over other programs. Not only accessibility, but also the range of potential applications was quite broad due to a large number of plug-ins to Grasshopper which extend its functionality into such disparate fields as digital sensors, evolutionary computing, and cellular automata. There are also a number of free "plug-ins" to Grasshopper which allow for interoperability with other programs such as Autodesk's Revit and Ecotect Analysis.

Mark Loomis, a landscape architect, created a chart (Table 2-1) that compares some of the various parametric design tools that are available to designers. The list below is not exhaustive but does highlight some of the various other parametric tools that are available. In an online article titled, "Rhino Grasshopper VS Generative Components", Loomis interviews the author of, "Elements of Parametric Design" Robert Woodbury about the various benefits and drawbacks of using Generative Components versus Grasshopper. The article limits the discussion to Generative Components and Grasshopper because these two programs had the most added functionality due to the ability to incorporate plug-ins on top of basic functionality.

Table 2-2 - Parametric Software Comparison Chart(Loomis, 2010)

Parametric Design Software	Developer	CAD Platform (s)	Object Based	Scripting	Plug-ins	Free
Generative Components	Bentley	Stand-alone (formerly MicroStation)	Yes	Yes (language)	Yes	Yes
Grasshopper	McNeel	Rhino	Yes	Yes (visual)	Yes	Yes
Paneling Tools	McNeel	Rhino	Yes	No	No	Yes
RhinoScripts	McNeel	Rhino	Yes	Yes	Yes	Yes
ParaCloud GEM	ParaCloud	SketchUp,Rhino, AutoCAD	Yes	No	No	No
ParaCloud Modeler	ParaCloud	SketchUp,Rhino, AutoCAD	Yes	No (spreadsheet)	No	No
GenoForm	Genometri	SolidWorks, Rhino	Yes	No (spreadsheet)	No	No
Project Vasari (Autodesk Labs)	Autodesk	Revit Architecture	Yes	No	No	Yes
DesignScript	Autodesk	AutoCAD	Yes	Yes (language)	Yes	TBA

The main difference between the two programs cited in the article was that Grasshopper was less powerful than Generative Components but easier to use. The article also mentions that one of the large developers of computer software, Autodesk had yet to create a program comparable to either Grasshopper or Generative Components, but that the company had recently hired the developer of Generative Components, Robert Aish to help create a similar software for Autodesk. As of 2012, Autodesk does have a product that is similar to Grasshopper called Dynamo. The program is an add on to the parametric tool Vasari, but is still in the early phases of development and does not have the same robust user support as Grasshopper. Autodesk has also developed a design language that is highly efficient, but is also still in development. The advantage to a parametric tool created by Autodesk is that it would likely work with the many other software in the Autodesk family. Though, it should be reiterated that Grasshopper is highly functional with other programs, and includes plug-ins to work with a variety of Autodesk products.

How Does Grasshopper Help to Visualize and Test Responsive Design Strategies?

Grasshopper allows designers to define the rules of how a design will respond to changes in design variables as well as explore the various outcomes of different scenarios. While Grasshopper is described as a tool for exploring new shapes, there are a variety of additional tools that enhance the functionality of the program. Additional tools include modeling physical interactions, reading real time sensor data, importing climactic data, evolutionary computing, as well as cellular automata and agent based simulations.

These additional tools allow landscape architects to manipulate and enhance abstract data in new ways. Previous technologies and mathematical equations have allowed designers to simulate and measure the flow of water over a surface. The digital technology for this is a series of spreadsheet calculations with a program called win tr-55. The way the program works is that calculations are manually taken for a design and input into a series of equations. The equations output a table of stormwater output values which can then be compared to the design to determine the success of the stormwater management. Parametric tools are starting to change this slow and non intuitive process. Grasshopper allows designers to simulate the flow of water over a surface visually and in immediate response to design changes. Where traditional methods of calculation rely on manually entering data into equations, Grasshopper allows data to be linked to equations so that a designer can manipulate the data visually by moving objects that are part of the design. The benefit of seeing stormwater interacting with a design is that the process of managing stormwater becomes more intuitive for the designer. Instead of designing stormwater systems with numbers, a landscape architect can design stormwater management systems with form.

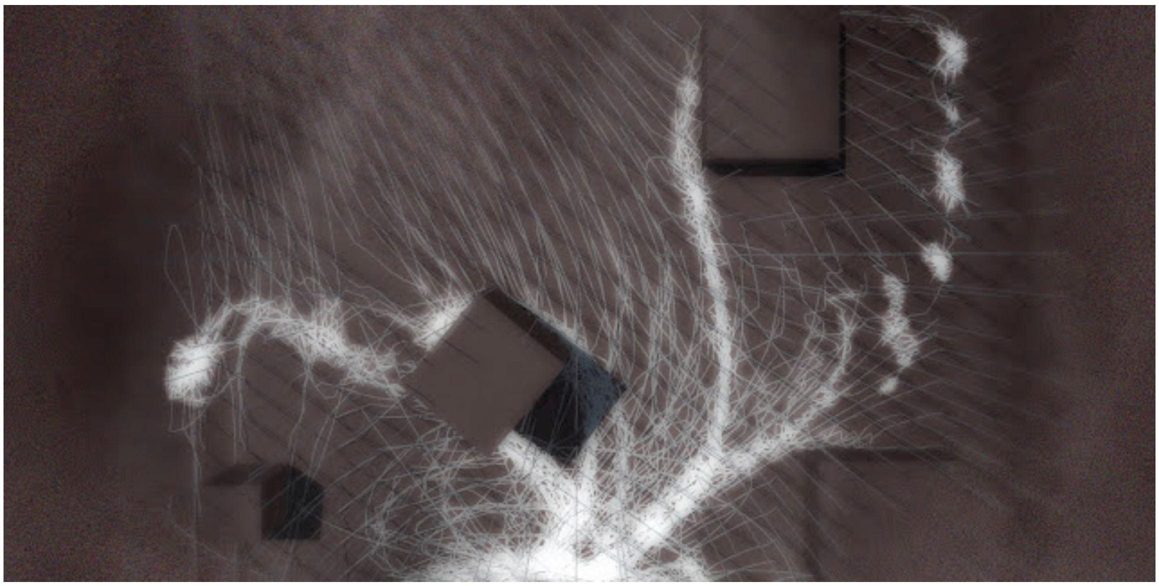


Figure 2-19 - Rainfall Simulation (Locuta, 2011)

Another example of the ability to visualize and test designs is the ability to simulate material response to energy. The amount of heat absorbed by pavement can be turned into a visual output of color which can let the designer visually understand which paved areas will be hot after the sun has gone down. Spanish designers have used this idea to create urban plazas that used the hot Spanish sun to heat their urban spaces in the cooler evenings (Brown, 2010).

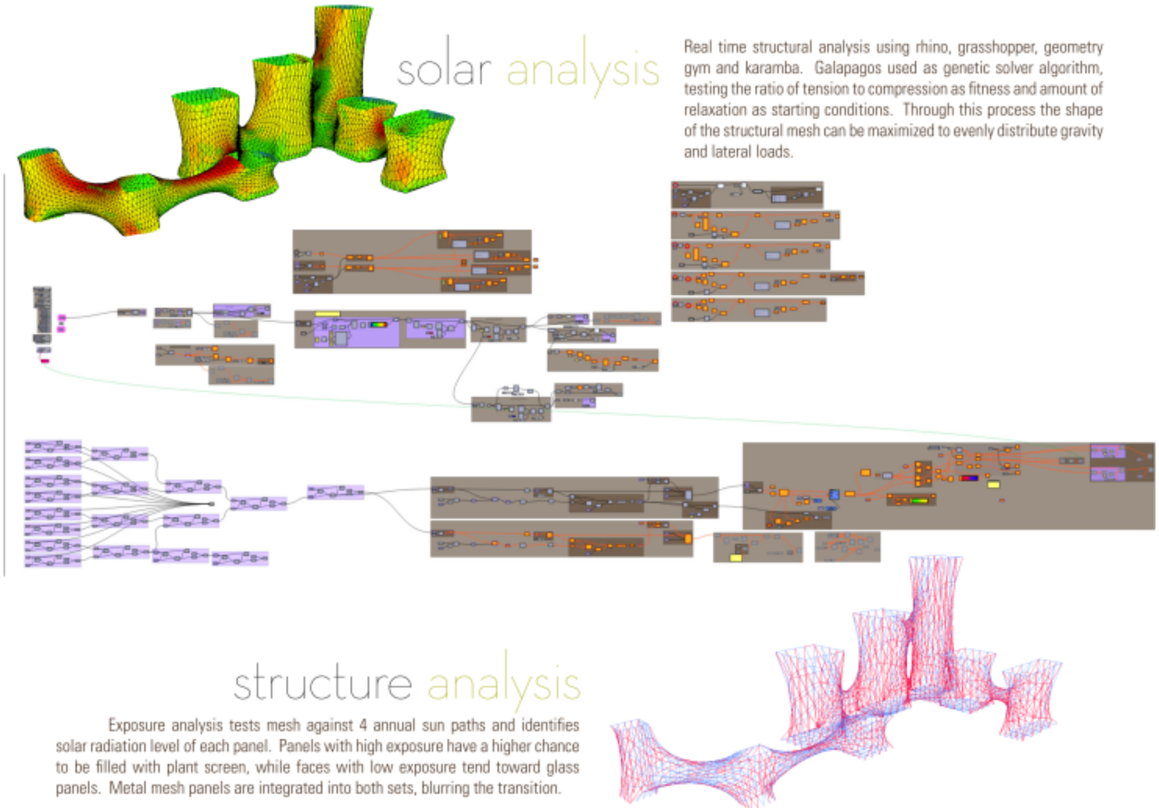


Figure 2-20 - Solar and Structural analysis plugin for Grasshopper. (Herbst, 2011)

Criticism

The Spanish most likely used intuition based on extended experience and study of local climactic conditions, rather than parametric tools, raising the criticism that parametric tools are not as powerful as intuition (Moussavi, 2011). Proponents of parametric tools such as Bradley Cantrell do not dispute that intuition and careful observation should play an important role in design; rather, they argue that parametric modeling acts as a way of extending and intensifying intuition (Cantrell, 2012).

Some critics, such as Farshid Mousavi argue that parametric tools are supplanting parametric thought (Moussavi, 2011). In other words, they suggest that the designs that are being created with parametric tools are becoming uniform. In the field of architecture, this is absolutely correct. Many of the renderings that are associated with parametric design share a similar expression of a small repeating patterns that changes over the skin of the structure. While parametric tools are powerful in their ability to create designs where every element is unique, it is unfortunate that the use of parametric tools in architectural design has essentially stopped there. The result is that buildings that are very similar despite being unique (Moussavi, 2011).

This line of criticism, however, is more of an indictment of particular designers than it is of parametric tools. Parametric tools are open-ended; their results depend on what the designer makes of them. Instead of simply using Grasshopper or other parametric tools to help construct impressive curving structures it is possible to incorporate a range of inquiry based on careful observation into the function of designs. Shifting focus from the novelty of these structures to the value of performance, as well as the relationships between designs and their environments, holds great potential for the design of landscapes that rely on an understanding of complex processes to change a landscape over time.

CHAPTER 3 DESIGNED LANDSCAPE SYSTEMS

Overview

The previous chapter discussed the ability of parametric tools to simulate and model various systems, such as the flow of water over a surface. This chapter discusses the various ways that landscape architects have understood and manipulated environmental as well as social systems throughout the history of landscape architecture. The chapter answers the questions, "What and why are landscape systems important to landscape architecture?", "Why is it important to visualize landscape systems?", "How have landscape architects visualized how landscape systems change in space and time?", and "How do parametric tools expand the way landscape architects visualize landscape systems?"

What and Why are Landscape Systems Important to Landscape Architecture?

Landscape systems are defined in this thesis as the interconnected pieces and processes of landscapes. Systems thinkers such as Donella Meadows define systems as, "an interconnected set of elements that is coherently organized in a way that achieves something" (2008). A landscape system is then the interconnected elements that are organized to create a landscape. In Donella Meadows words, "a tree is a system, and a forest is a larger system that encompasses sub systems of trees and animals." A landscape is everything surrounding a building, including trees and forests, as well as people and economics. Landscape architects typically look at many sub systems of the overall landscape system. George Hargreaves, a landscape architect, in his Orange County Great Park design proposal describes how the systems of , "water, nature, activity, culture, and infrastructure" are combined to create a park that is able to emphasize any or all of the sub systems of the overall landscape system.

In order to create a successful landscape design it is necessary to fit a design within the surrounding landscape systems. Landscape systems are the core of what a landscape architect designs.

Why is it Important to Visualize Landscape Systems?

Visualizing a landscape system is a way of understanding how a landscape operates. Visualizing landscape systems help landscape architects to understand how a design interacts and changes the existing landscape system, as well as communicate the design intention to clients and builders. Visualizing a landscape system requires that a landscape architect attempt to describe how a landscape operates. Without the knowledge of how a landscape operates it is impossible to visualize the landscape system. It could also be said that by visualizing a landscape system, the designer gains a deeper understanding of how landscape systems operate.

The landscape architects Ian McHarg and Carl Steinitz exemplify the importance of visualizing landscape systems. Their visualizations help to illuminate the complex processes that exist in a landscape. Steinitz in particular uses models and visualizations as a method of understanding both the existing patterns of a landscape but also potential interventions in those patterns. The development of new visualization techniques has helped landscape architects to better understand landscape systems.

How Have Landscape Architects Visualized Landscape Systems in Space and Time?

Landscape architects typically use conventional representation techniques of plan, section, and perspective to visualize landscape systems. One of the earliest representations of landscapes in space and time are the before and after drawings of the landscape gardener Humphry Repton (Figure 3-1). The images reflect a view of the landscape as an object that is relatively static and controllable.

Figure 3-1 - Humphry Repton's Red Books - Ferney Hall Before and After- The Morgan Library Online Exhibitions (Repton, 1789)

As the understanding of landscape systems as changing and dynamic systems increased, new techniques were developed to visualize landscapes in space and time. Both the development of our understanding of landscape systems as well as the capabilities of digital tools have enhanced the ability of landscape architects to visualize landscape systems. For example, Ian McHarg used advances in ecological thinking as the logical framework for using a series of overlaid maps of landscape systems to determine the location of future development. Contemporary landscape architects such as James Corner have also used advances of systems thinking as a reason for using collage as a representational technique of landscape systems in time, as well as space. The landscape architecture professor Carl Steinitz has used digital technologies such as geographic information systems (GIS) to develop dynamic models which enhance the processes developed by McHarg. Digital parametric tools, through integration of design with analysis, offers landscape architects a new method of visualization.

Landscape architects have always been interested in landscape systems and the way that systems change (Beveridge, 1995). Much of contemporary landscape architectural theory and discourse concerns the issue of systems, processes, flows, adaptation, Emergence, and Resilience. Practitioners and theorists describe the need for landscapes that adapt or respond to changing conditions over time (Corner, 1999; Lee, 2007; Mostafavi, 2010; Waldheim, 2006). Projects that are intended to change over time are being designed and built in cities all across the world (Berrizbeitia, 2009). Part of the reason for this interest in adaptive landscapes stems from a growing appreciation of the benefits of resilient ecologic systems (M. Hunter, 2011), a greater respect for the power of natural processes, greater technological ability, as well as a greater understanding of how systems interact. The allied design professions of landscape architecture, architecture, planning, and engineering are have recently re-acknowledged that environmental systems have many different and valuable functions and that our built systems need to do a better job of providing multifunctional use (Allen Berger, 2008).

The interest in functional landscapes is not new. As with most aspects of landscape architecture, the landscape architect Frederick Law Olmsted was ahead of his time. Olmsted was very much aware of the benefits that natural adaptive systems could play in the function of cities. Our understanding of how natural systems function has greatly increased since Olmsted in part due to the work of scientists and landscape architects such as Eugene Odum, Richard Forman, Ian McHarg, and Crawford Holling (Dramstad, 1996; Gunderson, 2002; McHarg, 1969; Spirn, 2000). Their work has helped to illuminate the interconnectedness of humans and natural systems as well as helped to bring the science of ecology explicitly into the realm of landscape architecture. It is through their work that landscapes architects such as MaryCarol Hunter can incorporate ecological principals such as resiliency into design.

The interest in resilient designs, combined with the computational power of computers, increasing scientific knowledge, and access to large amounts of data allows landscape architects to increase their understanding of, and ability to create dynamic landscapes.

Frederick Law Olmsted designed extensively with environmental and social systems when he created the Emerald Necklace in Boston (Beveridge, 1995). Olmsted designed Boston's Emerald necklace in harmony with the complex salt water and freshwater ecosystems that were present at the time (Beveridge, 1995). While Olmsted worked with natural systems, he also was not afraid to create new landscape systems. The Muddy River was dredged and sculpted to fit a curvilinear stream path. This is an example of how Olmsted manipulated natural systems in a manner that maintained much of their natural function but also conformed to Olmsted's aesthetic preference. Olmsted envisioned the string of parks working as a part of a system for the urban inhabitant (Zaitzevsky, 1982). The park had to function as more than just a space for residents to relax. Parts of the park such as the Back Bay Fens were restored to a salt water marsh and designed to be able to handle influxes of stormwater (Zaitzevsky, 1982). Olmsted is an example of a designer who was at least partially aware of the idea of ecology and systems before there was a way to describe it.

Olmsted was willing to let various landscape systems impact his design. When Olmsted designed the Fens, he used vegetated islands that could be temporarily submerged without harm to plants in order to achieve desirable aesthetic qualities for human enjoyment, as well as functional landscape system qualities as well. Olmsted could have engineered a system that was more structural and rigid, but instead worked closely with an engineer to allow the Fens to have soft vegetated edges (Beveridge, 1995). Olmsted recognized that his design goals could still be achieved but they had to be flexible and responsive to the surrounding landscape systems.

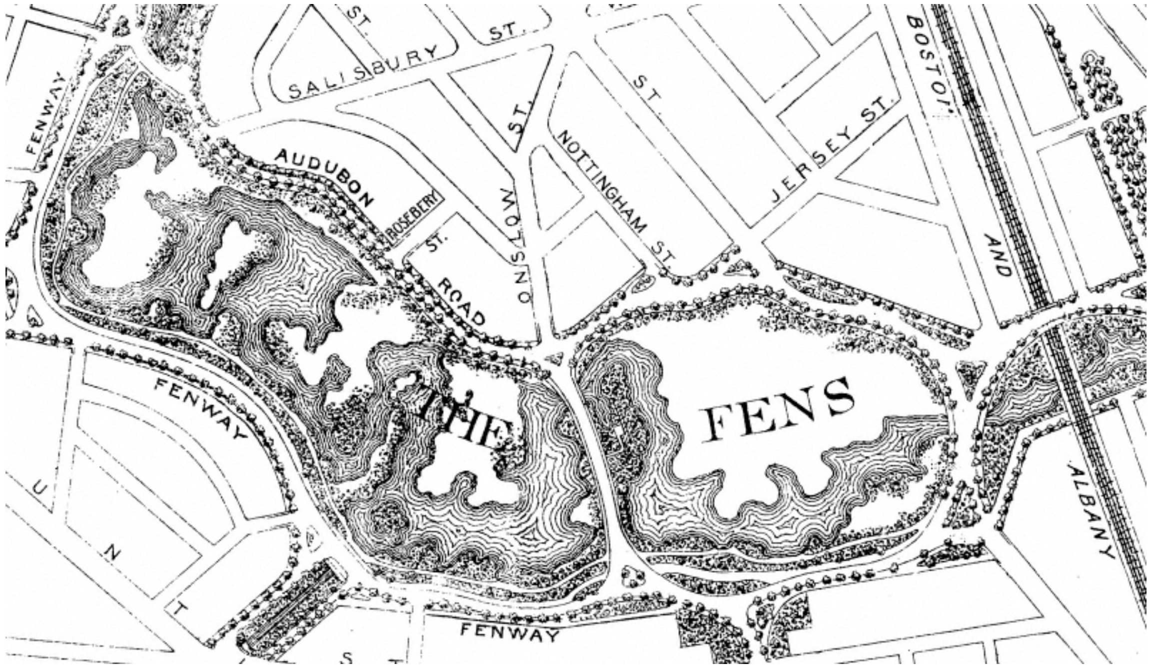


Figure 3-2 - “From the original plan for the "Improvements to the Muddy River", part of Boston's "Emerald Necklace" by Frederick Law Olmsted. These hypsographic contour lines in the bodies of water are more cartographic symbols than accurate indicators of sub-surface elevation.” (Ervin & Hasbrouck, 2001)

Ecology has advanced our understanding how different connections impact each other to create a larger whole. Ecology has also helped to highlight how various scales from small site specific scales to larger regional scales are all interconnected. The acknowledgment and study of how different systems are connected is part of the foundational theory of sustainability. The role of ecologic thought will be discussed in more detail in the next chapter, but it is important to mention how the understanding of interconnected systems has impacted the way landscape architects approach design.

Ian McHarg was professor as well as a practitioner of landscape architecture. McHarg is famous for creating a scientific method of evaluating landscapes called the overlay system. The overlay was a strategy that could be considered a form of parametric thinking. Based on the broad definition that parametric tools define design constraints in order to visualize design opportunities, McHarg's technique could be considered parametric because there are a series of rules that are applied to a set of variables. When the variable conditions of a specific site are run through the McHargian overlay system, the model creates infinitely different outcomes. The outcome of the design might not be adaptive, but the strategy that was used to get to the design, was adaptive. The system McHarg developed could be applied to any site and have a different outcome for every site.

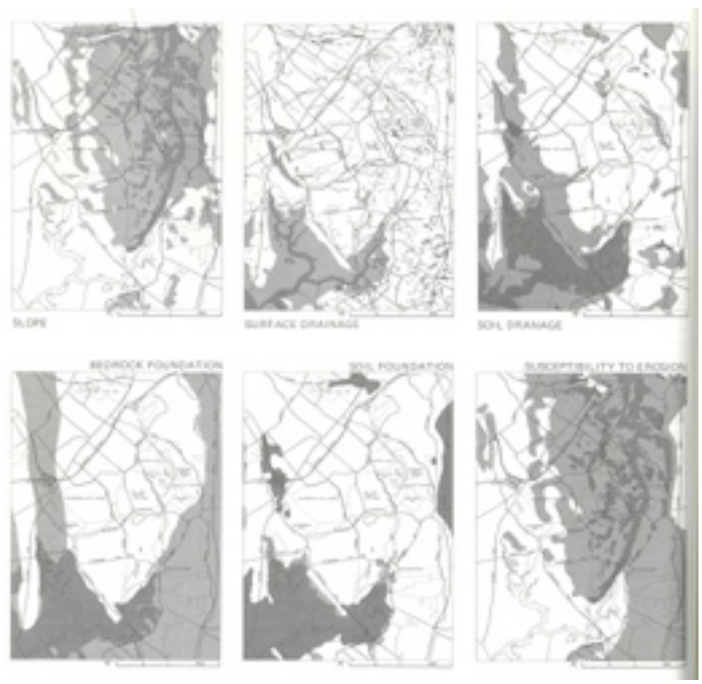


Figure 3-3 - McHarg Overlay (Corbett, 2011)

McHarg's technique is still taught in graduate level landscape architecture courses as a way of exploring otherwise unseen patterns in the landscape. The technique is typically incorporated into a digital GIS analysis tool which is separate from typical design tools. The irony of this separation of design and analysis is that the overlay method was intended to reveal how the landscapes had changed over time, but only results in a static image of the current state of the sight. The analysis does not incorporate how new structures would impact the existing conditions of the site over time. Parametric tools are one way to allow landscape architects to incorporate the dynamic processes of a design into the overlay process.

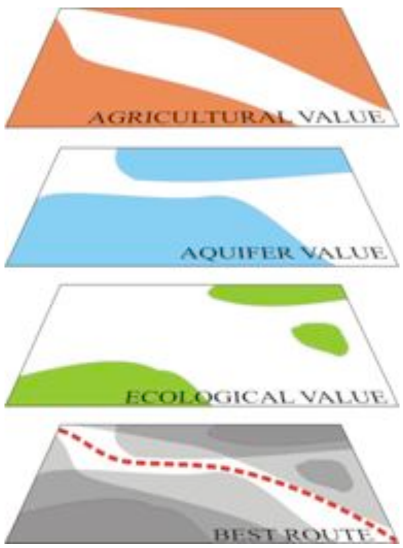


Figure 3-4 - McHarg Overlay (McHarg, 1969; Turner, 2001)

McHarg's design philosophy, while acknowledging that human development was inevitable, elevated nature and science to the primary significance. Humans were generally seen as a disconnected or completely negative part of the natural system. This view of ecology as being devoid of human interaction is now considered inadequate (S.T.A. Pickett, 2008). The study of urban ecology has developed to explicitly explore the interactions of humans and wildlife in urban spaces. Historians and urban planners such as William Cronon argue that human intervention has long played a key role in the development of various ecosystems, as can be seen in the management strategies of native americans who would burn the under growth of North Eastern forests to improve the hunting of deer (Cronon, 1983). Ian McHarg was right to be concerned with the environment, but by largely ignoring political and economic forces McHarg limited the impact and potential development of his designs. McHarg is still very influential in the teaching of landscape architecture, but his ideas have been tempered and paired with social concerns.

McHarg uses the plan view as a way to overlap the different systems that exist on a site. The trouble is that the systems that are mapped are dynamic and change in time. The great irony of McHarg's images is that they are intended to represent the dynamic history of the site, but they do little to forecast how the dynamics will change in the future. The overlay's were only capable of describing which areas development would cause the least amount of damage to the existing systems. There was no McHargian method for understanding the interactions of development with the site processes after the site was developed.

Parametric tools are beginning to provide a way to interact with the dynamic properties of a site. Carl Steinitz uses parametric tools as a method of exploring the alternative futures of a site. In the "Alternative Futures for Camp Pendleton" project, Steinitz uses a series of models (Figure 3-5) to analyze a predicted growth pattern over an extended period of time and suggest alternative growth strategies (Figure 3-6).

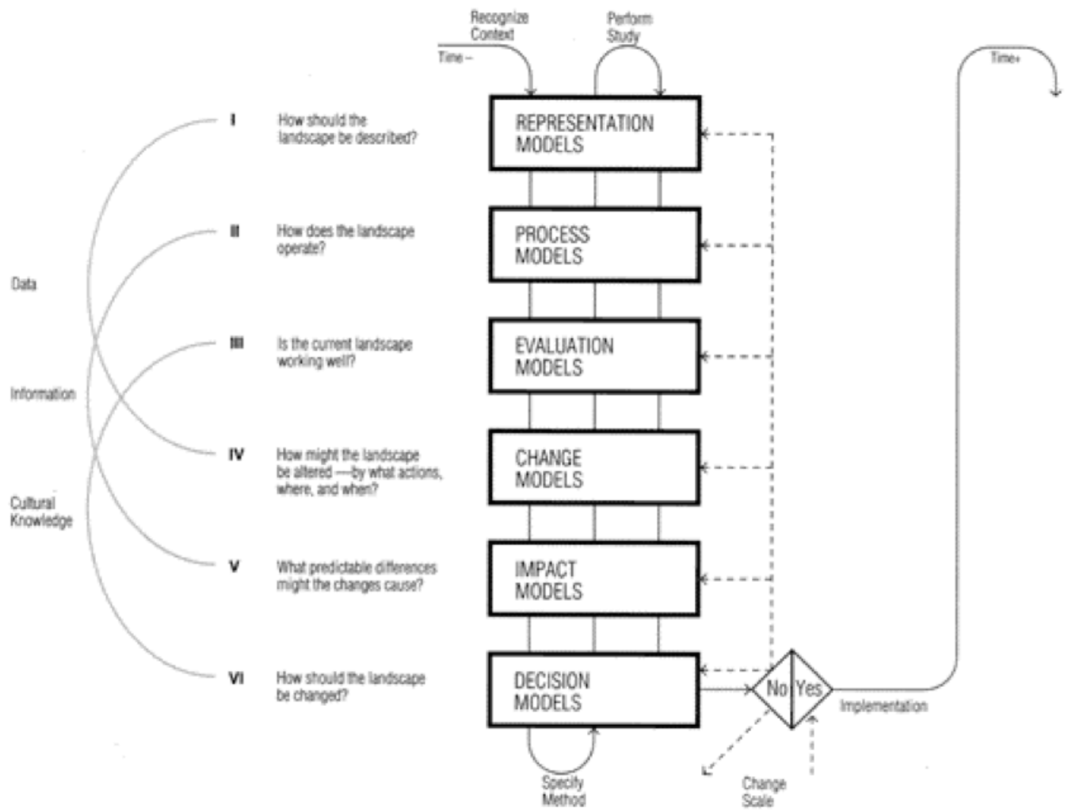


Figure 3-5 - Steinitz Framework for Camp Pendleton (Steinitz, 1997)

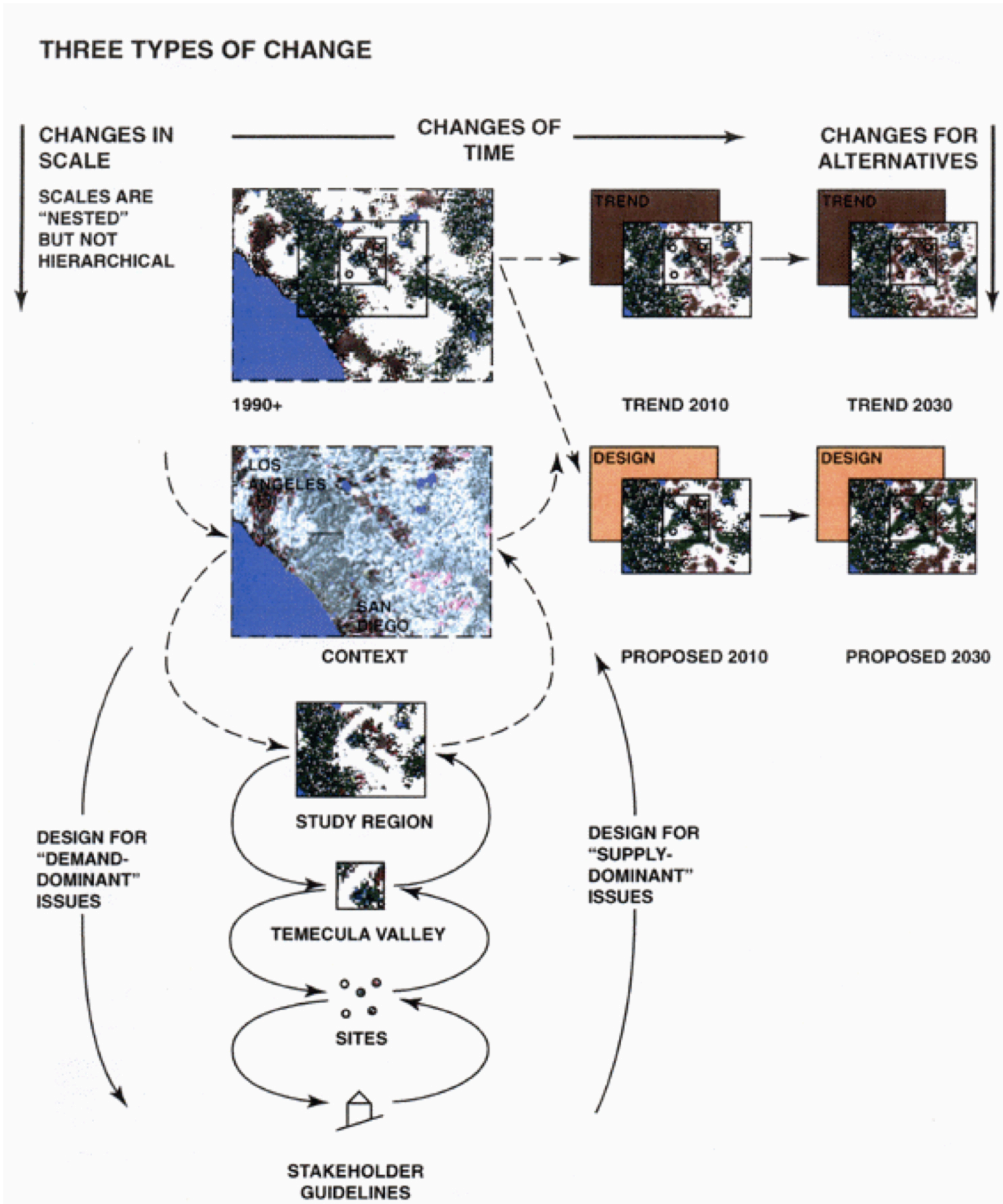


Figure 3-6 - Steinitz Change Diagram (Steinitz, 1997)

Steinitz's techniques, while typically applied to a large scale can also be applied to smaller scales as well. The example of simulating the movement of water on a site or the absorption of solar energy were used as examples of interacting with the dynamic properties of a site in the previous chapter.

In a 2009 interview Steinitz was asked, “How would GIS tools that simulate dynamic processes be best used in the design process?”. Steinitz answers that they would be best used as a way of comparing alternatives, “They can be useful in impact assessment when comparing alternatives, but would “best” be used in making designs—change models—iteratively, in immediate feedback interaction with impact evaluations.”

The use of a plan can still be used to visualize the system, the difference that parametric tools create is that the plan now has many images with slight changes as opposed to McHarg’s images which were static and singular.

Landscape Systems

James Corner, principal of the landscape architecture firm Field Operations, is an example a post McHargian landscape architect that works with multiple human and ecological systems. Corner, is as much aware of the social, political, and economic forces acting on a site as he is of the environmental forces. One of the earliest design decisions corner made for the huge 2,200 acre Fresh Kills Park on Staten Island was to hoist a billboard into the sky to ask residents who drove by the landfill everyday what they wanted the park to be (Corner, 2006). This strategy helped to initiate the transformation of Fresh Kills from the worlds largest trash pile into New York City’s largest park by engaging the local community and seeding the ground for the community to voice their support of the park to the politicians that control the funding of the park.

Figure 3-7 - Field Operations diagram of designing with landscape systems. (J. H. G. Czerniak, 2007)

This wasn't the only strategy Corner used and there were a number of other forces that worked in concert with Corner's strategy, including a mayor that was dedicating lots of money to parks as well as a small borough of New York that had large political power. Still, the billboard helped to get Staten Islanders to demand funding for the blight that had long been the dumping grounds of New York.

Corner is known for the idea of "setting landscapes in motion" (Corner, 2010). Setting a landscape in motion is the idea of creating the design to utilize the surrounding systems. In the case of Fresh Kills, the cost of building the park all at once would have been too expensive because of the park's scale. Corner devised an open design strategy that would be able to be developed slowly over time, while still providing for specific programmed areas to draw people to the park. Corner struck a balance between an open and low maintenance strategy, with a design that still had enough definition to be understood as a park. This balance between cost and identity helped to keep the public aware that a park was being created while still allowing politician’s to stay on budget.

The balance of definition and openness in Fresh Kills Park can be contrasted with the more problematic Downsview Park whose award winning design by Rem Koolhaas has been essentially redesigned by a landscape architect ("Downsview Park," 2010).

Downsview Park

One of the main drivers of the design for Downsview Park in the year 1999 was the requirement that the park, “remain open to change and growth over time” (Alan Berger & Oleson, 2001). There is a difference however, between, “open to change” and an undesigned space. The development of Downsview Park has been anything but smooth. Political turmoil encouraged one of the lead designers, Rem Koolhaas, to leave the project to his partner Bruce Mao. Since then, a landscape architect has been hired to develop the park. The park is still being built, but it is difficult to discern what, if anything was actually designed by Koolhaas and Mau. Downsview Park is an example of a design strategy which has been criticized as too open ended.

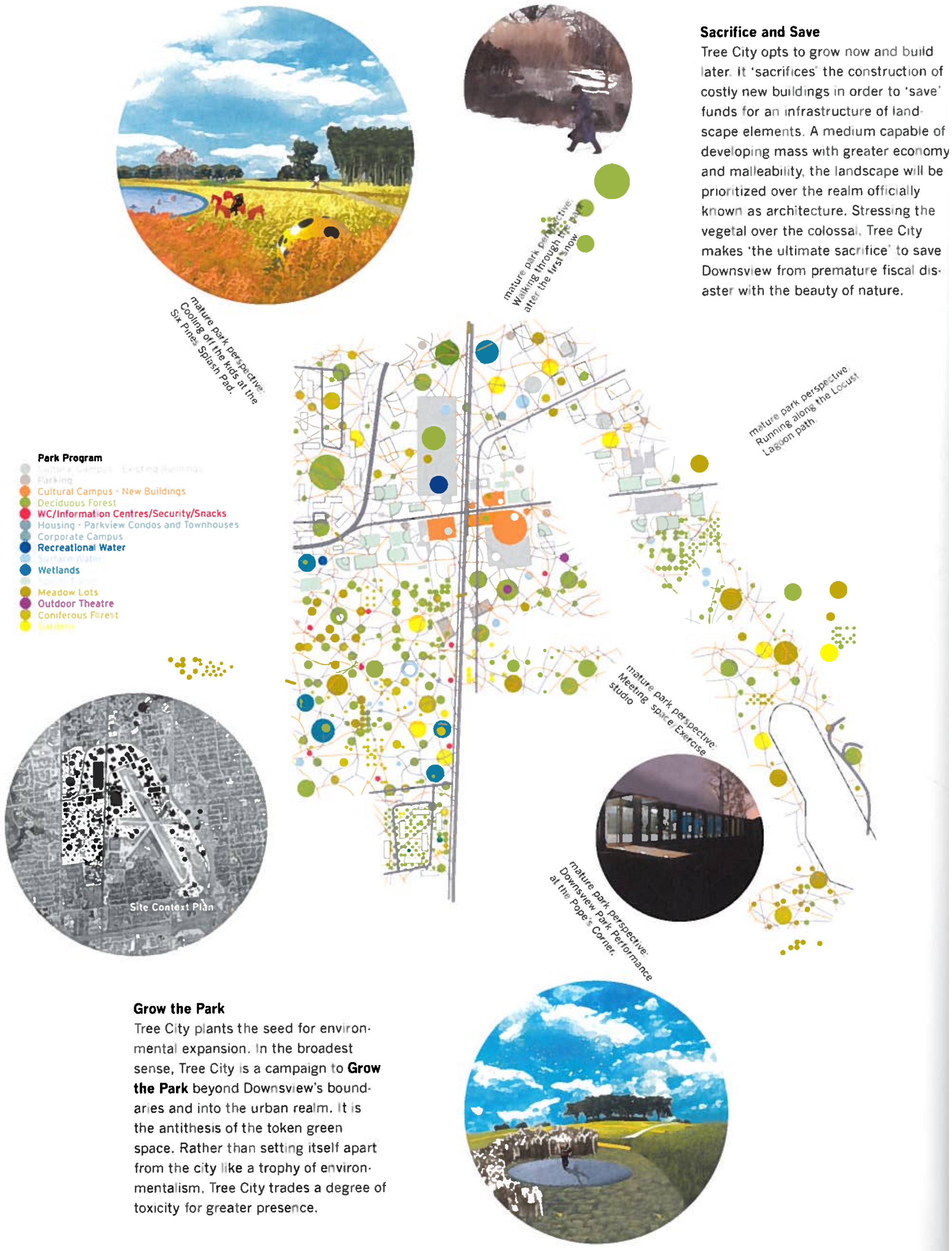


Figure 3-8 - OMA Tree City Downsview Park competition entry (J. Czerniak, 2001)

One of the challenges of Downsview park was that it was to be entirely self funded. As a result, private industry is the primary driving force of the park and as such has resulted in the development of condominiums and ice rinks, but very little actual park space. Indeed the park space keeps shrinking as parts of it are sold off to pay for the maintenance cost of the built park space. It shouldn't be much a surprise that a park with essentially no funding and no design, retracts to the stable equilibrium point of status quo development. Parks are not a naturally occurring phenomena in cities. They are deliberate actions. Eventually, after support for a park has been developed and a boundary laid out, parks can begin to have public private partnerships. Downsview Park is widely criticized by the Toronto Star as a dismal failure (Chantaie Allick Toronto; Chlo Fedio Toronto; James, 2010). The park was fatally flawed by being linked solely to private development. While modeling of the social and political dynamics of Toronto may have led to insight into the future of Downsview Park based on Koolhaas's design, intuition could have likely predicted that private development rarely creates public parks.

Perhaps Downsview can be a lesson to the potential pitfalls of designing with open strategies. An open strategy is intended to work towards a future goal, but allow for the unpredictability of systems to be able to impact the trajectory, but not necessarily the final goal. In the case of Downsview Park, a landscape was not set in motion, instead development simply continued, which negated the original intention of the park.

Why Change?

Landscapes that are resilient and able to respond to changing environments have many benefits including increasing human safety, lowering the costs of infrastructure, as well as impact how humans understand and value the changing environment. The landscape architect MaryCarol Hunter notes that as temperature and climates change, human created landscape can play a key role in developing resilient landscapes that can adapt to change and help to sustain the existing ecosystem services.

Kristina Hill, a landscape architect and professor at The University of Virginia, emphasizes that cities are more than just a collection of buildings (Kalcher, 2009). Rather, cities are society’s response to a multitude of physical, social, economic, and political forces. Designers need to be aware of the hierarchy of these various forces and the implications for their designs. Large constructions, such as the levees along the Mississippi River are doomed to failure if the change brought on by climactic forces are not taken into account. Instead of static engineered solutions, resilient management strategies are needed to adapt and respond to the forces that change a landscape.

Examples such as Hurricane Katrina and the rise of sea levels suggest that climactic forces often trump political and social forces. For this reason many contemporary landscape architects discuss the importance of designing landscapes that work with environmental forces rather than against them (Allen Berger, 2008; Corner, 1999; Mostafavi, 2010). Environments that have had time to adapt to climactic forces can be examined for desirable qualities as well as processes and used as models for future adaptive designs. In the case of New Orleans, cypress swamps and mangroves used to cover vast areas of the New Orleans lowlands (Grunwald, 2010). These ecosystems are particularly suited to areas that are prone to large tropical storms because of their ability to resist speeding hurricanes and absorb rising storm surge. These coastal landscapes are part of an adaptive system that can be used to protect human health and welfare (Grunwald, 2010).

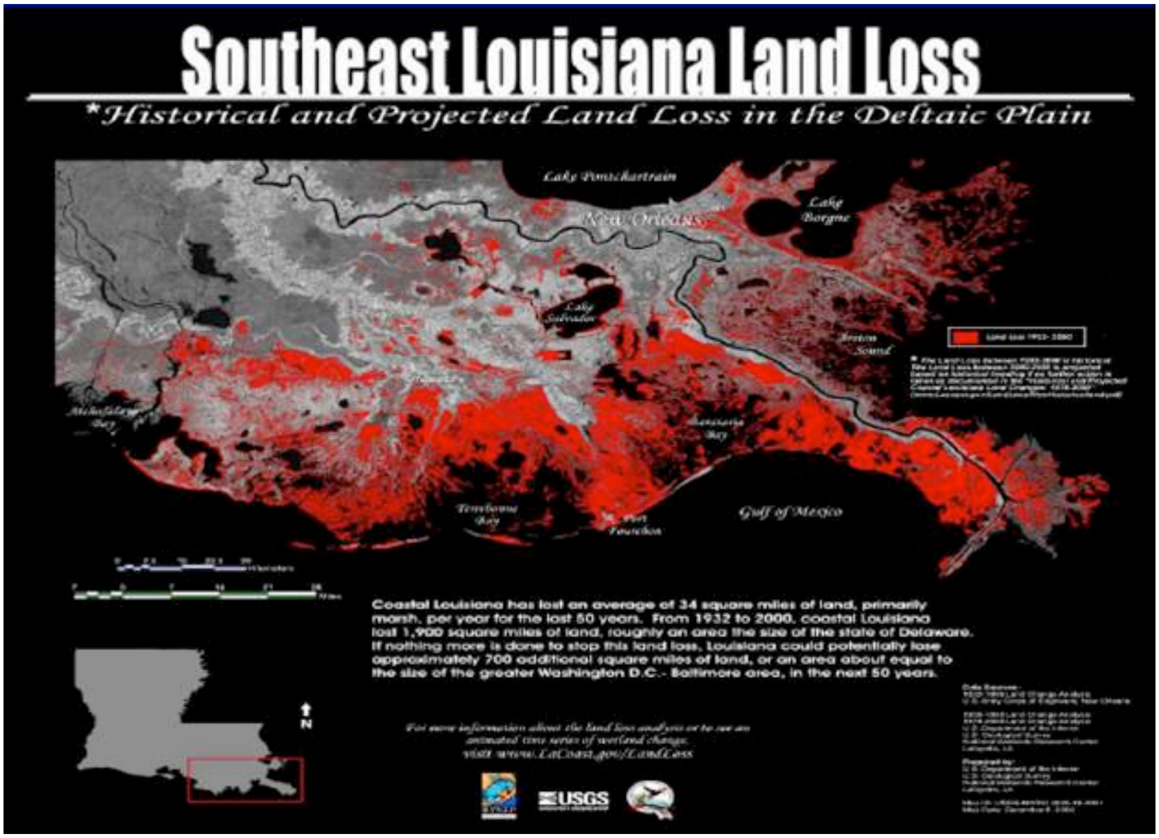


Figure 3-9 - Land Loss in Louisiana (McKnight)

Bradley Cantrell is exploring system dynamics through computational and analog simulation. As a professor, Cantrell is using a studio course he teaches to simulate digitally as well as with analog models, how river dynamics can be used to create new land in the gulf coast. While the Mississippi River and the Gulf coast are generally viewed negatively as forces of erosion, they can also be sources of deposition. Cantrell’s techniques attempt to balance using the science that we do know of the existing systems, with developing strategies that would work for the inherent unpredictable qualities of a complex system (Cantrell, 2012; Moser, 2012).

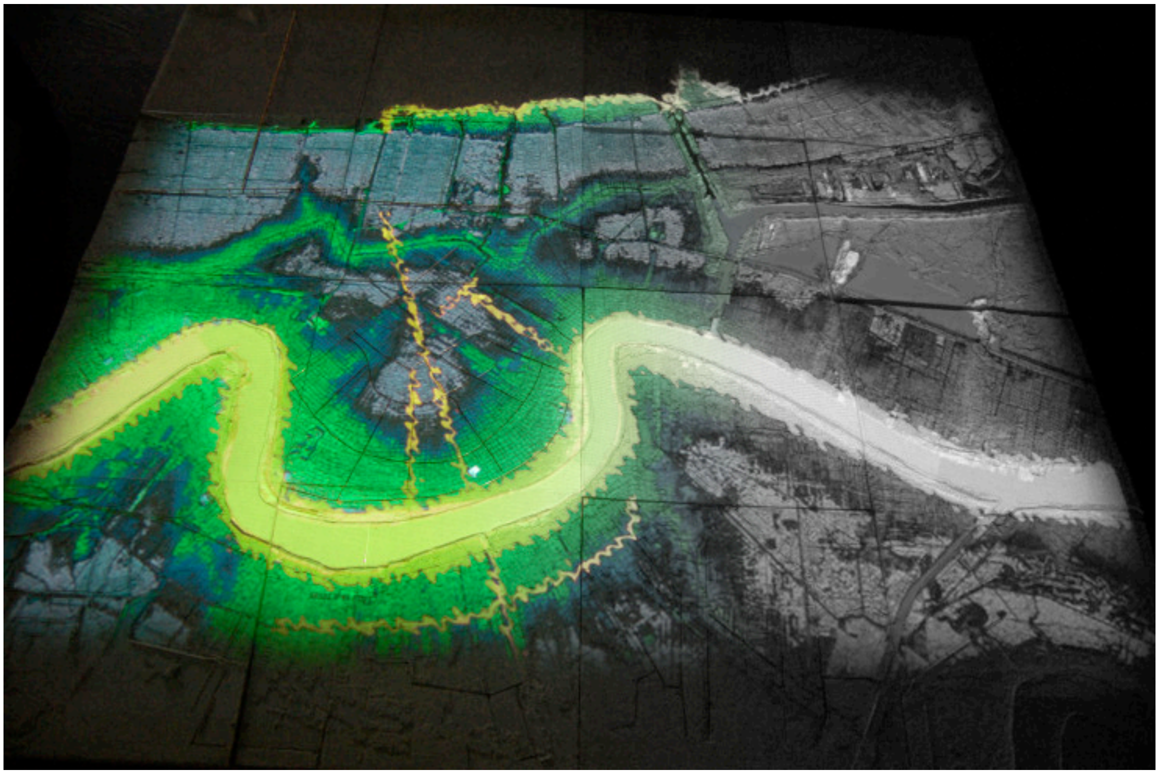


Figure 3-10 - Plaster model with projection (Cantrell, 2006)

Benefits and Limitations

While an awareness of systems can help designers to harness potentially unseen but powerful forces, there are many changes to systems that are completely unpredictable and potentially disruptive to design goals. Ultimately all designs are destined to change with time. Management and observation combined with open strategies are the only reliable way to direct a landscape towards desired goals over long periods of time. Anne Lister argues in Large Parks that open design strategies are beneficial for the ability to be redefined, flexible, and responsive. But, as was seen in the case of Downsview Park, open design strategies can be too flexible as well.

One way that parametric tools can help guide the initial decisions of a design strategy is to visualize the various outcomes of different future scenarios. A parametric model will never be able to predict with complete accuracy future events, but it can be useful as an initial hypothesis and exploration of potential outcomes. It is important to remember that the value of the parametric model is highly contingent on the accuracy of the relationships between design variables. While the need for specific understanding of relationships can be a limitation because many design relationships are not well understood, it can also be a benefit because parametric tools offer the ability to incorporate relationships that are well understood by those outside of the profession of landscape architecture. The next chapter discusses the ability to incorporate Complexity Science into parametric design strategies.

CHAPTER 4 COMPLEXITY SCIENCE

Overview

The previous chapter focused on landscape architecture's connection with landscape systems, this chapter discusses the theories and models of Complexity Science, Emergence, and Resilience and how they can be applied to the design of landscape systems with parametric tools. The chapter answers the questions, "What are the theories that landscape architects use to guide their understanding of how landscapes change over time?", "Why is Complexity Science a useful framework to understand landscape systems in space and time?", "Are parametric tools capable of incorporating Complexity Science into the visualization of landscape systems?", and "How are landscape architects visualizing Resilience?"

While there are many different theories that could also be applied to landscape architecture the theories of Complexity Science, Emergence, and Resilience are highlighted because they are mentioned frequently in landscape architecture literature (Corner, 1999) and are also particularly applicable in terms of parametric modeling (M. Hunter, 2011). This chapter will use the ideas of Emergence and Resilience to provide a lens through which landscape architects can begin to see the underlying relationships between interacting forces on a site.

Complexity Science

Emergence and Resilience share an overarching theory called Complexity Science (Mitchell, 2009). Complexity Science, while lacking an agreed upon definition, addresses the ways in which interconnected parts of a system change each other (Mitchell, 2009). In general, complexity scientists look for relationships that are able to describe complex phenomena. These relationships share properties of positive and negative feedback loops, non-linear relationships, sensitivity to initial conditions, emergence of new phenomena, the ability to self organize and random as well as deterministic behavior, which can be applied to landscape architecture through parametric models.

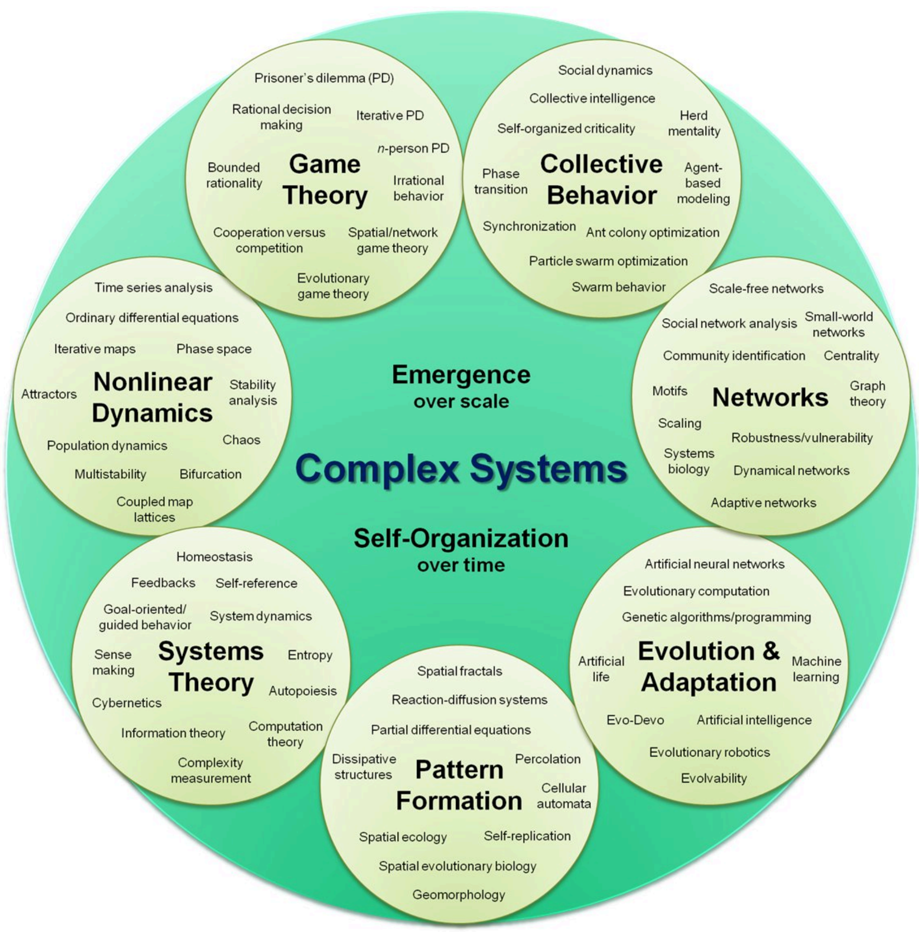


Figure 4-1 - Complex systems chart (Hiroki Sayama, 2010)

Emergence and Resilience are two sub-theories of Complexity Science that are particularly useful for landscape architects. Emergence explores how individual actions can create order from the bottom up, while Resilience is generally interested in the stability of ecosystems. Exploring the theories of Emergence and Resilience will help to illuminate the breadth of ideas that parametric modeling can incorporate into landscape architecture.

The principles of Complexity Science, which are currently being applied to the built environment by landscape ecologists, can be translated with parametric tools and used by landscape architects to test and visualize adaptive landscapes. Parametric tools are one way of helping landscape architects access the potential of Complexity Science because of their ability to incorporate complicated relationships with more intuitive visual forms. The application of parametric tools to a resilient planting strategy is discussed in the following chapter and clearly illustrates why this is the case.

Emergence

Emergence refers to the order that can appear from many individual and seemingly random individual actions (Johnson, 2001). Emergence theories argue that simple rules that govern individuals can create both random behavior as well higher-level organization (Strogatz, 2003). Emergence has been applied to many different systems, from the creation of ant colonies to the development of cities (Batty, 2005; Gleick, 1987; Johnson, 2001; Strogatz, 2003). Currently, researchers are using the theory of Emergence to model how humans move through space. For instance, modeling individuals' movements in a crowded environment and the impacts on collective crowd behavior have been used to simulate the amount of space needed for a crowd to safely exit a space (Batty, 2005). These simulations have then been used as a design tool for temporary spaces with large crowds such as fair grounds (Batty, 2005).

The nature of interconnected parts is that they can only be understood in reference to the whole system (Gleick, 1987). Dividing the system into separate parts that are understood separately and then recombined does not add up to the whole system (Strogatz, 2003). The whole of the system is greater than the sum of its parts. One example of this phenomena is the human body. Even though we know how the individual parts of the human body function, we still have very little understanding of how they add together to create a living, breathing, thinking human being. In other words, an individual’s sense of self does not rely on the individual cells of the body. Our cells die and regenerate constantly, but our sense of self remains constant. The ability of the whole to be greater than the sum of its parts is one way of describing Emergence (Johnson, 2001).

Another way of understanding Emergence is to think of the rules required to create a snowflake. From the simple combination of water and temperature, complex and unique shapes are formed. Snowflakes are an example of the infinite variation that is possible from the combination of simple rules.

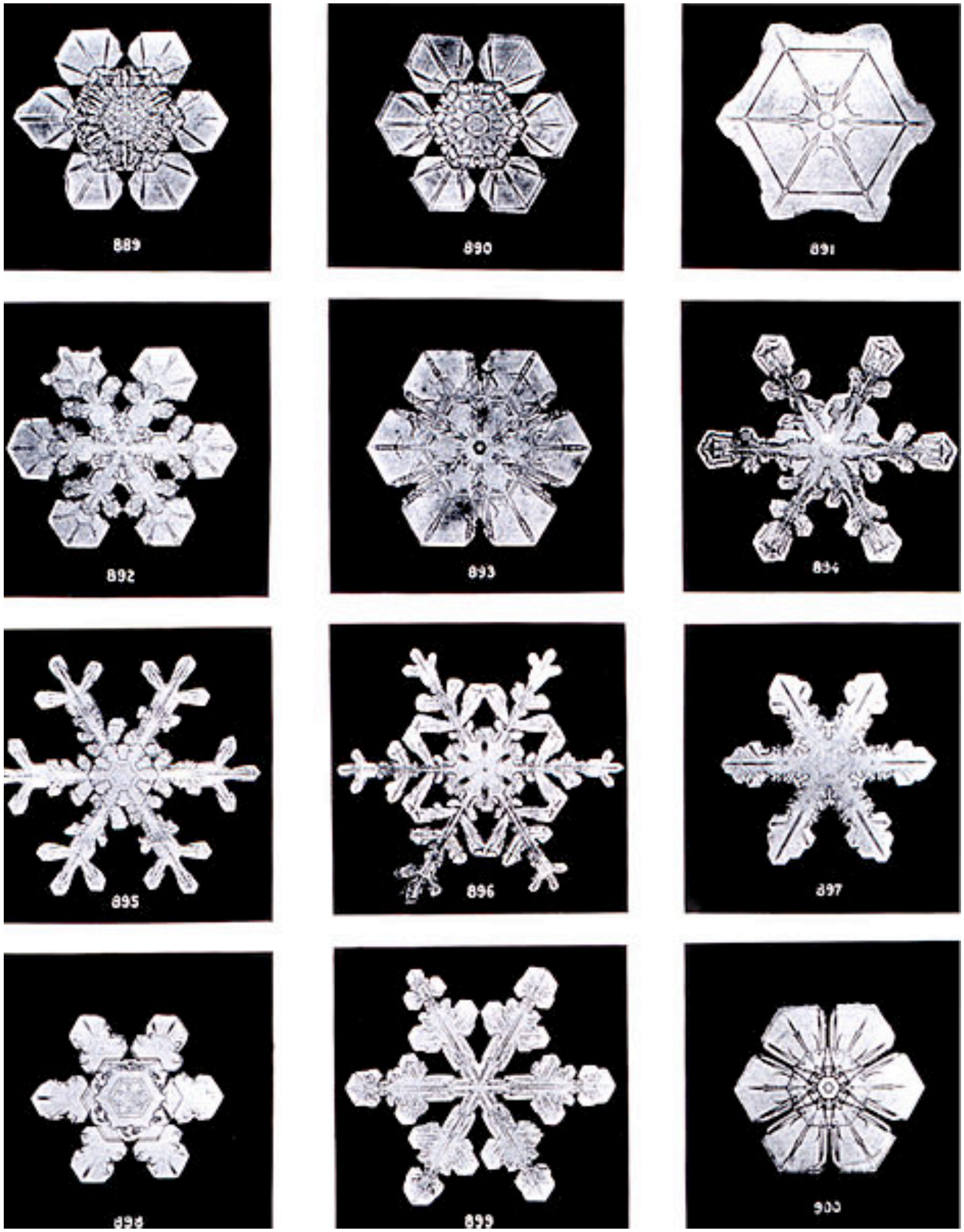


Figure 4-2 - Snowflakes emerge from the relatively simple relationship of Water and temperature. (Bentley, 1902)

Emergence describes how organization and patterns can form from seemingly random combination of individual elements. A typical example is the organization of ants. While ants do have a queen, the queen does not decree orders to her subjects. Ants typically receive all of their commands from scent trails. Computer simulations of ants have shown that ants can randomly search for food, but because of certain feedback mechanisms based on scent, their random search will become directed, efficient and productive. As soon as one ant finds food, it leaves a distinct scent trail for other ants to follow. When a second ant returns on that same path with food, the second ant will also leave a scent trail, making the trail more attractive for other ants to find. The more ants that find food on the trail, the easier the trail will be to find. Out of the seemingly randomness of ants searching comes organized and efficient food finding mechanisms.

Figure 4-3 - Ants following a pheromone trail (Service, 2012)

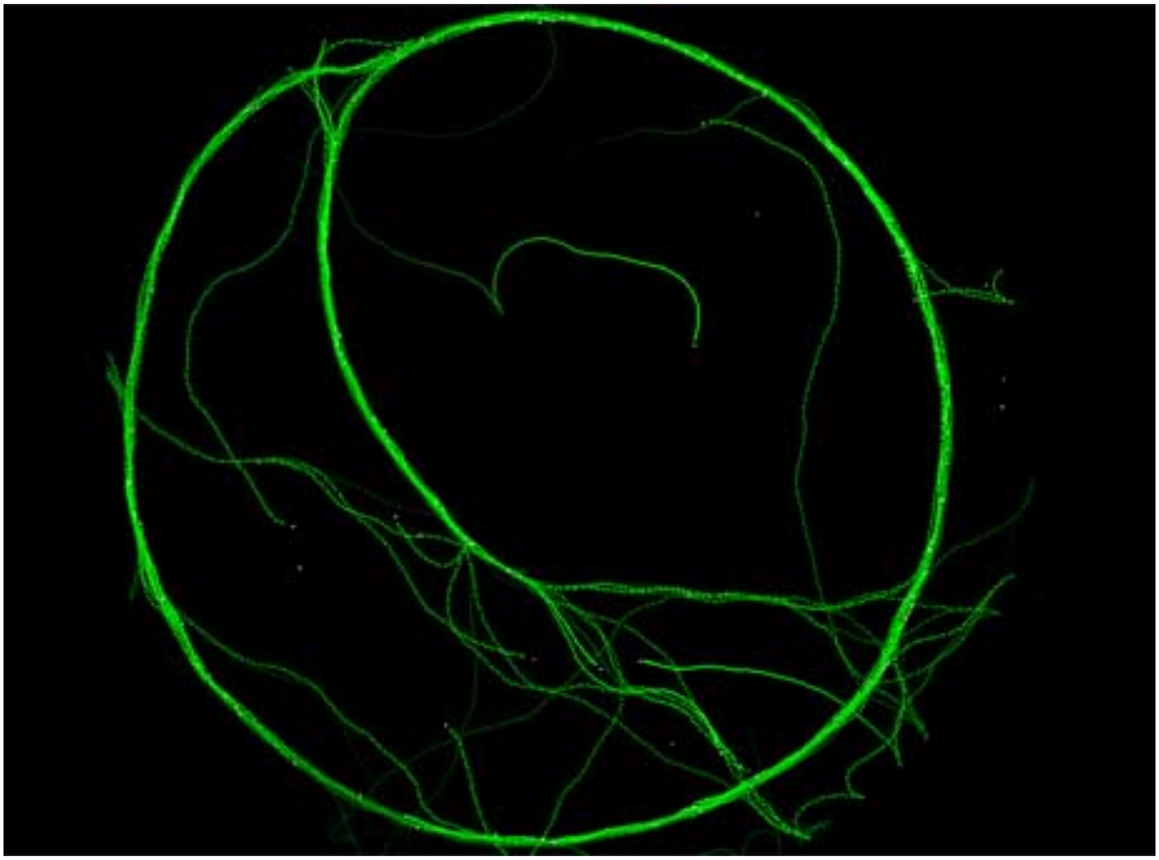


Figure 4-4 - Computer simulation of ants following a pheromone trail (Palmer, 2012)

Termite mounds are another example of the creation of complex structures through simple bottom up processes. Termite mounds are often noted not only for the huge size of the structure in comparison to the builders, but also for their climactic sensitivity. Not only are they structurally complex but they are environmentally complex as well.

Figure 4-5 - Termite Mound (Yap, 2005)

Emergent properties have been shown to exist in many different species, including humans. Cities are often cited as examples of how the seemingly random actions of humans can create a bottom-up order. Michael Batty, a researcher using computer programs to simulate a variety of human-focused urban phenomena, is exploring how individuals move through space. Batty points out that when humans move through space, they generally do not bump into each other, tending to keep an invisible bubble of space between themselves and the people around them. This simple rule of not bumping into people has the organizing effect of efficient movement through space. Batty uses a computer model to illustrate how, when people do not bump into each other, large crowds can efficiently exit a space. His model also shows that as people begin to bump into each other, the efficiency of the crowd vanishes. Small disturbances in movement can lead to major delays in exiting.

The effect of small disturbances has been well documented and likely experienced by anyone who has ever driven on the highway. Models, in addition to world experience, have shown that a single individual quickly slamming on the brakes in traffic may have a ripple effect that can move through a long chain of cars. In the real world, the ripple effect is often experienced as a phantom traffic jam where the line of cars had been slowed or stopped with no apparent accident or other cause for the delay.

The creation of these models can be quite simple. They generally require certain rules to be applied to an individual and then simulate the interaction of many individuals. Northwestern University has created an open source set of parametric computer tools to allow for researchers to explore the emergent properties of simple rules. The program, called NetLogo, has been used to simulate a wide range of subjects from the spread of disease to the formation of streams due to erosion.

The scientific term for these models include Cellular Automata (CA) or Agent Based Modeling. A discussion of these types of models is beyond the scope of this paper, however, it is relevant to note that Grasshopper has the ability to apply these models to a design before the design is built as a way of testing how people might move through a space. These types of models have been applied to the movement of people through architectural spaces such as shopping centers and museums in order to understand the flow of people through a space.

Other analysis tools, such Arc GIS, are also capable of running these types of simulations on designs. What makes Grasshopper unique is that it allows dynamic feedback between the design and the simulation, whereas other analysis tools are static in their simulations and not as well connected to a typical design interface. In the latter case, a design is input into the simulation and a result is output; the designer then must reconfigure the model based on the output. Grasshopper, on the other hand, is able to link the input to the output so that design variations seamlessly interact with the analysis.

This dynamic feedback can be compared to an individual that covers the end of a hose with their thumb to change the spray of the water. The water represents movement of people through space, while the thumb is the different variations of the space that will impact the flow of people. To push the metaphor, typical analysis tools like Arc GIS are less dynamic. Instead of being able to quickly adjust the flow of water, the hose would have to be turned off and a different thumb position would have to be made before turning the hose back on. While many design programs are customizable to achieve more dynamic interactions with the designer, they are not the typical interface.

Resilience

The definition of Resilience has taken different forms over it's forty year history (Gunderson, 2002). One definition is the amount of disturbance a system can tolerate and remain the same, another is the degree to which a system is able to self organize. Resilience can also mean the degree to which a system can increase it's ability for adaptation (Cumming, 2011). Another way to describe Resilience is to think about ecosystems as having an identity. The meaning of identity is used in the same way landscape architects use the word to describe the essence or core of a place. Graeme Cumming, a landscape ecologist, describes identity as being strongly subjective but as a way to define key characteristics of a system.

The identity of the small grid of downtown Athens, GA could be described by the aesthetic of the mostly Italianate structures, the height of structures, the use of certain structures could be important, or some other quality that gives Athens its identity. Even though deciding the identify of an ecosystem or town may be subjective, Cumming argues that the definition can be quantitative (2011). In the case of Athens, GA, once the identity of the town was agreed upon, there could be a threshold where identity would be lost. Assuming that building height characterized the identity of downtown Athens, it could be argued that after some numerical threshold the town would lose its identity. For example a threshold could be that if 50% of the downtown buildings were to become taller than two stories, downtown Athens would change its identity. Resilience, is the amount of change that Athens could absorb and still maintain its identity.

While Resilience was developed as an ecological term, it is can also be applied to social systems. Marina Alberti, an urban design professor at the University of Washington, has written about urban ecosystems and the ability to link, “urban patterns to human and ecological functions” (Alberti, 2008). Alberti argues that, “Resilience in urban ecosystems is a function of the patterns of human activities and natural habitats that control and are controlled by both socio-economic and biophysical processes operating at various scales.“ One of the ways that landscape architects can use the ideas of Resilience is through parametric modeling.

Parametric modeling allows designers and scientists to collaborate on more than just conceptual models of urban systems, but quantitative models that can begin to visualize the complex relationships of urban spaces. Landscape architects are using the theory of Resilience to create design frameworks and define parameters which aim to meet the socio-economic as well as the bio-physical processes of urban space.

Emergence and Resilience are only parts of Complexity Science. They help to highlight that the research coming out of Complexity Science is directly tied to the understanding and function of the human systems that landscape architects modify and create. Emergence and Resilience are just two examples of how the ideas of Complexity Science apply directly to the practice of landscape architecture. Though Complexity Science is very broad, parametric modeling can act as a bridge between scientist and designer. The relationship would likely work best where a researcher and landscape architect would communicate about mutually beneficially areas of interest, before discussing and modeling potential collaborative designs. Parametric tools offer a way to expand the knowledge of both science and design because of the ability of parametric modeling to apply models of complexity to the designs of real world spaces.

MaryCarol Hunter is an example of a landscape architect that is applying Resilience theory to real world spaces. Hunter, a landscape ecologist as well as a landscape architect, has developed an adaptive planting strategy that is intended to mitigate the potential negative impacts of climate change. Hunter relies on a comparison of two planting strategies to demonstrate how a more diverse planting strategy can help an ecosystem maintain its identity. The planting strategy relies on the theory of Resilience as a guiding principal for her strategy.

The next chapter focuses on the specifics of how Resilience is applied to an urban planting design and how parametric tools can help to visualize and test the adaptive strategy.

Benefits and Limitations

The ability to incorporate scientific understanding into landscape architecture is a powerful benefit of parametric tools. By making abstract equations visual and interactive, parametric tools can not only increase landscape architects' understanding of how design elements change and impact other design elements, but also allow the incorporation of advanced scientific knowledge into a design.

A simple example is the use of a sin wave as part of a design. The equation for a sin wave is taught in high school physics (Figure 4-6). Using geometry, it is possible to predict aspects of the wave such as the amplitude or wave length. With the parametric program Grasshopper, a sin wave function can be made into a visual sin wave by imputing adjustable numerical values into the equation. Grasshopper allows the computer to process the algorithm and convert the numerical values into a visual representation of the function in the Rhino 3-D modeling environment. The designer can then manipulate the variables and visualize the relationship of the algorithm. Visualizing complex data is one way for a designer to more intuitively understand complex processes.

$$y(x,t) = A \cdot \sin(\omega t - kx + \phi) + D$$

Figure 4-6 - Sin Wave Equation (Wikipedia, 2012)

Other scientific principles which are described by algorithms can also be made more intuitive for designers through visualization. While there are already computer programs such as Mathematica that allow us to visualize scientific equations, Grasshopper is unique in that it works directly with the more typical design application Rhino. The power of Grasshopper's tools is that they act as bridge between designers and the scientific information they want to use in their designs.

It is important to note that these models are only simulations of the real world. While the models attempt to simplify the world to expose the core rules that describe interactions, they cannot replace real-world observation. In the past, designers such William Whyte would use observation as a research tool to understand how people used space. Whyte searched for simple rules that could begin to describe how people use space. For example, Whyte concluded that in New York City public spaces the presence of people tended to attract other people (Figure 4-7). This simple rule seemed to contradict a design style that was favoring privacy.

Figure 4-7 -William Whyte observations of public space use. (Whyte, 2001)

While models are not replacements for real world observation, the ability to combine real world observation with models creates a process of improved understanding over time. This type of calibration is often used for the predictive energy use of a LEED certified building. A model will be used to predict how much energy will be used. The model generally cannot predict the exact way that occupants will use energy. Once occupants have moved in and started using the building however, it is possible to tailor the model to actual use to get a very accurate predictive model of energy use. When there are major discrepancies in the initial model and the calibrated model, there is an opportunity for engineers to re-asses their assumptions about how energy is used in a building. The act of modeling, observation, and calibration, is to be expected (Figure 4-8).

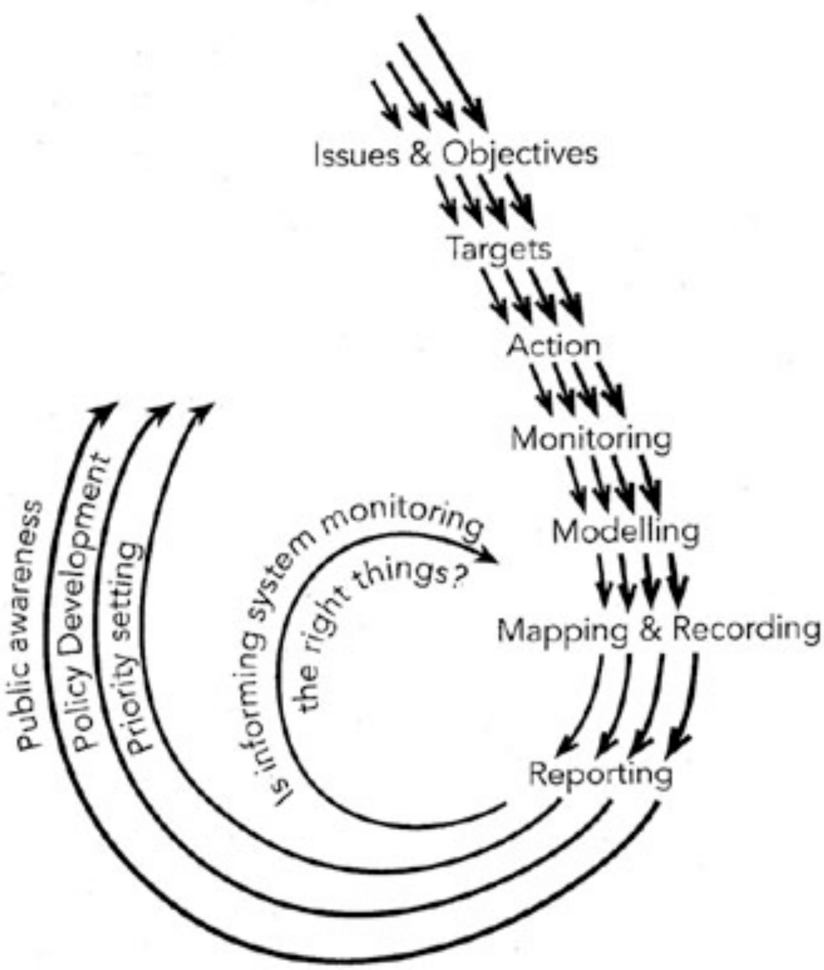


Figure 4-8 - The Adaptive Management Cycle - (Alexandra 1998)
http://www.communitysolutions.com.au/papers/LMpartnerships.html

Using a scientific model as part of a design results in problems as well as benefits. The principal disadvantage of model use is that the model may not represent the true dynamic properties of the site. The benefit of model use, however, is that by testing theories we can monitor sites, collect data, and use that real-world observation as a method of improving not only the model, but also subsequent designs. Computer simulation does not replace human intuition, it is a tool that expands on our understanding of the physical world.

One of the main elements of Complexity Science and specifically Resilience is the importance of tipping points or thresholds. A major potential benefit of modeling is the ability to explore the thresholds of systems under various potential futures. Much of the design work that landscape architects do is based on mitigating future negative impacts of design decisions. The next chapter describes in detail how Resilience theory and modeling can be applied to landscape architecture.

CHAPTER 5 RESILIENT LANDSCAPE DESIGN STRATEGY PARAMETERIZED

This chapter answers, “What is needed in order to parameterize MaryCarol Hunter’s resilient design strategy?”, “What are the benefits and limitations of using parametric tools to visualize MaryCarol Hunter’s design strategy?”, and “What lessons can be learned from modeling MaryCarol Hunter’s strategy that could be used for future projects?”.

MaryCarol Hunter is a landscape architect that is applying the theories of Resilience to planting design strategies in an attempt to mitigate the potential negative outcomes of climate change (M. Hunter, 2011). Part of the reason for highlighting Hunter’s strategy is that her adaptive framework, is already a form parametric modeling that helps to visualize Resilience. As mentioned in the previous chapter, parametric models are one way to incorporate scientific theories such as Complexity Science and Resilience into landscape architecture.

A parametric model relies on data and precise relationships. Hunter has collected plant data as well as defined explicit relationships with which to test her strategy. For example, Hunter creates a plasticity measure for bloom period that is the sum of all the months that a plant blooms. This simple summation of data is a way to create more data from relating the existing data to each other. The summation is also an example of an operation that could be quickly and repeatedly carried out by Grasshopper.

The steps that Hunter took to quantify her resilient design strategy are the same steps that need to occur to create a parametric model in Grasshopper. The advantage of translating Hunter's strategy into Grasshopper is that it can provide more robust visualization of the existing strategy, as well as explore how different strategies would change over time. A translation into Grasshopper could also allow for a more seamless connection between the planting design processes and the development of the strategy.

Grasshopper can also be used to expand the strategy and begin to utilize the spatial connection of Grasshopper to simulate the impact of different design strategies over an entire city. Temporal qualities such as growth rates can be associated with plant types and simulated over time. Site specific data such as topography and soil conditions can also be added to the model for greater modeling accuracy. These additions to Hunter's strategy will be discussed in greater detail later in the chapter.

Summary of Hunter's Strategy

The main purpose of Hunter's paper is to create a planting strategy that can mitigate the potential negative outcomes of global climate change while still meeting key aesthetic and cultural goals. Hunter used the concepts of plasticity, functional redundancy, response diversity, and structural diversity to create a resilient planting strategy that focuses on habitat and migration assistance for generalist bird and butterfly pollinators (Figure 5-1) (M. Hunter, 2011). The terms plasticity, functional redundancy, response diversity, and structural diversity are the defining metrics that Hunter uses to compare different planting strategies.

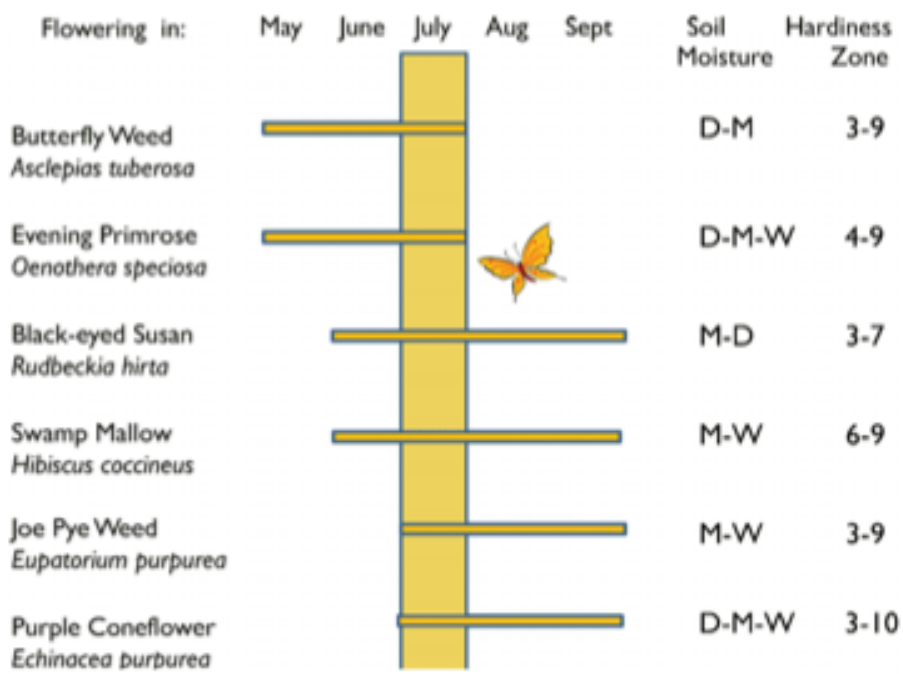


Figure 5-1 - "Graphical representations of functional redundancy and response diversity for pollinator resources throughout the growing season with greatest insurance of nectar in July. Bars indicate blooming period. Moisture requirements range from D=dry, to M=moist to W=wet soils." (M. Hunter, 2011)

Ecological Resilience is a specific subset of the Resilience theory that was discussed in the previous chapter (Gunderson, 2002). Hunter describes ecological Resilience as, "the ability of an ecosystem to maintain function in the face of environmental disturbance". Function in the case of the planting design is the ability to provide habitat for generalist bird and butterfly pollinators (Figure 5-2) (M. Hunter, 2011). The four metrics are defined as follows:

Plasticity - A specific ecological term which generally refers to the range of conditions that a species can survive. A plant with high plasticity is able to survive at many different climactic variations. In Hunter's scenario, a plant with greater plasticity will increase the overall strategy's resilience.

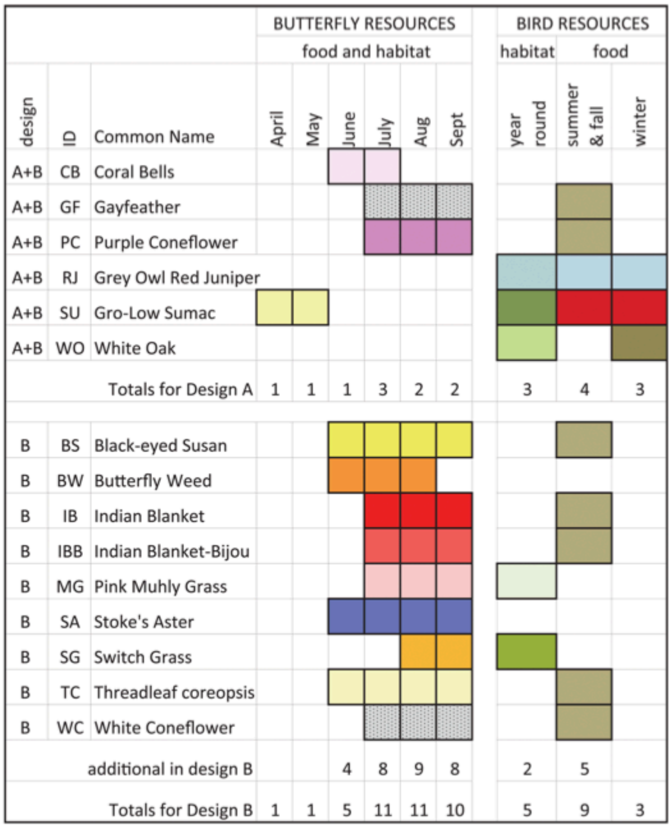


Figure 5-2 - “Seasonal resource and aesthetic presence chart for species in Designs A and B. Bloom time and flower color are shown for bird resources. Totals indicate the number of species/varieties contributing to functional redundancy in resource provisioning by month (pollinators) or season (birds).”(M. Hunter, 2011)

Functional redundancy - The overall overlap of plant traits. Hunter focusses on the plant traits that overlap to provide pollinator habitat. The theory is that the more overlap there is in a design, the less impact the loss of any single species will have on the system.

Response diversity - The plant response to different weather patterns and conditions (Figure 5-3). For example a particularly wet spring may stop certain plants from blooming but have no impact on other plants. This metric looks at how the planting strategy as a whole would respond to climactic changes, such as flooding or drought.

				BUTTERFLY RESOURCES						BIRD RESOURCES		
				food & habitat						habitat	food	
design	ID	Common Name	soil moisture	April	May	June	July	Aug	Sept	year round	summer & fall	winter
A+B	CB	Coral Bells	M,D									
A+B	GF	Gayfeather	M,D									
A+B	PC	Purple Coneflower	D,M,W									
A+B	RJ	Grey Owl Red Cedar	D,M									
A+B	SU	Gro-Low Sumac	M,D									
A+B	WO	White Oak	D,M,W									
		Totals for Design A		0	0	0	1	1	1	1	1	1
B	BS	Black-eyed Susan	M,D									
B	BW	Butterfly Weed	D,M									
B	IB	Indian Blanket	D,M									
B	IBB	Indian Blanket-Bijou	D,M									
B	MG	Pink Muhly Grass	D,M,W									
B	SA	Stoke's Aster	M,D									
B	SG	Switch Grass	D,M,W									
B	TC	Threadleaf coreopsis	M,D									
B	WC	White Coneflower	D,M,W									
		additional in design B					2	3	3	2	1	
		Totals for Design B		0	0	0	3	4	4	3	2	1

Figure 5-3 - "Evaluation of response diversity in Designs A and B for year(s) of abnormally high rainfall. Shaded squares indicate the species able to provide ecosystem services owing to their ability to sustain themselves through extended periods with wet soil. Empty boxes indicate lost ecosystem function for species that cannot function when soils remain wet. Soil moisture capacity for D=dry, M=moist, W=wet soils" (M. Hunter, 2011)

Structural diversity - is concerned with the impact of different forms of plants on animal habitat. A tree provides a different structural habitat than a shrub. Hunter argues that greater structural diversity can aid in overall Resilience because the greater range of habitat can support greater diversity.

Hunter applies these four metrics to two planting strategies that have different amounts of biodiversity . The planting strategy with the greater diversity is considered more resilient because the extra diversity increases the amount and range of functions that could occur under changing climactic conditions.

Figure 5-4 - “Summer comparison of aesthetic presence and spatial location of butterfly and bird resources between Design A (above) and Design B (below)” (M. Hunter, 2011)

Figure 5-5 - “Winter comparison of aesthetic presence and spatial location of butterfly and bird resources between Design A (above) and Design B (below)” (M. Hunter, 2011)

The use of measurable targets such as, year round interest, low impact management, no growth zone of 1-2 meters for visual safety, drought and salt tolerant, as well as habitat for birds and butterflies is essential to a successful parametric model. There has to be a target for which the design is aiming in order to assess the output of the model. The target acts as boundary parameters of the design. In this particular example, the no growth zone of 1-2 meters automatically eliminates many potential outcomes. One of the advantages of parametric design is that because all of the rules for selecting are hard coded into the design, a variable such as the no growth zone can be easily modified to see the impacts on the potential design solutions.

After setting a target two different designs are compared, one design with six plant species and the second design with the same six plants species plus nine more species to make a total of fifteen plant species. The two different designs were then compared for their ability to meet the aesthetic, cultural, and ecological goals (Figure 5-4, Figure 5-5). The planting design with greater diversity did a better job of meeting the ecological goals. The results are showed on a spread sheet, as well as a color coded planting plan and color rendered sections, one for summer and one for winter.

The specific results of the paper are of less interest to this thesis than the way that the different results are developed and compared. In the paper, perhaps for the point of illustration, there were only two planting designs compared. There were only two planting plans out of a huge variety of possibilities. Parametric tools, by the aid of rapid variation of variables, can quickly produce many different designs that still meet the design criteria. This ability to explore many variations allows designers to fine tune a design for the most desired qualities.

Hunter Translated into Grasshopper

This section of the thesis discusses the process and results of incorporating MaryCarol Hunter's planting strategy into the parametric tool Grasshopper. Parametric modeling requires well defined bounds or parameters in order to determine the potential variation of the design. The metrics that Hunter creates start to highlight how existing databases (Table 5-1, Table 5-2) can be manipulated parametrically in order to extend the values of the database. The searchable nature of the plant database allows for specific attributes of plants to be gathered and compared quantitatively by the computer. The abstracted data can then be turned into a meaningful output. For example bloom color can be linked to bloom time and visually represented in a planting plan. The advantage of Grasshopper is that the data can be more than a simple graphic typical of spreadsheets (Figure 5-23).

The next step in developing a parametric model, after collecting data and creating plasticity measurements, is to define the criteria for the optimal design. This is likely one of the most critical steps in developing a parametric tool because there is no quantitative way to determine the appropriate goals of a design. The target of any design is fundamentally based on values. Hunter's strategy is tailored for the setback space between a residential road and the sidewalk, which is typically a long thin strip of land. Her criteria for a successful design are intended to meet measurable aesthetic, cultural, and ecological targets and are reflected in the selected plant palette.

Table 5-1 - Plant List for Designs A and B with Traits used for Plasticity, Functional Redundancy, and Response Diversity. (M. Hunter, 2011)

Design	Design Plan ID	Common Name	Botanical Name	Hardiness	*Temp Plasticity	Soil Moisture	*Soil Moisture plasticity	Bloom Time
A+B	CB	Coral Bells	*Heuchera americana* 'Ring of Fire'	4–9	6	MD	2	Jn–Ag
A+B	GF	Gayfeather	*Liatris spicata* 'Alba'	3–8	6	MD	2	Jl–Ag
A+B	PC	Purple Coneflower	*Echinacea purpurea*	3–10	8	DMW	3	Jl–S
A+B	RJ	Grey Owl Red Juniper	*Juniperus virginiana* 'Grey Owl'	3–9	7	DM	2	Mr
A+B	SU	Gro-Low Fragrant Sumac	*Rhus aromatica* 'Gro Low'	3–9	7	MD	2	A–My
A+B	WO	White Oak	*Quercus alba*	3–9	7	DMW	3	My
B	BS	Black Eyed Susan	*Rudbeckia hirta* 'Indian Summer'	3–7	5	MD	2	Jn–S
B	BW	Butterfly Weed	*Asclepias tuberosa*	3–9	7	DM	2	Jn–Ag
B	IB	Indian Blanket	*Gaillardia aristata*	3–10	8	DM	2	Jl–S
B	IBB	Indian Blanket-Bijou	*Gaillardia aristata* 'Bijou'	3–8	6	DM	2	Jl–S
B	MG	Pink Muhly Grass	*Sporobolus capillaris / Muhlenbergia capillaris*	5–9	5	DMW	3	Jl–S
B	SA	Stokes Aster	*Stokesia laevis* 'Blue Danube'	5–9	5	MD	2	Jn–S
B	SG	Switchgrass	*Panicum virgatum* 'Shenandoah'	3–9	7	DMW	3	Ag–S
B	TC	Threadleaf coreopsis	*Coreopsis verticillata* 'Moonbeam'	3–9	7	MD	2	Jn–S
B	WC	White Coneflower	*Echinacea purpurea*	3–10	8	DMW	3	Jl–S

Table 5-2 - Complete Trait Data for Plants Used on Designs A and B (M. Hunter, 2011)

Plant type	Common Name	Botanical Name	Persistence	Nativity	Hardiness	*Temp Plasticity	Light Type	*Light Plasticity	Light preference	Soil Type	*Soils Plasticity	Soil pH	Soil Moisture	*Soil Moisture plasticity	Details on soil moisture needs	*Drought tolerance	*Salt tolerance
3	Butterfly Weed	*Asclepias tuberosa*	1	2	3–9	7	F–PSh	2		L,S,C	3	AC	DM	2	Does well in poor, dry soils	4	ST
3	Threadleaf coreopsis	*Coreopsis verticillata* 'Moonbeam'	1	1	3–9	7	F	1	full sun	S,L	2	AC	MD	2	Thrives in poor soil w/ good drainage	4	ST
3	Purple Coneflower	*Echinacea purpurea*	1	2	3–10	8	F	1	best in full sun	L,S	2	ALK	DMW	3	Tolerates poor soil	4	ST
3	Indian Blanket	*Gaillardia aristata*	1	1	3–10	8	F	1	full sun	S,L	2	AC	DM	2	Prefers well-drained soils	4	ST
3	Indian Blanket-Bijou	*Gaillardia aristata* 'Bijou'	1	1	3–8	6	F	1	full sun	S,L	2	AC	DM	2	Prefers well-drained soils	4	ST
3	Rock Geranium	*Heuchera americana* 'Ring of Fire'	1	2	4–9	6	F–PSh	2	prefers afternoon shade	L,S	2	Neutral	MD	2	medium moisture, well-drained	4	ST
2	Grey Owl Red Juniper	*Juniperus virginiana* 'Grey Owl'	2	2	3–9	7	F–PSh	2		L,S,C	3	sl AC- ALK	DM	2	Intolerant of wet soils	4	ST
3	Blazing Star	*Liatris spicata* 'Alba'	1	2	3–8	6	F	1		L	1	Neutral	MD	2	Intolerant of wet	4	ST
4	Switchgrass	*Panicum virgatum* 'Shenandoah'	1	2	5–9	5	F	1	slumps in shade	L,S,C	3	Neutral	DMW	3	Flops in rich soils, prefers moist	2	ST
1	White Oak	*Quercus alba*	1	2	3–9	7	F–PSh	2	full sun	L,S,C	3	AC	DMW	3	Prefers moist, acidic soil	4	ST
2	Gro-Low Fragrant	*Rhus aromatica*	1	2	3–9	7	F–PSh	2		L,S,C	3	sl AC-Neutral	MD	2	Not tolerant	4	ST

The following images are details of how the planting strategy was translated into Grasshopper. The basic organization of the Grasshopper script relies on collecting data, creating relationships from the data, applying those relationships to individual plant characteristics, creating environmental controls to manipulate those characteristics, and then developing a style of representing the characteristics (Figure 5-6). In this case, relationships associated with plant data are relationships that visualize when a plant is blooming or not blooming depending on the time of year and whether or not there is too little or too much rain. The style of representation was chosen to be a simple color coded 2-D planting plan that automatically updated depending on variations in the environmental controls. The environmental controls allow the designer to visualize how bloom times change depending on changes in the time of year, the USDA hardiness zone, drought, or excess precipitation.

A more detailed description of the organization and relationships of the parametric model are described by a series of images of the Grasshopper script.

Methods

All of MaryCarol Hunter's data (Figure 5-8) was copied into grasshopper as comma separated values (CSV) text. CSV is a common text based spreadsheet format that separates the values of a spreadsheet commas. The text looks like a single collection of words but maintains the ability to be separated and sorted. An alternative to copying the data into grasshopper as text would have been to directly link to a spreadsheet file.

All of the data is held in the single white text box (Figure 5-8). That data is then separated through a series of components. A component is visually represented as a box.

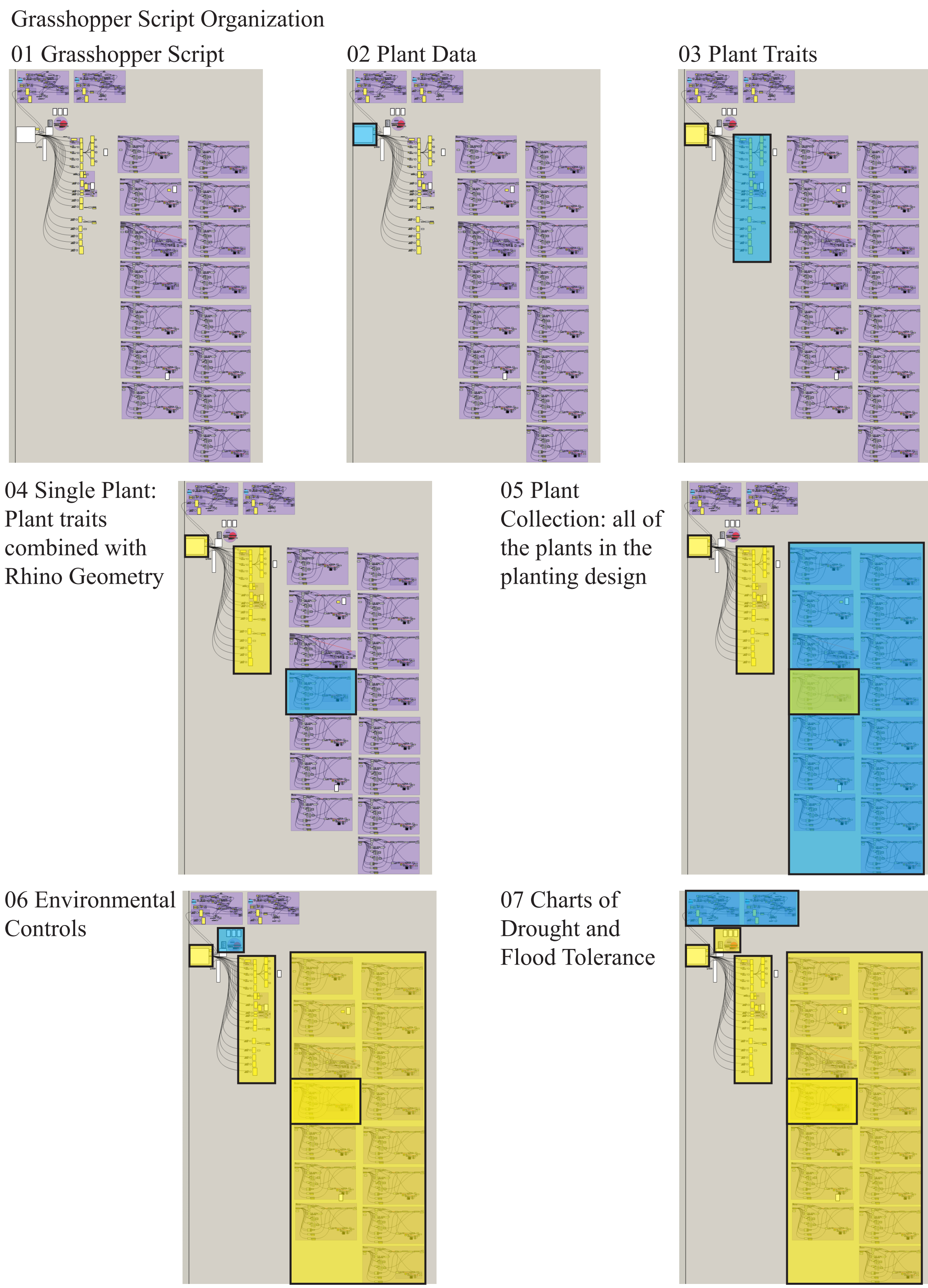


Figure 5-6 - Grasshopper Script Organization

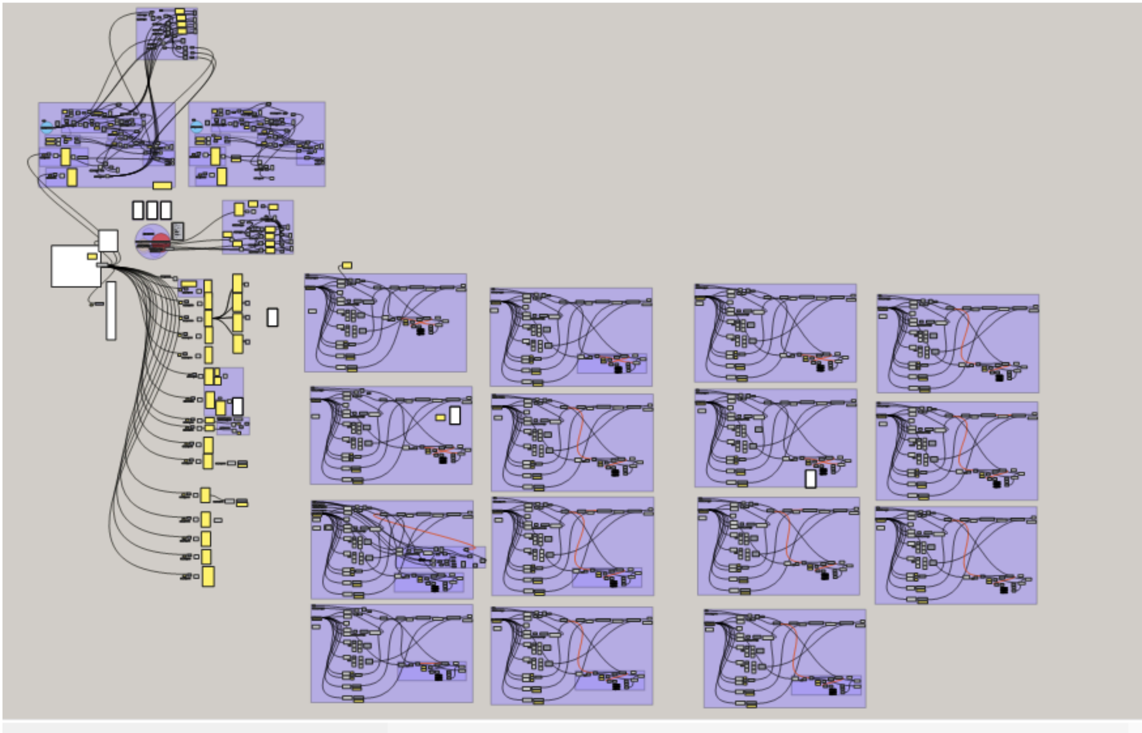


Figure 5-7 - Entire Grasshopper Script

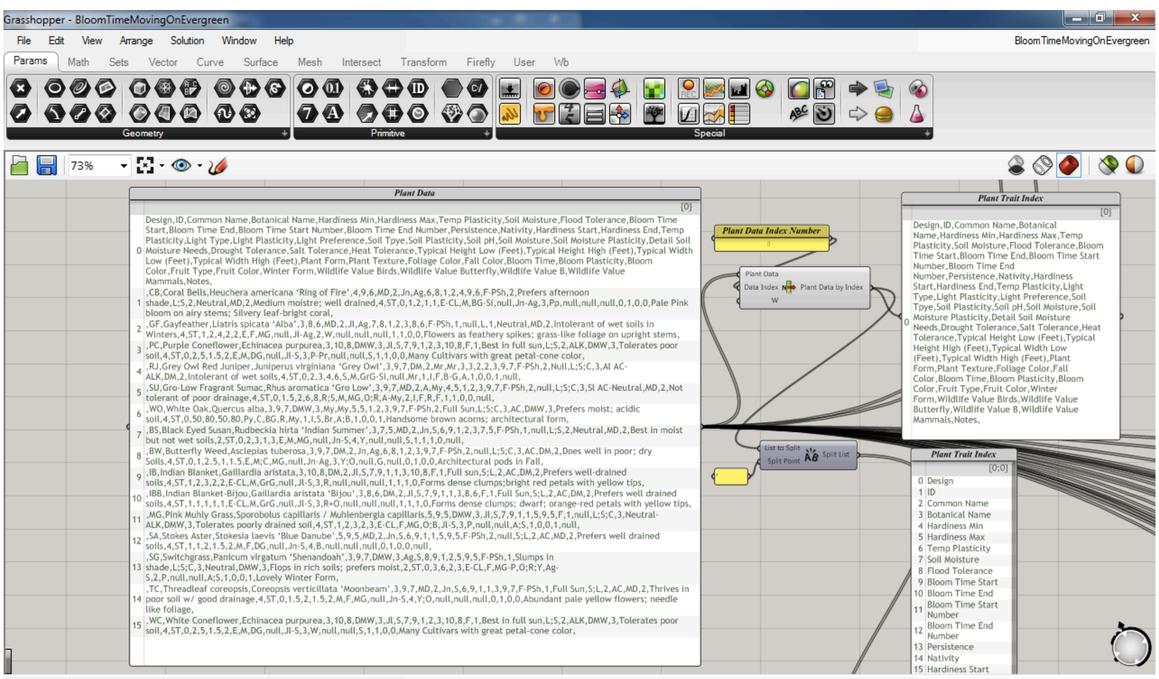


Figure 5-8 - Plant Data in Comma Separated Values Format

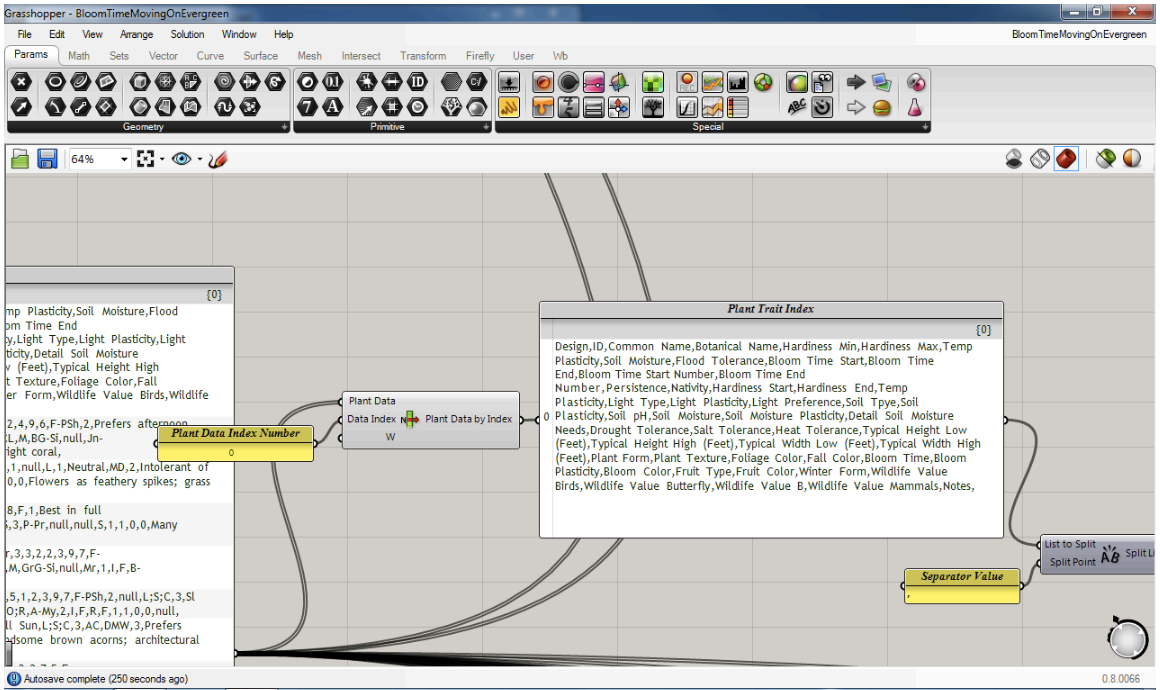


Figure 5-9 - Individual Data Extraction

The component that separates the data receives two pieces of information. The first is a list of items, in this case rows of plant data from Hunter. The second piece of information is a number. The number describes which row the component should output. In this example the 0 row is the output of the component. Row 0 contains the index of categories in the data. The categories (Table 5-1, Table 5-2) include Common Name, Scientific Name, Soil Plasticity, etc. The next component (Figure 5-10) takes an individual row of data and separates the data into individual items. The list on the left shows the unseparated data and the list on the right shows the same data in the new separated form. Understanding the connections that are made in Grasshopper requires frequent zooming in (Figure 5-10) and out (Figure 5-11) in order to see the individual connection and the relationship to the rest of the components.

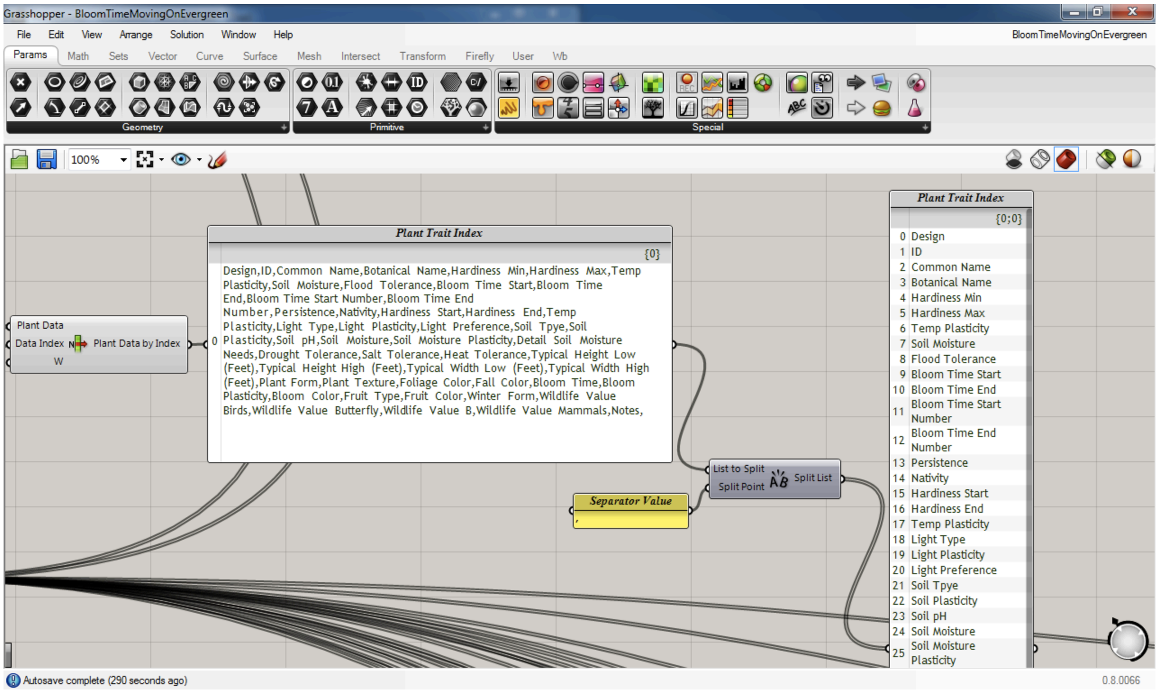


Figure 5-10 - Row of Data Separated into Individual Items

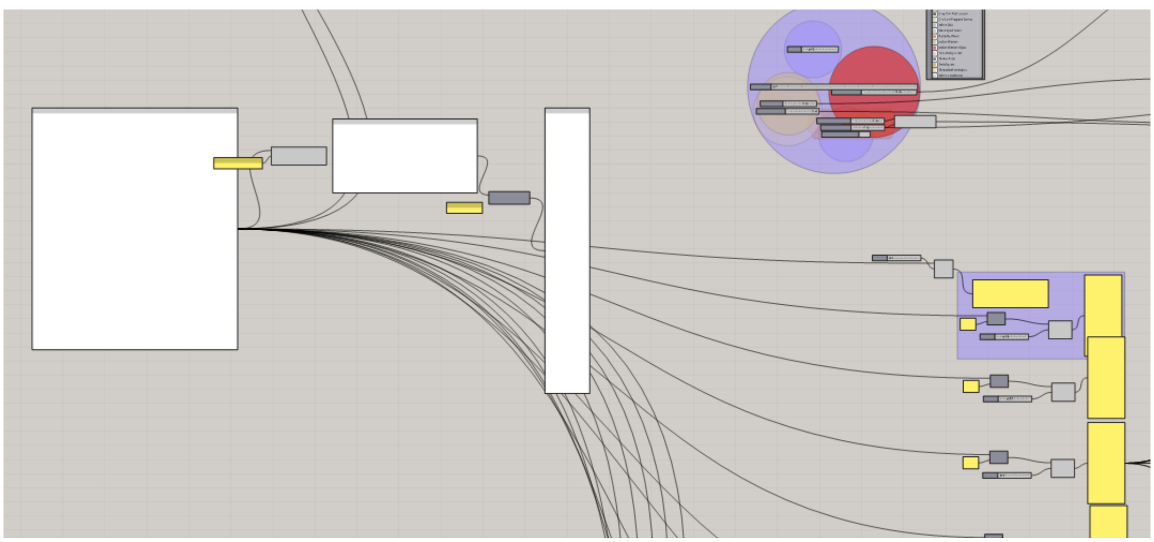


Figure 5-11 - Data Separation Components

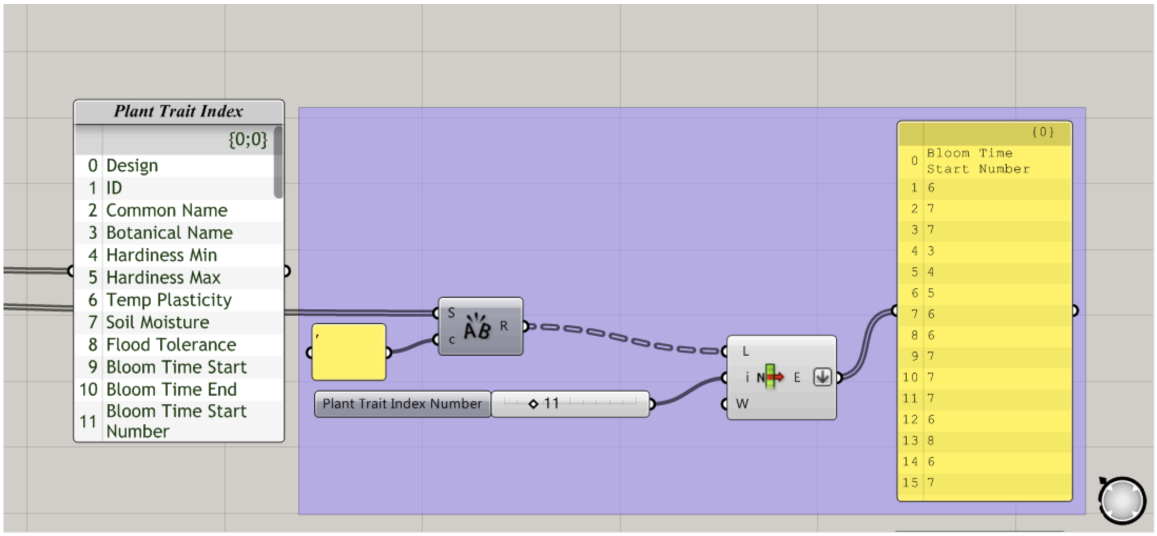


Figure 5-12 - Plant Traits - Bloom Time Start

Plant traits are separated individually through a series of Grasshopper components similar to the process of data separation previously described. Individual traits are individual pieces of data such as the different bloom times for the entire collection of plants (Figure 5-13). In this case bloom time is defined as the numerical month of when a plant blooms. For example if a plant starts blooming in April the the plant is given a corresponding value of 4. The list of plant traits are derived form MaryCarol Hunter's data (Table 5-1, Table 5-2). Some of the traits that are used in the plant relationships are, bloom start, bloom end, plant width minimum, plant width maximum, minimum height, maximum height, hardiness zone minimum, hardiness zone maximum, drought tolerance, soil moisture plasticity, foliage color, persistence.

The plant traits in the central grouping of yellow boxes (Figure 5-13) are connected to all of the individual plants in the purple boxes (Figure 5-14). The connections have been made invisible in order to visually simplify the image. Each yellow box has an invisible line connected to all of the purple boxes on the the right

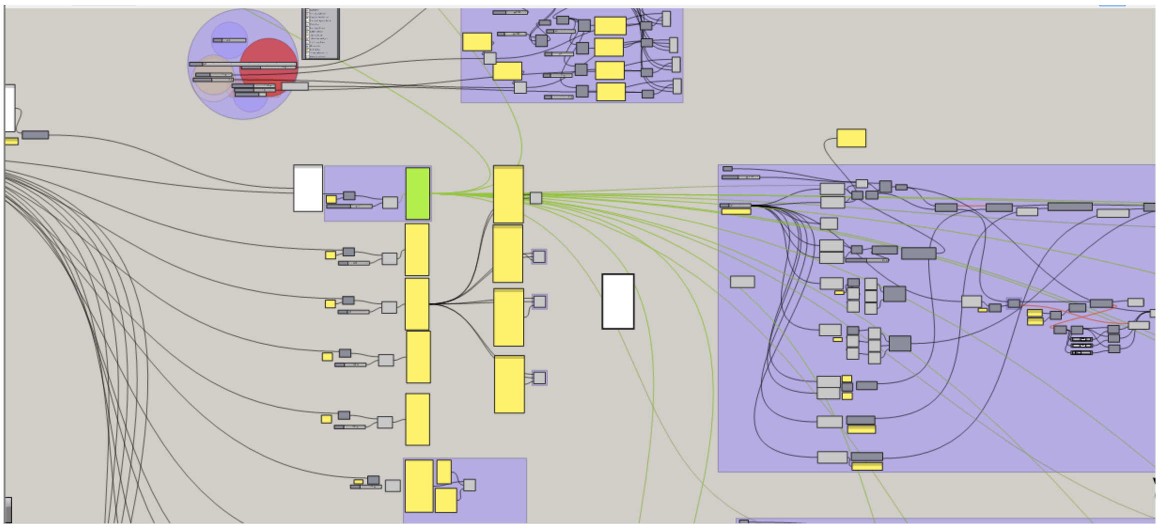


Figure 5-13 - Plant Trait Connections

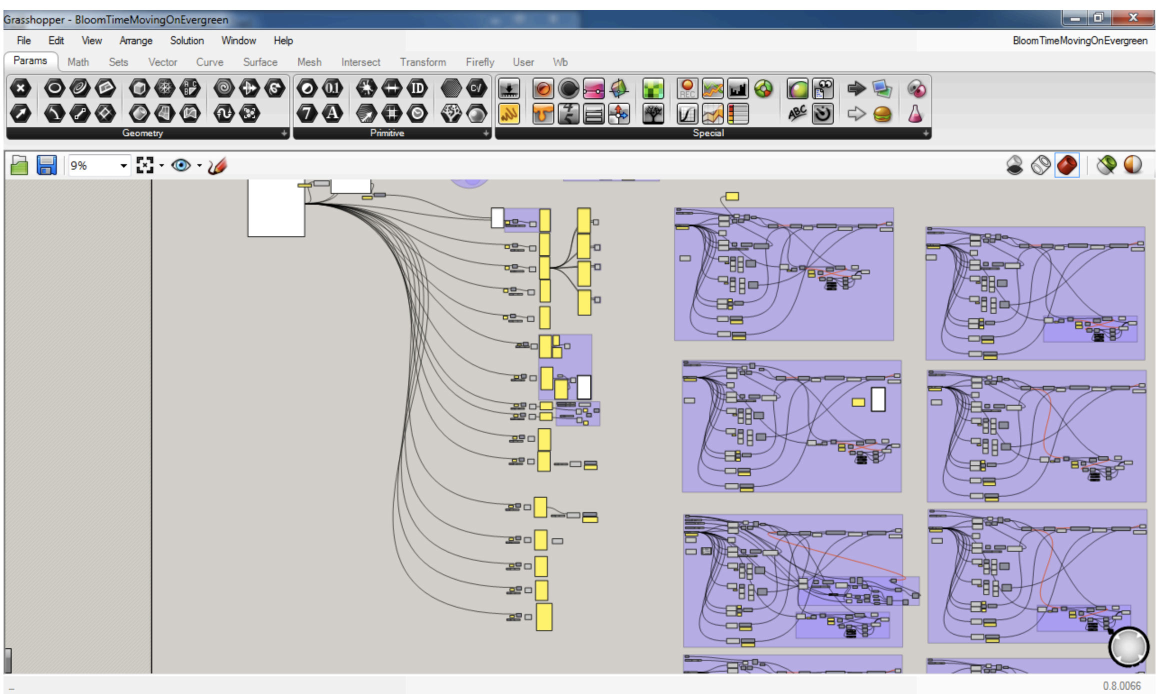


Figure 5-14 - Plant Traits and Plants - Connections Visibly Hidden

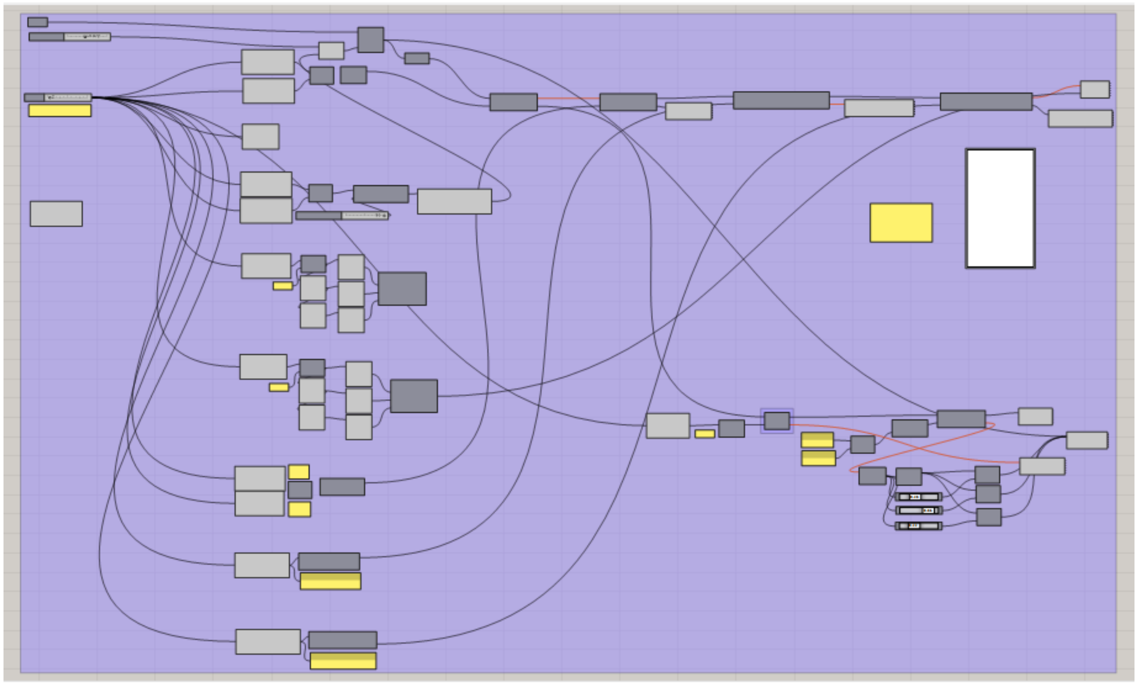


Figure 5-15 - Individual Plant Connections

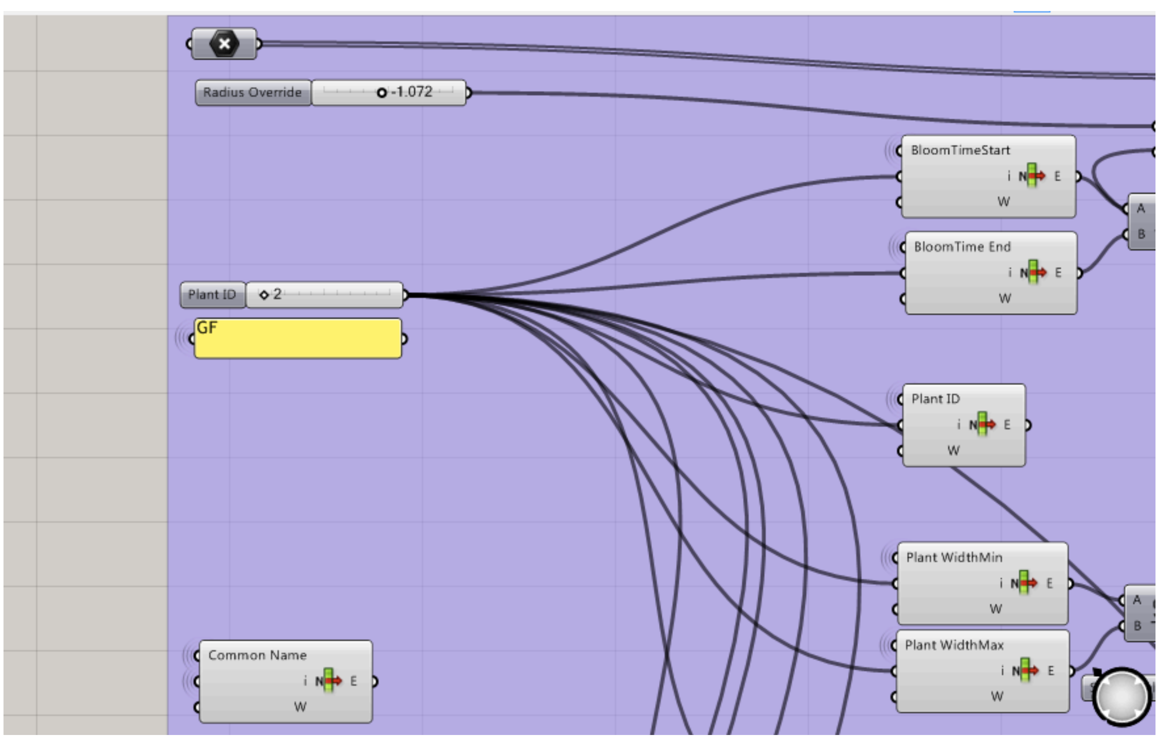


Figure 5-16 - Plant ID Index Number Control

Each of the individual plants are grouped in a purple box (Figure 5-15) and have a series of relationships based on the combination of individual plant traits (Figure 5-16). While all of the traits are connected to individual plants, each plant uses a plant ID index number to ensure it is associated with the appropriate plant data.

The individual plant traits are combined to visually display characteristics such as the particular month a plant blooms. Each plant has data associated with the month a plant begins and ends it's bloom (Figure 5-17, Figure 5-18). That information is linked to an environmental control which allows a user to select any month of the year (Figure 5-19). Depending on the month the user chooses, different plants will be in bloom (Figure 5-23).

The Grasshopper mechanics of this visualization rely on comparing the environmental control month with the range of bloom months. If the environmental control month is equal to any of the months in the range of bloom times (Figure 5-20) then the plant will display it's bloom color (Figure 5-21). In this example the month has been set to "9" and the bloom time start and end range is "7.0 to 8.0" which result in a "false" outcome (Figure 5-20). The true or false component, which acts as a switch, determines which color to represent a plant.

There are a series of true or false switches which test for different environmental conditions (Figure 5-21). If the user selected month is not within a plant's bloom range then the plant will display a non-bloom color (Figure 5-24). The color of the non-bloom color depends on the reason for not blooming. The color white was chosen to represent plants that were not in bloom because of the time of year. Black was chosen to represent plants that would be blooming but were not blooming due to drought. Color choices are defined within the Grasshopper script and any level of customization is possible.

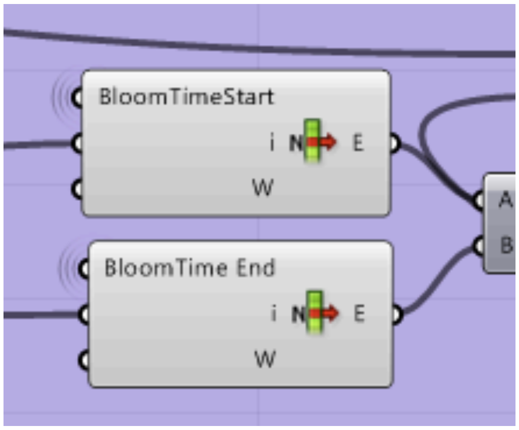


Figure 5-17 - Bloom Start and End

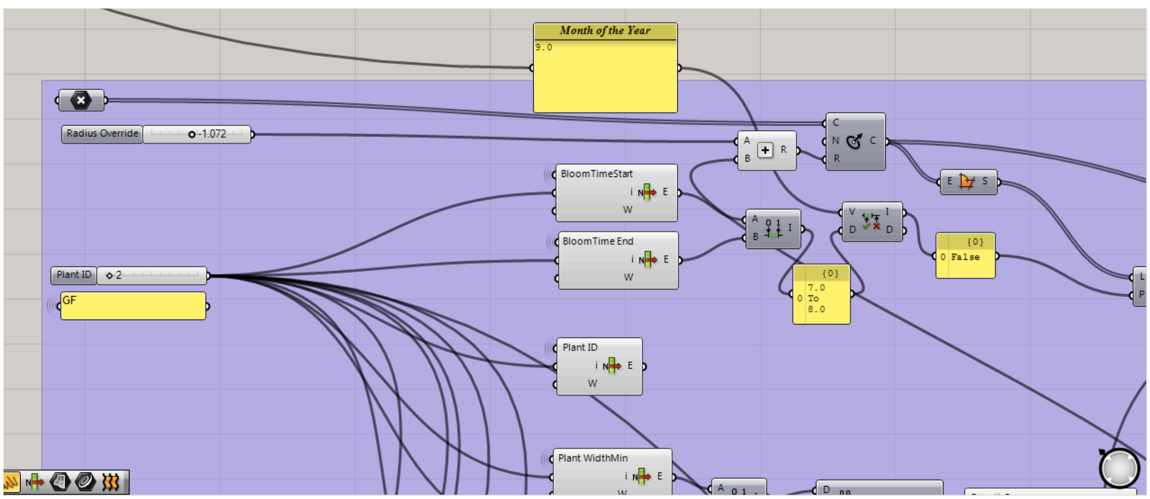


Figure 5-18 - Bloom Time Connections

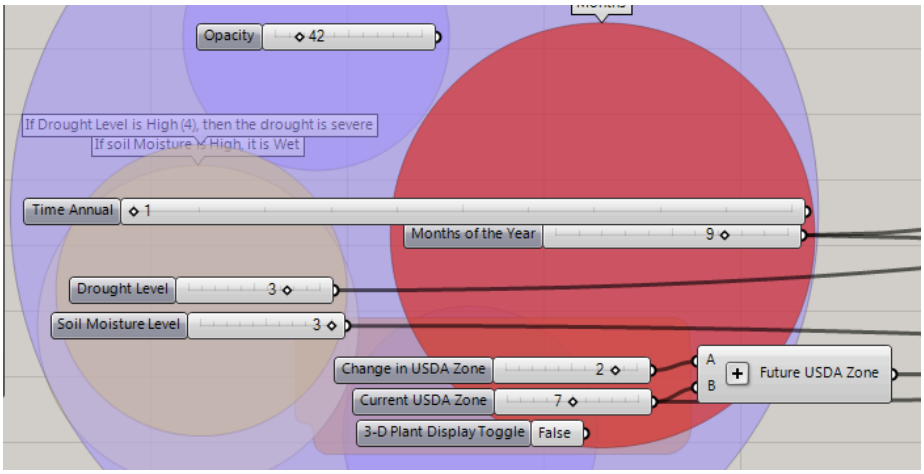


Figure 5-19 - Environmental Controls

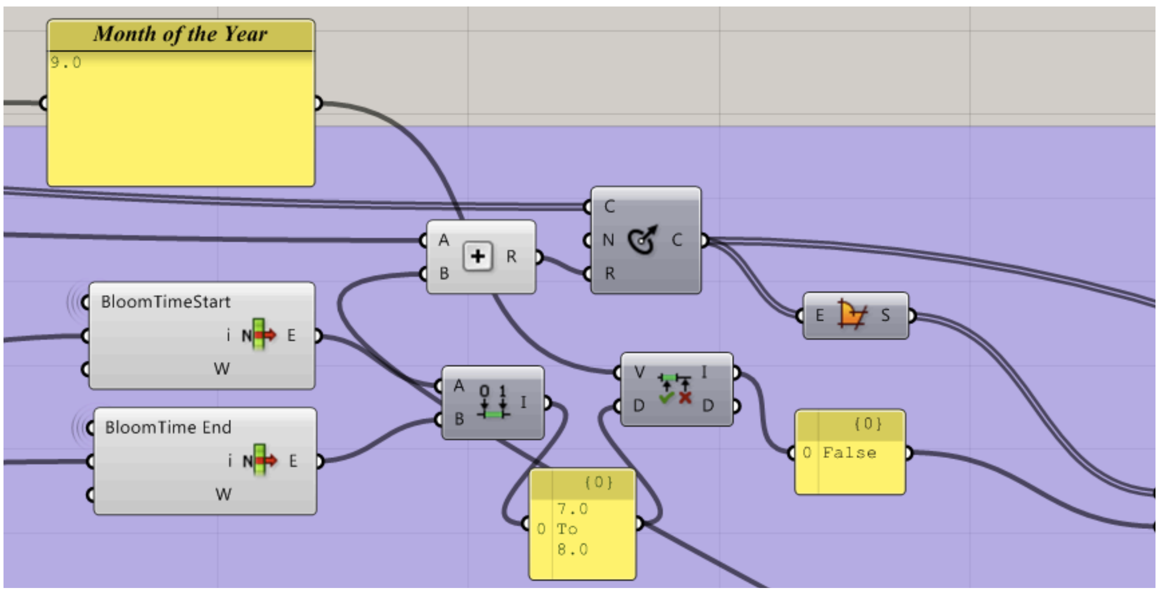


Figure 5-20 - Bloom Time True or False

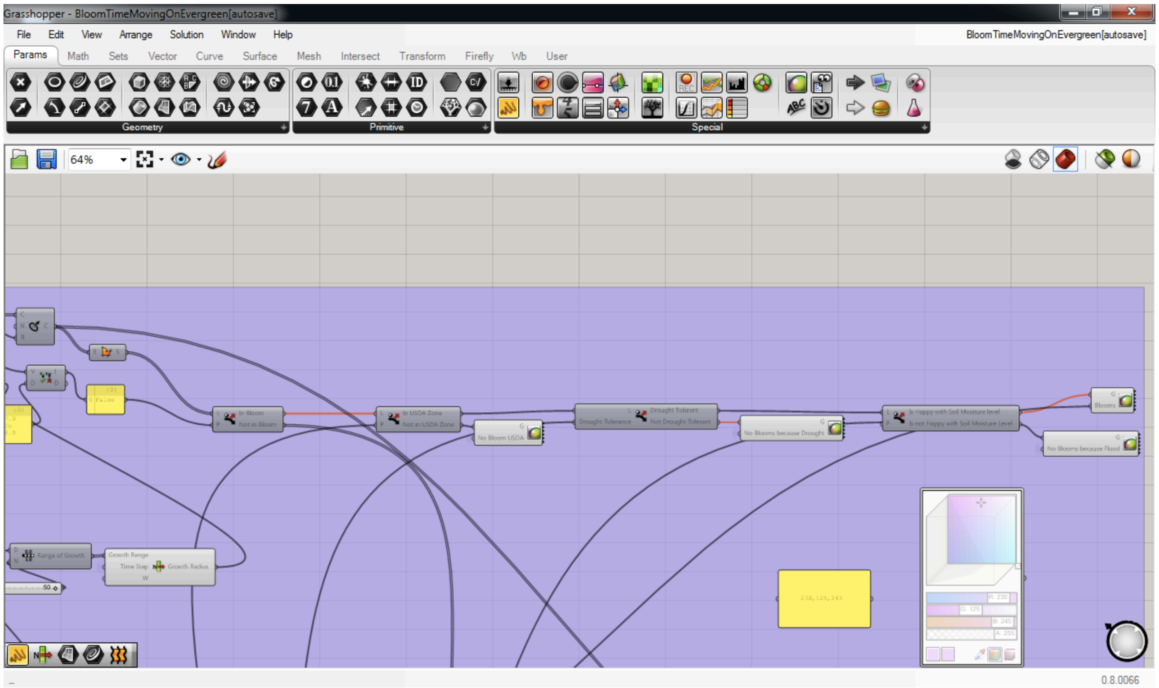


Figure 5-21 - Chain of Bloom Color Alternatives

In order to display the information developed in the Grasshopper script there needs to be a connection to the 3-D modeling program Rhino. For this model, center points of individual plants were created in Rhino and then connected to the Grasshopper script (Figure 5-22). In Grasshopper the center points were given a circle with a radius which was extracted from the plant data. As previously mentioned, the color of the circle represents different states of bloom and depends on the environmental settings selected by the user.

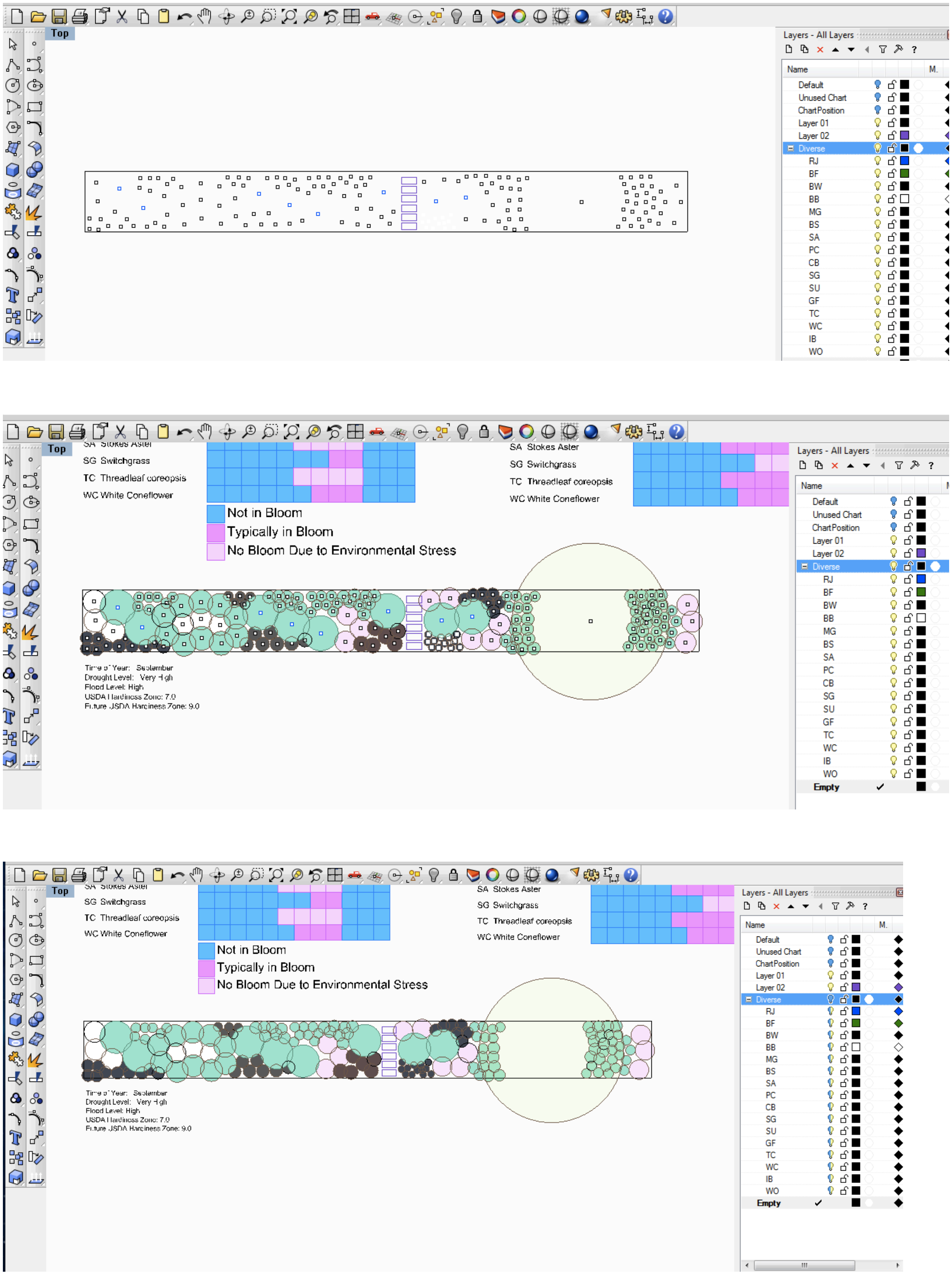


Figure 5-22 - Plant Centers in Rhino

Results of the Parametric Conversion

The following is a series of images that capture some of the outputs of the parametric model. (Figure 5-23). The images have been altered from their original format which is based in the Rhino 3-D modeling program (Figure 5-24). The images show the impact of increased precipitation on the bloom time of a planting design (Figure 5-24).

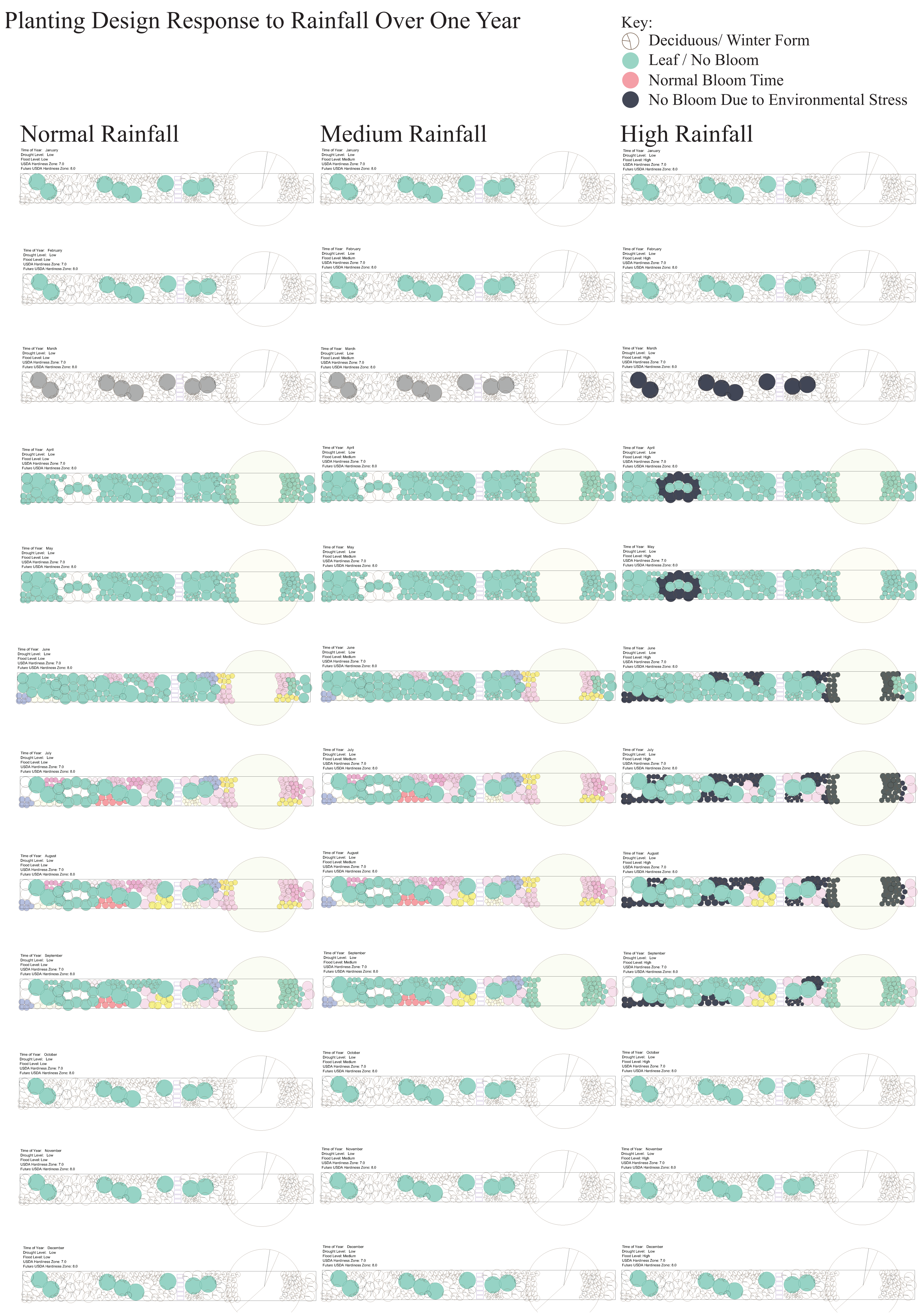
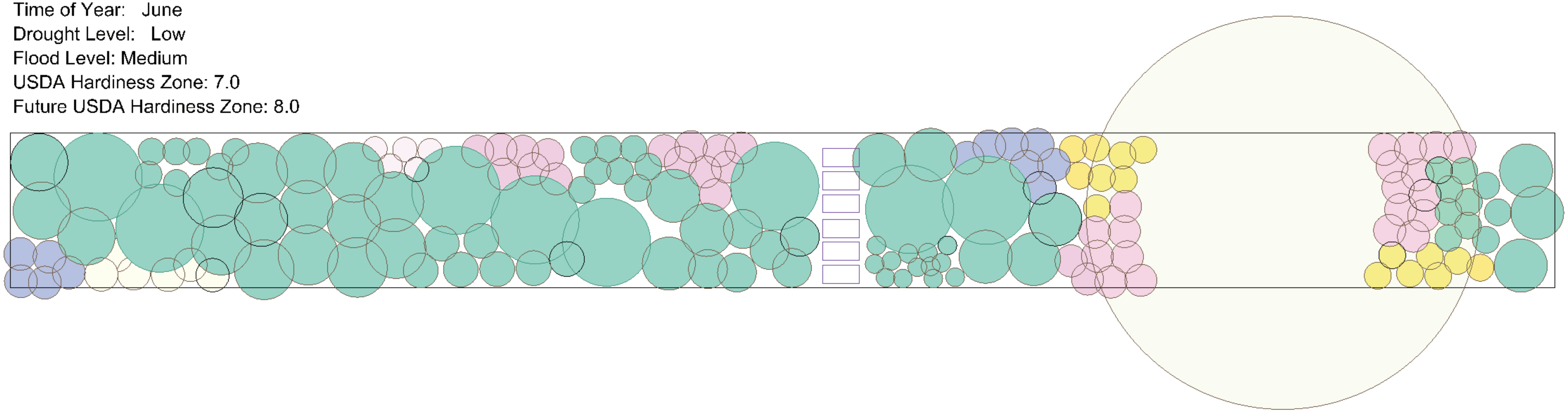


Figure 5-23 - Grasshopper Spatial Visualizations Compiled

Figure 5-24 - Grasshopper Output Detail

Time of Year: June
Drought Level: Low
Flood Level: Medium
USDA Hardiness Zone: 7.0
Future USDA Hardiness Zone: 8.0



Time of Year: June
Drought Level: Low
Flood Level: High
USDA Hardiness Zone: 7.0
Future USDA Hardiness Zone: 8.0

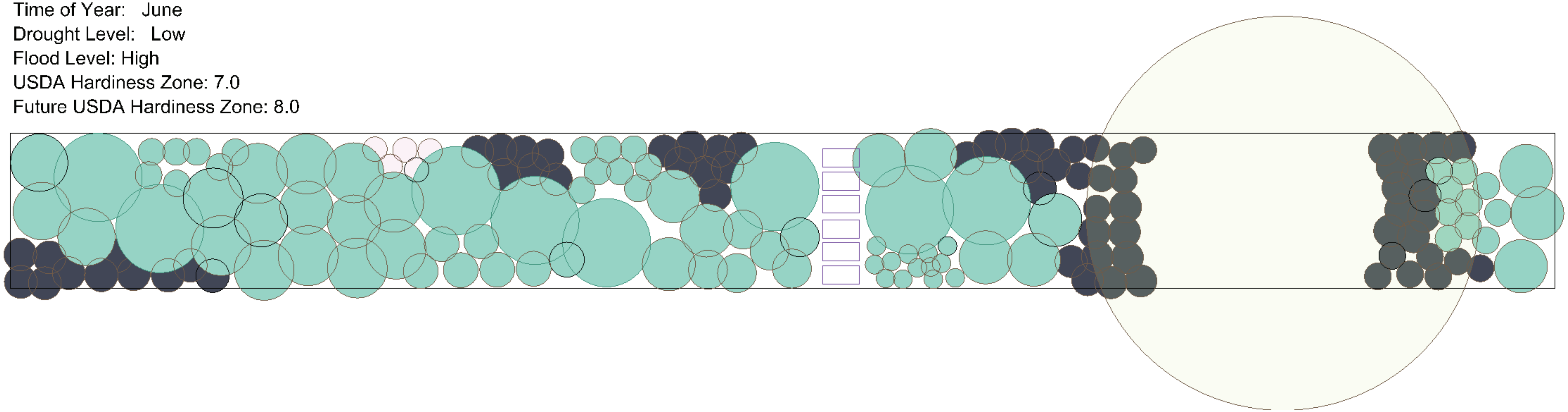


Figure 5-25 - Bloom Detail

The dark black circles are plants that would normally be blooming but are not in bloom due to an increase in precipitation (Figure 5-25). The image shows that there is little impact of increased precipitation at medium levels but that their are major impacts of higher amounts of precipitation. This would help to visually inform the designer that the design is resilient only at medium precipitation levels. The information and relationships can be presented in whichever fashion is most useful for the designer. While a planting plan allows a designer to see the spatial relationships between blooming and non blooming plants, it does not succinctly display the overall impact of precipitation. Instead a chart similar to the one developed by MaryCarol Hunter can be useful (Figure 5-26). While not developed for this model, it would be possible to include other charts visualizations and comparisons between competing planting plans.

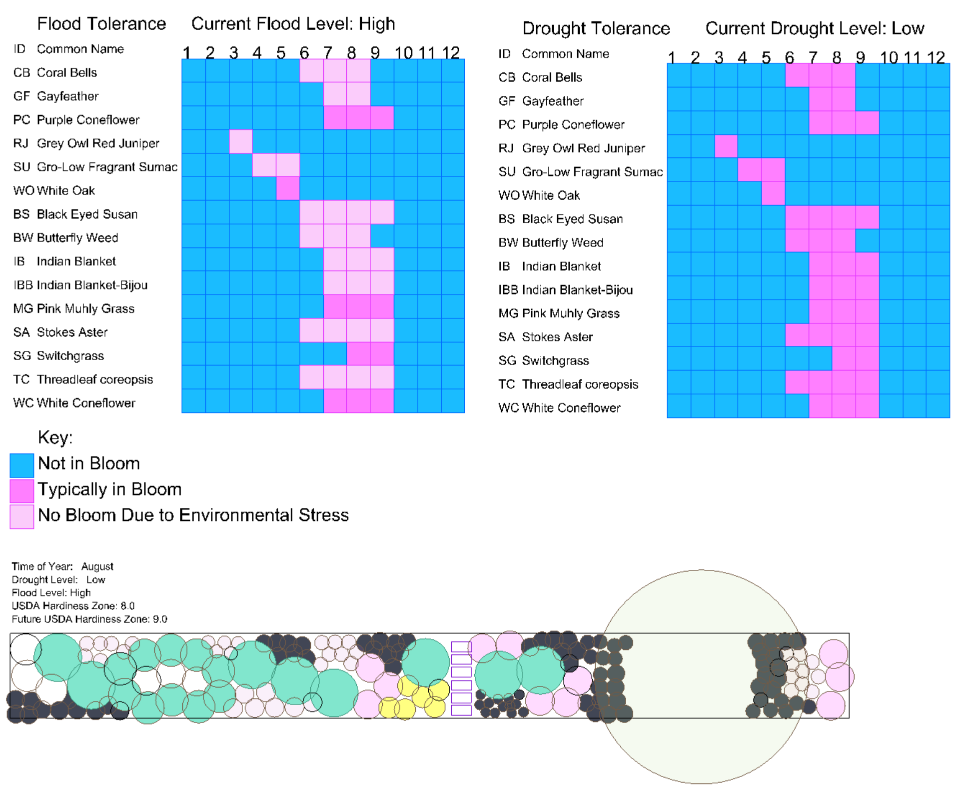


Figure 5-26 - Dynamic Grasshopper Charts with Spatial Visualization

A detail shows that the two charts display all of the plant responses to both drought and flooding. The flood and drought levels are able to be adjusted by the user (Figure 5-19). When the user adjusts the environmental condition, flooding or drought, the chart automatically updates to display the individual plant's respond to the environmental change.

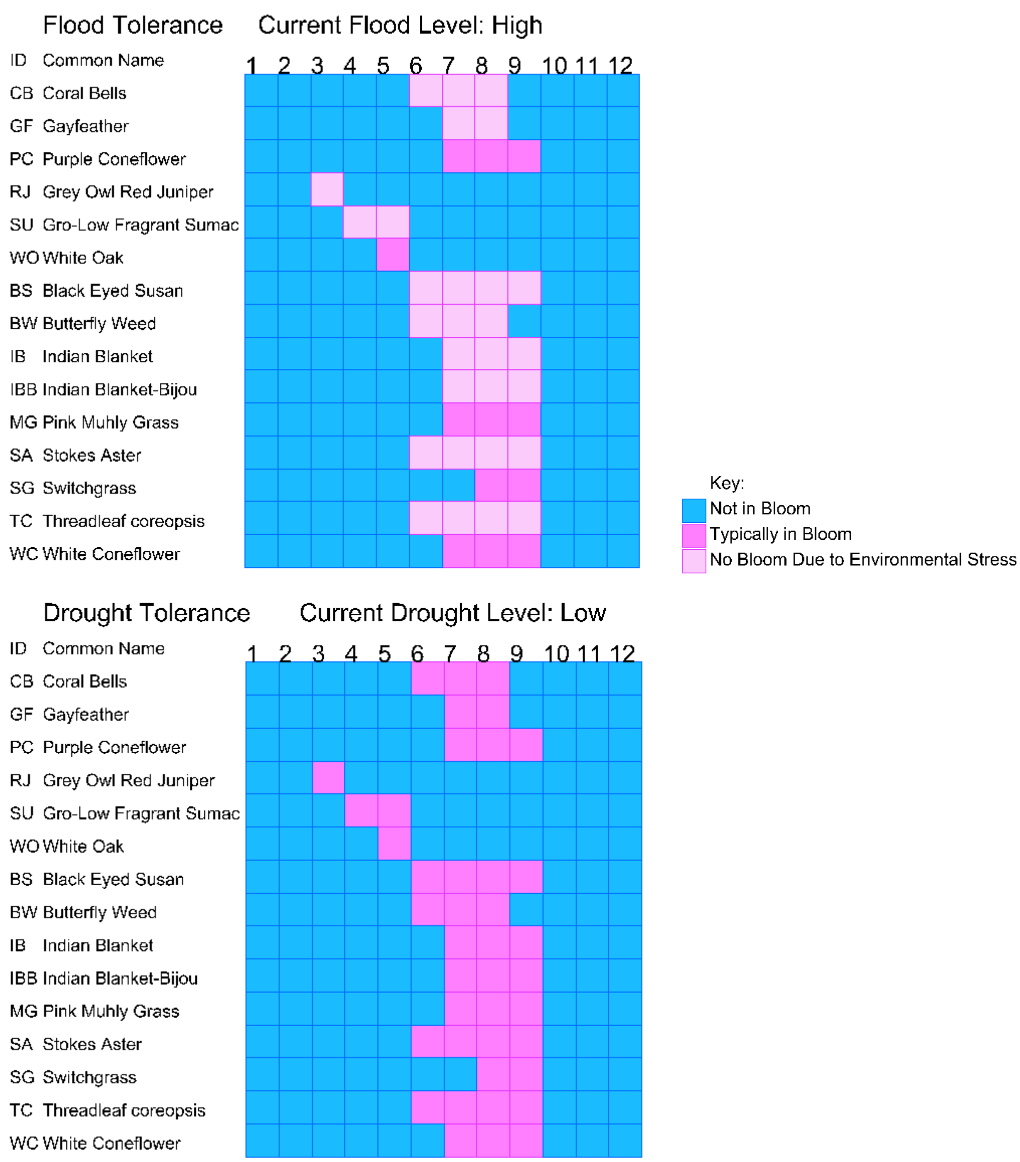


Figure 5-27 - Chart Detail

Benefits and Limitations

The benefits and limitations of the parametric model as developed are summarized in two tables (Table 5-3, Table 5-4). One of the major benefits of the parametric model is the ability to rapidly visualize a large collection of plants spatially. Once plants are added to the database switching between different collections of plants is as simple as changing a single number. Being able to incorporate a large collection of plants allows the model to be tailored to specific geographies.

Another benefit of the parametric model is the ability to visualize the spatial qualities of the planting plan. Spatial patterns help the designer understand the quantity and location of plants in bloom under different environmental conditions. This information helps the designer make design decisions on where new plant selections need to be made in order to improve the design's resilience. A limitation to this system is that altering the spatial position of the plants must be done manually. Possible improvements to this limitation are discussed later in the chapter.

Another limitation to the parametric model is the absence of information that tells the designer how different designs compare in their resilience. The designer is forced to process a large amount of visual data. Having too much information without enough feedback can easily lead to "analysis paralysis".

The parametric model is not perfect, but it does support the idea that it is possible to incorporate scientific theories from other disciplines and incorporate them into landscape architecture in order to visualize landscape systems.

Table 5-3 - Benefits and Limitations of the Grasshopper Resilient Design Strategy as Developed

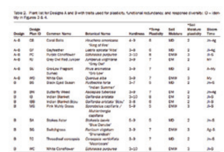
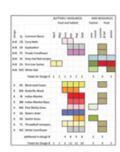
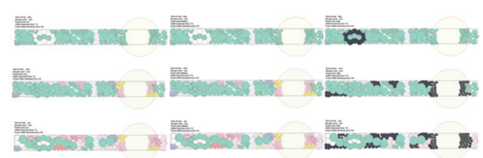
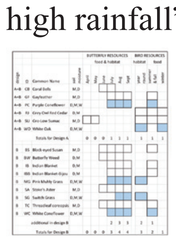
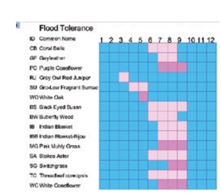
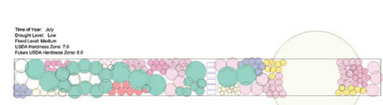
Metric	Data	Mary Carol Hunter Visualization	Grasshopper Visualization	Benefits of the developed Grasshopper model	Limitations of the developed Grasshopper model
Plasticity “As plasticity increases, plant species can persist under a greater diversity of environmental conditions and are better able to manage environmental fluctuations”	USDA Planting zone, Moisture (D,M,W),	Represented as a number in a table for each specie, combined into a chart displaying bloom time 	Represented as a number in a table for each specie, combined into a chart displaying bloom time dependent on plasticity, spatially displayed one month a time in a planting plan at any point in a year	Rapid visualization of a greater selection of plants and their plasticity.	The chart has similar results and techniques as expressed in spread sheet software. The planting plan plasticity can be difficult to visualize over the course of a year
Functional Redundancy “The number of species contributing to an ecosystem function”	Bloom time, pollinator ecosystem contribution	Bloom time and flower color are shown for butterfly resources; flower/ seed color and availability shown for bird resources 	MCH chart translated into grasshopper. Functional redundancy expressed spatially and seasonally in the planting plan 	Automation of the design strategy visualization. Greater detail in the spatial impacts of ecosystem functions	There is no information that helps the designer determine which spatial configuration is more appropriate for the design strategy. Visualization are not as elaborate as hand rendered images
Response Diversity “The range of reaction to environmental change among species contributing to the same ecosystem function”	Plasticity calculations compared to climate change predictions	Chart representing the response diversity of “abnormally high rainfall” 	MCH chart translated into Grasshopper. A planting plan spatially visualizing response diversity monthly 	More detailed visualization of spatial response diversity over time.	Increased detail can be difficult to process.
Structural Diversity “Describes the spatial complexity offered by plant form and is generally applied to a collection of plants, rather than an individual.”	Typical plant width and height	Planting plan diagrammatic and rendered, Section in Summer and Winter. 	Planting plan that “grows” the plants over time 	More complete visualization of structural relationships over time.	Rough approximation of plant growth. More detailed growth knowledge needs to be incorporated

Table 5-4 - Visual Comparison of MaryCarol Hunter and the Grasshopper Resilient Design Strategy as Developed

Metric	Mary Carol Hunter Visualization	Grasshopper Visualization

Plasticity

"As plasticity increases, plant species can persist under a greater diversity of environmental conditions and are better able to manage environmental fluctuations"

Table 2. Plant list for Designs A and B with traits used for plasticity, functional redundancy, and response diversity; ID = identity in Figures 3 & 4.

Design	Design Plan ID	Common Name	Botanical Name	Hardiness	*Temp Plasticity	Soil Moisture	*Soil Moisture plasticity	Bloom Time
A+B	CB	Coral Bells	*Heuchera americana* 'Ring of Fire'	4–9	6	MD	2	Jn–Ag
A+B	GF	Gayfeather	*Liatris spicata* 'Alba'	3–8	6	MD	2	Jl–Ag
A+B	PC	Purple Coneflower	*Echinacea purpurea*	3–10	8	DMW	3	Jl–S
A+B	RJ	Grey Owl Red Juniper	*Juniperus virginiana* 'Grey Owl'	3–9	7	DM	2	Mr
A+B	SU	Gro-Low Fragrant Sumac	*Rhus aromatica* 'Gro Low'	3–9	7	MD	2	A–My
A+B	WO	White Oak	*Quercus alba*	3–9	7	DMW	3	My
B	BS	Black Eyed Susan	*Rudbeckia hirta* 'Indian Summer'	3–7	5	MD	2	Jn–S
B	BW	Butterfly Weed	*Asclepias tuberosa*	3–9	7	DM	2	Jn–Ag
B	IB	Indian Blanket	*Gaillardia aristata*	3–10	8	DM	2	Jl–S
B	IBB	Indian Blanket-Bijou	*Gaillardia aristata* 'Bijou'	3–8	6	DM	2	Jl–S
B	MG	Pink Muhly Grass	*Sporobolus capillaris / Muhlenbergia capillaris*	5–9	5	DMW	3	Jl–S
B	SA	Stokes Aster	*Stokesia laevis* 'Blue Danube'	5–9	5	MD	2	Jn–S
B	SG	Switchgrass	*Panicum virgatum* 'Shenandoah'	3–9	7	DMW	3	Ag–S
B	TC	Threadleaf coreopsis	*Coreopsis verticillata* 'Moonbeam'	3–9	7	MD	2	Jn–S
B	WC	White Coneflower	*Echinacea purpurea*	3–10	8	DMW	3	Jl–S

Table 2. Plant list for Designs A and B with traits used for plasticity, functional redundancy, and response diversity; ID = identity in Figures 3 & 4.

Functional Redundancy

"The number of species contributing to an ecosystem function"

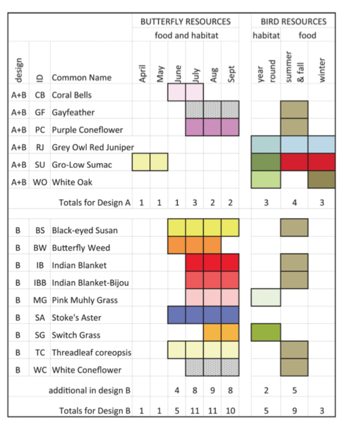
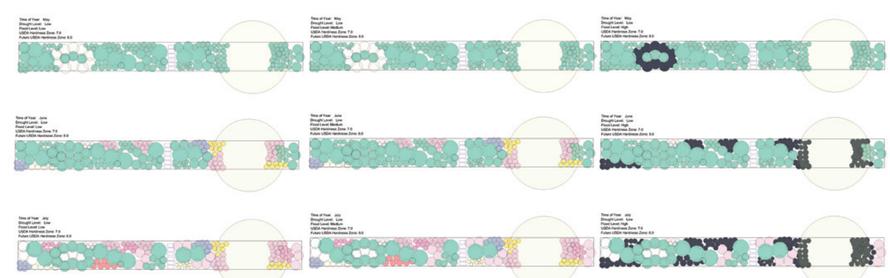
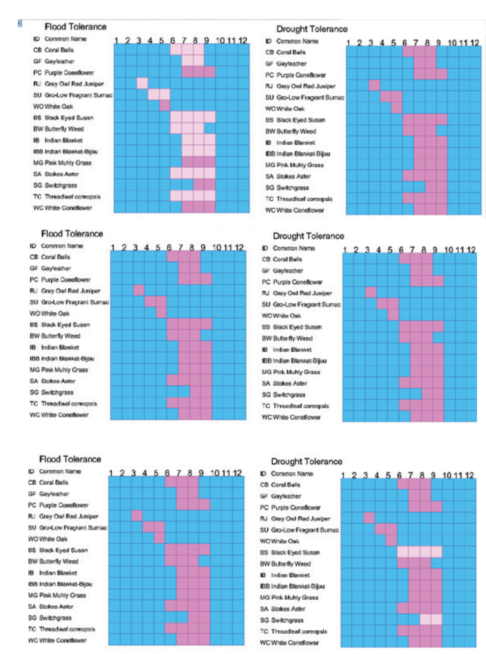


Figure 5. Seasonal resource and aesthetic presence chart for species in Designs A and B. Bloom time and flower color are shown for butterfly resources; flower and fruit/seed color and availability are shown for bird resources. Totals indicate the number of species/varieties contributing to functional redundancy in resource provisioning by month (pollinators) or season (birds).





Response Diversity

"The range of reaction to environmental change among species contributing to the same ecosystem function"

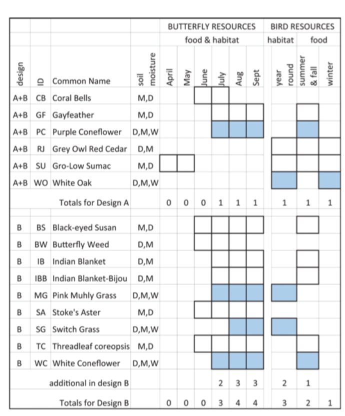
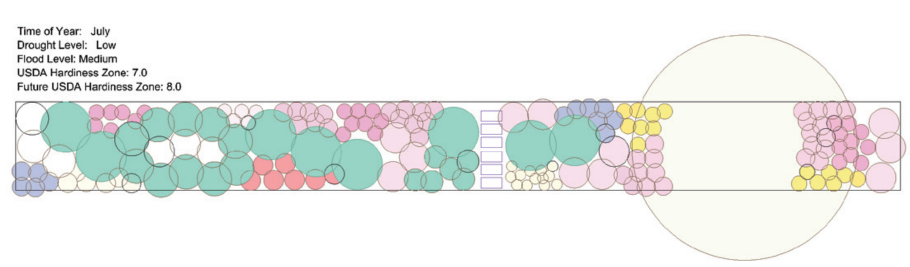


Figure 6. Evaluation of response diversity in Designs A and B for year(s) of abnormally high rainfall. Shaded squares indicate the species able to provide ecosystem services owing to their ability to sustain themselves through extended periods with wet soil. Empty boxes indicate lost ecosystem function for species that cannot function when soils remain wet. Soil moisture capacity for D=dry, M=moist, W=wet soils.

Structural Diversity

"Describes the spatial complexity offered by plant form and is generally applied to a collection of plants, rather than an individual."



Enhanced Parameterized Ideas

Based on the experience of modeling MaryCarol Hunter's resilient design strategy with parametric tools, it is possible to describe avenues of future parametric modeling. Parametric tools can enhance the ability to test and visualize adaptive designs by allowing alternative plant selection methods, simulating growth over time, alternative outcomes based on different climactic assumptions, identify thresholds, incorporate alternative data such as topography, recommend watering strategies, as well creating a reusable framework for alternative locations.

Sentient Planting List

One of the ways Grasshopper can enhance Hunter's strategy is to link plants that have known symbiotic properties. When particular species are selected by the designer Grasshopper can generate complimentary species based on desired traits. In this way plants could be selected as part of an ecosystem rather than simply based on the whims of the designer or their maximum USDA plant hardiness zone. An analogy to the ability of Grasshopper to generate complimentary plant species could be the way that online merchants can recommend new purchases based on previous purchases. The difference is that the designer would be in control of the types of suggestions that the computer generated.

Individual Plant Growth

While the element of climate change was central to the planting design, there was no estimate of how the growth of plants would be impacted by changing climate. Parametric tools begin to allow designers to explore this complex relationship.

The key elements to understanding the growth of plants over time are based on plant specific properties and the climactic data. The accuracy of the simulation of plant growth is entirely dependent on how much is known about the plant and the predictability of climate. Fortunately it can be relatively easy to access very specific plant data. The free computational search engine Wolfram Alpha contains growth rates of tree species, like the White Oak used in MaryCarol Hunter's planting strategy. The data is from the US forest service and contains data from over fourteen thousand White Oaks. The graph cleanly separates into an optimal growth rate and an average growth rate. The curve of the growth rate of the white oak can be input into the parametric model as can the initial height, spread, and geographic location in the design. From this collection of data the size and shadow of the tree can be estimated over time. The shadow information of the tree can be passed along to the surrounding plants to get a fairly accurate understanding of precisely how much light there will be.

A good designer will know that the white oak is going to grow and cast a shadow on neighboring plants, and for a simple design incorporating a single tree the exercise is more to show the detail with which we can simulate tree growth rather than any surprising outcomes. Still, it is possible for the designer to now visualize the spread of the tree as well as the shadow it casts over time.

Shadow Impacts on Growth

The shadow that is cast by the tree can be used to update Hunter's light plasticity measurement. Any plant that falls within the shadow of the Oak should have a higher shade plasticity. There is no mention of the self referential impacts of the design on itself in Hunter's paper. In other words there is a bit of circular logic in the growth of the planting strategy. The planting strategy's growth rate is continually impacted by itself as well as outside conditions. This is an example of some of the complex dynamics that parametric modeling can start to turn from a designers mental model into a visual dynamic model.

The growth rate of the white oak could also be increased or decreased by climactic variables. In this way various potential outcomes of climate change could be simulated and their impact on the growth of the white oak and subsequent shade could be explored visually and quickly by the designer.

Long Term Monitoring

While abundant data on the growth characteristics of certain plants can help to predict plant growth, predicting accurate long term climate change is close to impossible. Climate models begin to show trends, but they fail to provide accuracy. The inability to accurately predict long term climate can be overcome by Grasshopper in a number of ways. Parametric models can be updated with more accurate temperature readings as time goes on. This information could be used by managers to understand and make decisions on how the existing strategies were likely to develop.

This information could be particularly useful in decision making during a time of drought. Decisions based on different plants stress levels could be used to determine water allocation. Depending on the scale of the system, water allocation could even be tailored to specific planting areas and based on soil moisture sensors and local weather data. In this way watering systems could automatically turn on or off based on weather conditions. While not practical for a city scale, this type of control is possible on smaller scales and is well within the realm of Grasshopper.

Incorporation of Site Specific Data

Not only can the growth characteristics of plants be captured by parametric tools but other characteristics can also be combined. While it is typical for a designer to select plants from a spread sheet, which is the same way that a parametric tool selects plants, plants can be chosen based on the combination of all the interacting pieces of data that exist for a single location. This includes local climate, topography, soil, etc. Plants with similar or compatible traits can be linked together based on growth, nutrient needs, or color combination and bloom time. These are all traits that a good planting designer will internalize, that parametric modeling makes visual and explicit.

There are a few advantages to taking the complex calculations out of the designers head and making them visual. First is that even skilled practitioners make mistakes. It has been shown that doctors that follow an explicit check list do a better job of practicing medicine. Parametric tools can act as a checklist to help ensure that designers have not overlooked any important planting relationships. The potential drawback to this is that it is possible that designers will never internalize the rules of good planting design and will lack intuition in design.

Parametric tools should never supplant careful observation. Real world experience and observation is how designers develop intuition about how plants interact. Parametric tools are only approximations of reality, they are not a substitute for the real world.

Ideally there is a feedback loop of testing ideas with parametric tools and using observation to confirm or disprove the idea which can then be used to improve the tool.

Scale Shift

Hunter's planting strategy is intended to be replicated many times over in the sidewalk medians of Michigan. Parametric tools can be used to apply the planting strategy to an entire city, while also incorporating site specific information to vary the planting strategy. From this replication of the planting strategy, patterns will start to emerge which will reflect the impacts of the planting strategy. Tolerances to the individual planting strategies can be adjusted and the outcomes re-assessed at the city scale. Hunter mentions in her discussion the potential for a loss of bio-diversity if plasticity metrics are too broad. Parametric tools would allow for the plasticity measures to be adjusted on the scale of the city in order to observe the impact on overall biodiversity.

Spatial Contagion

So far all of these enhancements have ignored social systems. Hunter has recently expanded her research of planting medians to incorporate human systems. The brief summation of her work is that when a neighbor creates a garden in one of the medians, it is likely to encourage another person within a certain distance to also plant in the median. Looking back to Emergence, Hunter has uncovered a simple rule which she describes as "spatial contagion". Hunter has developed the spatial contagion rule based on observations on where garden medians appear throughout a city (M. C. R. Hunter &

Brown, 2012). Parametric tools can use these same rules to explore how encouraging neighborhoods to plant in the medians could start to have a larger effect on the entire city.

General Benefits and Limitations of Parametric Modeling

The relationships that can be created with parametric tools are limited by our imagination, the ability to collect data on meaningful relationships, and the ability to distill those relationships into the parametric tool. Of these three limitations, distilling the relationships into a parametric tool is most likely the biggest challenge for landscape architects. The challenge is thinking like a computer. Even with tools like Grasshopper, which are sometimes described as computer programming with training wheels, the shift in thought process may be too great a challenge. Meanwhile, landscape architects like MaryCarol Hunter, are quite comfortable with parametric thought even if they are unfamiliar with the software. The strangeness of parametric thinking is likely due to a lack of computational thinking in the typical landscape architects educational development. As computational thinking starts to become a fundamental part of a students early curriculum, the ability to use parametric tools will seem less like a foreign language and more like a second language (Barr, Harrison, & Conery, 2011).

Discussing some of the specific difficulties of translating MaryCarol Hunter's strategy into Grasshopper can help to clarify the meaning of, "computational thinking" or "thinking like a computer".

One of the difficulties of parametric modeling is determining the best form of the data. It can be difficult to determine whether to use textual or numeric data. Hunter turns the semi qualitative data of bloom period, "April, May, June" into a quantitative and abstract number, 3. The same is true for the use of calculations in spreadsheets. Parametric tools use the same techniques that are needed for spread sheets but extend the use of the spreadsheet into a more visual and dynamic design tool.

Even though computational thought can be foreign, it can also help to illuminate potentials areas of growth. The way that Hunter quantified some of her data raises key points in how our understanding of planting design could be improved. Hunter uses three sub categories of soil moisture: dry, moist, and wet. While these general terms are fine for a rough understanding of plant characteristics, they are relatively meaningless because there is no definitive boundary between dry and moist. Without criteria for measurement it can be difficult to understand the dynamics of a site. The quality that Hunter is attempting to measure is the likelihood that a plant will survive under, “increased amplitude of rainfall”. In this case a better piece of data to associate would be the amount and duration of rainfall that would kill a plant. The reason this would be better is because parametric tools allow designers to access local weather data. This means that not only can more accurate local predictions be made, but also that models can be calibrated to real time events, warning of potential impacts to planting designs.

Summary

Hunter’s planting strategy highlights how existing parametric thought can be translated and enhanced with parametric tools. The enhancements can go beyond simple improvements of speed or visualization by adding entirely new levels of information, analysis, and synthesis. There are a number of limitations to working with parametric tools, there are potentially substantial rewards as well.

CHAPTER 6 CONCLUSION

Parametric tools offer landscape architects new ways to synthesize data from many different disciplines. As more data becomes available about our built environment, the ability to manipulate and make sense of that data becomes ever more import. Parametric tools are unique in their ability to combine visual design interfaces with the power of computer scripting.

Parametric Tools

There are many different kinds of parametric tools available that range from simple tools with a very specific use, to much more complex tools that are open to the imagination of the designer.

The tool Grasshopper is of particular interest to landscape architects because it is affordable, has a highly visual user interface, is powerful, and has a robust user support base. There are similar programs available from Autodesk and Bently, but the learning curve on those two programs can be steep. As landscape architects become more familiar with scripting, it is possible competing programs will become more efficient.

Grasshopper, though described as a visual algorithm editor has been shown to be able to incorporate many different kinds of information into a single program. Grasshopper has the ability to work with many different programs such as environmental analysis tools, as well as simulate physics, communicate with digital sensors, and simulate fluids and other physical properties.

Landscape Systems

Simulating flows is one way to start to develop the process language that Kristina Hill argues landscape architects should be using. While systems have long been part of landscape architecture, parametric tools' ability to simulate systems as well as act as a bridge between disciplines offers the potential to greatly expand our understanding of how systems impact design as well as how designs impact systems.

Practitioners are using programs like Space Syntax to demonstrate the impact that formal spaces have on the systems of cities. Every design has an impact on it's surrounding systems, but often times, the true nature of that impact is not understood until after the design is completed. Even after the design is completed it is never revisited to ensure it is functioning properly. Without monitoring the finished constructions of our designs it will be impossible to understand how landscapes work within different systems.

Complexity Science

Complexity Science helps to highlight how parametric tools can act as a bridge between disciplines. Parametric tools provide landscape architects with a method of collaboration with other disciplines that are interested in landscape systems.

Emergence is the theory that the whole is larger than the sum of the parts. The theory is able to describe small scale systems such as ant colonies as well as the organization of cities. From Emergence landscape architects can start to understand how certain phenomena seem to appear from nothingness. There are a number of ways that Emergence has been explored with computer simulation. Parametric tools offer the ability to translate these models of emergent behavior and apply them to designs. While this may sound fanciful, mainstream stores such as Ikea have used these agent based models to understand how crowds will form in their stores.

Resilience is another sub theory of Complexity Science. Resilience is an ecological term that describes how much change a system can go through and maintain its identity. Landscape architects are interested in Resilience because of the implications it has for landscape systems.

Complexity Science and the sub sciences of Emergence and Resilience can help landscape architects think about the various systems occurring on a site. They can take that information and apply the theories of Complexity Science to their designs in order to simulate potential flows through a site.

MaryCarol Hunter

As both a landscape architect as well as a landscape ecologist MaryCarol Hunter has created a resilient planting strategy that is already parametric. Her resilient planting strategy is an example of ecological principles that can be applied to semi urban landscapes.

Using Grasshopper as a parametric tool to describe Hunter's work allowed for a wide range of enhancements to be made. While Parametric tools can be challenging to work with due to a general lack of computational thinking in landscape architecture, they also offer a potential expansion of understanding for landscape architects.

The Future of Landscape Architecture and Parametric Tools

One of the most promising benefits of parametric tools is the ability to combine the four main elements of sustainability, economics, environment, society, and culture into a single analysis tool. The flexibility of parametric tools allow designers to incorporate climactic data along side economic and social data. The challenge is not in having a tool that is powerful enough to combine the four legs of sustainability, rather there needs to be a deeper understanding of how the four legs of sustainability interact with each other. In order to fully utilize parametric tools more research is needed.

Further research is primarily needed in the understanding of the societal and cultural impacts of designs. While there is currently a well developed understanding of climatic as well as economic impacts of materials and spaces, there is less scientific data on how different design decisions impact individuals or the culture of a space. While urbanists like Jane Jacobs and William Whyte have laid the conceptual groundwork for how form impacts societal function, the data is not as robust as compared to the physical understanding of the movement of the sun. While the task of understanding societal change based on form may seem daunting, there have been efforts to collect such data, such as the earlier discussion of human movement by the researcher Michael Batty. The continued expansion of digital sensors capable of recording a wide range of data at once such as the iPhone have the potential to provide large amounts of data on how societies use and interact with space.

However, landscape architects are generally focussed more on application than on research. For example, there are relatively few PHD programs in landscape architecture.

It is unlikely that the research that is needed will come from landscape architects. Instead, landscape architects, being generalists, will need to have the ability to incorporate the latest thinking into parametric models.

There are many areas that are already highly researched where landscape architects could begin to develop models. Any area where there are well defined rules would be a good place to start. Example include zoning requirements, turning radii, American Disability Act requirements, grading and drainage, and dynamic stream equilibrium are a few possible starting points.

In order to be able to implement the existing data into parametric tools landscape architects will need to have the ability to think parametrically. In other words, the thought processes will involve very specific relationships. Computer science is a field of study that would likely help landscape architects develop the style of thinking needed to develop parametric models.

The computational power needed for parametric tools is already well developed, the ability to share knowledge is great, the need for synthesis of knowledge is even greater, and more landscape architects are going to have the ability to create meaningful parametric models. Parametric modeling may never replace a designers intuition, but it may play a key role in informing that intuition by helping landscape architects visualize complex landscape systems.

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APPENDIX

Emerging Landscapes

Using Ecological Theory to Guide Urban Planting Design:

An adaptation strategy for climate change

MaryCarol Hunter

ABSTRACT Global climate change threatens the structure and function of ecological communities in urban areas, including public and private gardens. An adaptation strategy was developed to accommodate the challenges of urban greenspace design under a changing climate. The strategy offers a protocol for planting design that focuses on adding resilience to plantings rather than matching specific plant species to specific predictions of climate change. The adaptation strategy begins by rating locally appropriate plant species on ecological criteria for plasticity, functional redundancy, response diversity, and structural diversity. The plant palette is then developed within the confines set by ecological value and aesthetic goals, plus cultural and financial considerations. Collective application of the strategy at smaller scales across the urban landscape has the potential to protect and expand nature corridors that are resilient to climate change and to provide a low cost version of assisted migration. Examples of how to apply the adaptation strategy demonstrate that the approach is not specific to place or scale, and does not require extensive training or bring added expense. The benefits and manageable challenges of the strategy are discussed in relation to biodiversity conservation, social impact, the opportunity for "designed" experiments that examine urban ecosystem processes, and existing model forecasts for climate change.

KEYWORDS climate change adaptation, urban garden design, biodiversity conservation, ecological resilience, translational research, habitat connectivity, ecological urbanism, urban green space, adaptive design, landscape architecture

Landscape Journal 30:2–11 ISSN 0277-2426

INTRODUCTION

Ecosystem-level consequences of climate change are now well documented. Measureable effects within cities include warmer average temperatures and greater extremes in temperature and precipitation, both of which contribute to changes in the timing of seasons (Hamlet et al. 2007; IPCC 2007). Beyond the urban environment, climate change has been associated with shifts in plant and animal phenology (Parmesan and Yohe 2003; Visser and Both 2005; Wilson et al. 2007) and in the geographic distribution of plants and animals (Iverson and Prasad 1998; Parmesan 2006; Walther et al. 2009). The realized impact is evident when comparing the geographic position of US plant cold hardiness zones in 1990 and 2006 (Figure 1). For example, minimum winter lows in southeastern Michigan have increased by 5.5°C changing its hardiness designation from Zone 5b to 6a over a 15-year period. This means that plants that could not persist any farther north than southern Ohio / northern Kentucky in 1990 can now manage the winter cold of southern Michigan. Beyond effects on individual species, differential responses to climate change among organisms can disrupt networks of community interactions such as predation and pollination, critical components of ecosystem health (Brooker et al. 2007; Gilman et al. 2010).

The capacity of ecosystems to deliver services defines their "health" from the perspective of human need (Rapport 1998). Healthy ecosystem function depends on interactions among species and their abiotic environment that may be compromised by the unpredictable impacts of climate change (Parmesan 2006). Consequently, there has been a call for the development of adaptation strategies to buffer ecosystems against uncertainty (Blanco et al. 2009; Pielke 1998). Adaptation in this sense refers to "adjustments in individual, group, and institutional behavior in order to reduce society's vulnerabilities to climate change, and thus reduce its impacts" (Pielke 1998, 159).

Increasingly, researchers and professional practitioners in urban planning and design are identifying and applying methods to better protect urban ecosystem services (Baschak and Brown 1995; Botequilha-Leitão and Ahern 2002; Colding 2007; Li et al. 2005; Lovell and Johnston 2009; Musacchio 2009; Tratalos et al. 2007; Zhang et al. 2007). Gardens and managed greenspace offer the chance to create urban habitats that provide and enhance urban ecosystem structure, function, and services. Planting design plays a significant role in stormwater management, biodiversity conservation, and human health (Horwitz, Lindsay, and O'Connor 2001). Planting design for green space at any scale, from front yards to city parks, supports human well being, reduces heat island effects, offers refuge for wildlife, and provides the spatial habitat linkage that is needed for the long term viability of plants, animals, and beneficial microbes (Pickett and Cadenasso 2008).

In urban environments, planting designers and horticulturalists have begun to realize that protocols for plant selection must be modified to accommodate global warming and increasingly unpredictable weather (Dehnen-Schmutz et al. 2010; Marris 2007; Primack and Miller-Rushing 2009; Wolfe et al. 2004). However, most adaptation strategies are focused on urban planning solutions for sea level rise, heat island effects, health impacts, and water treatment (Blanco et al. 2009). Guidance on adaptation of urban plant communities to global climate change remains limited. Most efforts have focused on methods to assist migration of tree species in forested landscapes (Aitken et al. 2008). For urban plant communities, Hunter (2008) proposed an adaptive strategy for managing aesthetic aspects of plant selection to safeguard sense of place within a changing ecological context. This paper builds on those ideas and offers methods and examples of an adaptive strategy to buffer urban plant communities from the impacts of climate change. The strategy focuses on planting designs for urban gardens, the dominant green infrastructure of cities, but can be extrapolated to programs for larger scale landscape restoration and assisted plant migration. The adaptive strategy translates aspects of ecological theory to practical guidelines for planting design. Because the guidelines promote greater biodiversity and ecosystem resilience, they also offer a general roadmap for ecological planting design.

ECOLOGICAL, AESTHETIC, AND CULTURAL COMPONENTS OF AN ADAPTIVE STRATEGY FOR URBAN PLANTING DESIGN

Two ecological concepts are fundamental to the adaptation strategy proposed here: plasticity and resilience. A third concept, structural diversity, is also a cornerstone of good ecological design, whether or not it is in response to climate change.

Plasticity

Plasticity describes how well species perform across a range of environmental conditions. Although beyond the scope of the current discussion, plasticity emerges from interactions between genetic variation within species and the phenotypic plasticity of individuals (Rossiter 1996, aka MCR Hunter). As plasticity increases, plant species can persist under a greater diversity of environmental conditions and are better able to manage environmental fluctuations (Charmantier et al. 2008; Chown et al. 2007). Plasticity is expressed on multiple axes including temperature, soil moisture, tolerance of urban pollution, flood and drought, etc. For example, both American mountain ash (*Sorbus americana*) and Pin Cherry (*Prunus pennsylvanica*) are small trees that are architecturally striking and offer beautiful colored berries that are a good food source for birds. However, American mountain ash has a geographic range that includes plant hardiness zones 2 through 9 while Pin Cherry has a much narrower and more northerly range, confined to hardiness zones 2 through 6. Mountain Ash is capable of thriving under a much wider range of climatic conditions including very warm and very cold winters. Hence, it has more overwinter temperature plasticity than does Pin Cherry. Plant hardiness zone is also a proxy for capacity to fare well under lengthened periods of warm weather given its correlation with latitude.

Ecological Resilience

Ecological resilience is the ability of an ecosystem to maintain function in the face of environmental disturbance (Elmqvist et al. 2003). Ecosystem resilience depends on the way that biodiversity is partitioned relative to ecosystem function and emerges both from functional redundancy—the number of species contributing to an ecosystem function (Lawton and Brown 1993) and response diversity—the range of reaction to environmental change among species contributing to the same ecosystem function (Elmqvist et al. 2003). The combination of functional redundancy and response diversity acts as an insurance policy in the face of uncertainty (Yachi and Loreau 1999) and both are essential when designing for adaptation to climate change.

For example, consider a planting design with goals that include support for generalist pollinators. It is not enough to simply select a set of plant species that offer nectar—the timing of nectar flow must provide resources throughout the pollinator season (Hunter and Hunter 2008). To achieve functional redundancy, the plant palette must include species with overlapping bloom times to ensure that there are multiple pollinator resources at any given time. For response diversity, plants providing pollinator resources must collectively bring broad competence in the face of environmental variation. For example, at a single point in the season, there must be both drought tolerant and flood tolerant plant species providing nectar rewards. The plant palette shown in Figure 2 provides multiple flowering species in each month of summer (functional redundancy for pollinator support). Within a functional group (for example, pollinator resources in July), there is competence for handling variation in soil moisture (response diversity). If climate change favors some plant species at the expense of others, there will still be nectar provided in each month throughout the pollinator season.

Structural Diversity

Structural diversity describes the spatial complexity offered by plant form and is generally applied to a collection of plants, rather than an individual. Diversity of physical or architectural form within a collection of plants produces structural diversity. Although structural diversity is not a direct casualty of climate change, it ranks high in importance for healthy ecosystem structure. The physical form of trees, shrubs, and groundcovers, some deciduous, some evergreen, determines the availability of shelter and space for organisms to nest, forage and reproduce throughout the year (Goddard, Dougill, and Benton 2010). As plants are chosen to increase plasticity, ensure functional redundancy, and provide response diversity, they must also provide diversity in architectural form because structural complexity supports biodiversity (Hansen et al. 1991).

In the design fields, there are considerations beyond ecological function that demand adaptation strategies for climate change. Chief among these, aesthetic matching of signature species aims to protect sense of place under circumstances of change (Hunter 2008). The urban plant community supports human well being in part owing to its role in the construction of place identity (Hull, Lam, and Vigo 1994). Some plant species become signatures of place such as palm trees in warm coastal areas or heather in the Scottish highlands. After identifying signature species, alternative species with broader ecological tolerance but similar aesthetic presence can be added to planting designs as an adaptation to climate change (Hunter 2008). For example, American Basswood is a native tree commonly found in urban areas of SE Michigan. This species is likely to disappear from southeastern Michigan under several scenarios of climate change (Iverson and Prasad 1998). Its loss will change the sense of place and remove its functional contribution to local urban ecosystem processes. An aesthetic and ecological substitute exists in White Basswood, a congeneric and more southerly member of the same Central Hardwood forest community. An adaptive planting design would call for use of both species to maintain sense of place and support local ecosystem function throughout the transition brought on by climate change.

Finally, any discussion of ecological design in the urban environment must consider the use of non-native species in planting designs, a subject of contention among designers and ecologists for practical and ecological reasons (Gould 1997; Warren 2007). Compelling arguments for the use of native species center on the reliance of co-evolved community members for healthy ecosystem function (Tallamy 2009). The bias favoring introduced ornamental species in garden design has a longstanding tradition in cultures worldwide and is related to place identity (for migrant peoples) and the human desire for novelty (Horwitz, Lindsay, and O'Connor 2001; Jarvis 1973; Kendle and Rose 2000). Non-native species that become invasive can have clear negative impacts on ecosystem structure and function (Alberti 2005). However, current research on the utility and harm of using non-native species in urban settings illustrates the complexity of prescribing a balance between cultural and ecological goals (Bergerot et al. 2010; Bjerknes et al. 2007; Burghardt, Tallamy, and Shriver 2009; Calkins 2005; Daniels and Kirkpatrick 2006;

Heneghan and Hunter 2004; McKinney 2006; Tallamy and Shropshire 2009), particularly in light of climate change (Bardsley and Edwards-Jones 2007; Hahs et al. 2009). An adaptation strategy for climate change using the ecological characteristics described above emphasizes the use of native plants, but allows incorporation of popular non-invasive, non-native ornamental species to achieve ecological goals and acknowledge socio-cultural sensibilities.

METHODS

Assembly of a Plant Database to Enable Adaptive Design

In brief, the adaptation strategy proposed here for the design of urban plantings that are resilient to climate change includes exploiting plasticity in the ecological traits of plants, in concert with structurally diverse design that exhibits functional redundancy and response diversity. Implementation requires a catalogue of horticultural and plasticity traits for commercially available plants that are appropriate for the region of interest. Cataloging species in this way provides a structurally diverse palette for choosing plants to meet ecological, aesthetic, cultural, and financial parameters of a project.

Coding species characteristics. To apply the adaptive strategy for planting design, I compiled a list of plants suitable for urban areas in southeastern Michigan. The majority of species were native to the region. Some locally popular non-native species that are not considered invasive (Brooklyn Botanic Garden 2006; USDA-NISC 2010) and were readily available from nurseries were included for reasons of practicality and cost. Coding for each species involved characterization of aesthetic features, life history, and ecological traits based on data corroborated across multiple sources (Table 1). Data came from reference books including Aniski (2008) for perennials, Dirr (1998) for woody plants, Shaw et al. (2007) for stormwater management plants, and Darke (2007) for ornamental grasses. The US Department of Agriculture's website (USDA-NRCS 2011) was especially useful for data on plant water requirements. Since adaptation strategies for climate change must be tailored to local characteristics (Blanco et al. 2009), the best information on phenology often came from local or regional sources (for example, Boland, Coit, and Hart 2002; Shaw et al. 2007) and the Missouri Botanical Garden (2011). When these sources failed, I drew a consensus from data published by multiple sources including commercial horticulture companies (for example, Monrovia 2011).

Coding plasticity characteristics. In addition to horticultural traits typically used by ecological plant designers, I added plasticity characteristics. The plasticity traits summarize the capacity of plant species to accommodate variation in temperature, light, soil type, soil moisture conditions, and bloom period (Table 1). Based on the number of hardiness zones a species can occupy, the temperature plasticity trait addresses the ability of a species to withstand a range of temperatures and seasonality. Values range from 1 to 8 where higher values indicate greater plasticity. The soil moisture plasticity trait is the sum of acceptable moisture categories (dry, moist, and wet) for a given species; values range from 1 to 3. Higher values indicate greater likelihood that a species will persist under increased amplitude of rainfall typical of climate change.

Several other plasticity traits were included in the database to reflect challenges faced in urban planting design, in addition to those of climate change. For each trait defined below, higher values indicate greater capacity for managing unpredictable variation in conditions of the urban landscape. Light plasticity is the sum of acceptable light conditions for a species (full sun = 6 or more hours of direct sunlight, partial shade = 2–6 hours, full shade = less than 2 hours); values range from 1 to 3. Light plasticity is valuable where climate change impacts cloud cover and in settings where maturing shade trees and development alter light availability. The number of major soil types (clay, loam, and sand) acceptable to a plant species defines soil plasticity; values range from 1 to 3. The relevance of soil plasticity comes

Table 1. List of plant traits for each species entry with efficient coding conventions; emergent plasticity traits are preceded by an asterisk.

Plant Type: 1 = tree, 2 = shrub, 3 = flowering herbaceous perennial, 4 = grass/rush/sedge, 5 = fern, 6 = vine, 7 = groundcover, 8 = annual
Botanical Name
Common Name
Persistence: 1 = deciduous, 2 = evergreen, 3 = facultative evergreen (= semi-evergreen)
Nativity: 0 = not native to US, 1 = US native, 2 = Great Lakes native
Hardiness: USDA (1990) overwintering hardiness zone range; e.g., 4–9 or 4b-9a
***Temperature Plasticity:** count number of overwintering hardiness zones
Light Type: F = full sun, PSh = partial shade, Sh = shade
***Light Plasticity:** count number of acceptable light types; range = 1–3, least to most plastic
Light preference: notes; e.g., greater blooms in full sun; avoid afternoon sun
Soil Type (if known, preferred condition first): C = clay, L = loam, S = sand, SL = sandy-loam, SCL = sandy-clay-loam
***Soils Plasticity:** count number of acceptable soil types; range = 1–3, least to most plastic
Soil pH: AC = acidic (<6.8); ALK = alkaline soil (>7.2); N = neutral (6.8–7.2); sl = slightly
Soil Moisture (if known, preferred condition first): D = dry, DM = dry to moist, MD = moist to dry, M = moist, MW = moist to wet, WM = wet to moist, W = wet, WMD = plant do well under all conditions
***Soil Moisture Plasticity:** count number of acceptable soil moisture conditions; range = 1–3, least to most plastic
Details on soil moisture needs: preferences, e.g., can handle standing water
Drought Tolerance: 0 = no drought tolerance; 4 = yes; and 1 = low tolerance; 2 = medium tolerance, 3 = high tolerance
Salt Tolerance: ST = salt tolerant; SS = salt sensitive; undocumented for many species
Heat Tolerance: HT = heat tolerant; HS = heat sensitive; undocumented for many species
Typical Height: height range (feet)
Typical Height in bloom: height range (feet)
Typical Width: width range at widest point (feet)
Plant Form: C = columnar, CL = clumped, E = erect, H = horizontal, I = irregular, M = mounded, O = oval, P = prostrate, Py = pyramidal, R = rounded, S = spreading
Plant Texture: F = fine, M = medium, C = coarse
Foliage Color: B = brown, BG = blue-green, Cr = cream, DG = dark green, G = bright green, Gr = Gray, GrG = Gray Green, MG = medium green, O = olive, P = purple, PG = pale green, R = red, Si = silver , V = variegated, Y = yellow, YG = yellow-green
Fall Color: B = brown, Cr = cream, DG = dull green, G = green, M = maroon, O = orange, OG = olive, P = purple, R = red, Sc = Scarlet, Y = yellow, YB = yellow-brown, YG = yellow-green
Bloom Time: Jn = January, F = February, Mr = March, A = April, My = May, Jn = June, Jl = July, Ag = August, S = September, O = October, N = November, D = December
***Bloom Time Plasticity:** count number of months when blooming occurs
Bloom Color: B = blue, Br = brown, Cr = Cream, i = inconspicuous, G = green, L = lavender, O = orange, p = pale, P = pink, Pr = purple, R = red, Ro = rose, S = silver, W = white, Y = yellow
Fruit/Edible Type: C = cone, B = berry, F = fruit, S = seed
Fruit/Edible Type Color: B = blue, Br = brown, Cr = Cream, G = green, L = lavender, O = orange, P = pink, Pr = purple, R = red, Ro = rose, S = silver, W = white, Y = yellow
Winter Form: A = architectural (e.g., interesting branching patterns), B = bark of interest, F = fruit thru winter, S = seed head
Wildlife Value: B = bee, Bd = bird, Bf = butterfly, D = deer, Ma = Mammal, Mi = mice, Sq = squirrel
Ecosystem Restorative Value: BT = bioremediation ability, EC = erosion control, NF = nitrogen fixer
Human Health Restorative Value: F = food, HM = herbal medicine, give details

from the reality that soil type is often unknown or the planting beds are amended with commercial garden soil mixes that be may unable to ameliorate poor drainage or mitigate adverse effects of deeper soil layers. Consequently, a high value for soil plasticity indicates greater likelihood that a plant species will accommodate urban soil. Bloom period plasticity is the sum of months during which a species can produce flowers; values range from 1 to 5. Bloom period is a plasticity trait because it describes the plant's opportunity for outcrossing (nonselfing reproduction) and its capacity to accommodate unpredictable timing of pollinators and other fauna that use its floral resources.

Development of Two Case Demonstrations of Urban Planting Designs Illustrating Use of Climate Change Adaptation Strategy

Two urban planting design case demonstrations illustrate use of the database (see Hunter 2009) in developing climate change adaptation strategies. The two case

demonstrations illustrate the consideration of ecological goals within the context of other cultural and aesthetic design goals. Not every design can include all components of the adaptation strategy but even limited application is a good starting point and valuable in the context of a collective effort across neighborhoods and cities.

The demonstrations described here involve a type of space familiar to residents of American cities—the easement area, the strip of land in front of a house, bordered by the street on one side and the sidewalk on the other. In addition to the adaptive ecological strategy, there are additional design criteria typically established by the client, local government, and designer. In the following example, developed for southeastern Michigan, the accompanying criteria fall into several groups:

1. Aesthetic: generate a landscape form that is visually engaging year round.
2. Cultural: select species for low-input management that do not occupy space between about 1 and 2 m from the ground to ensure a safety vision zone for motorists.
3. Ecological: select species that are drought and salt tolerant to accommodate lack of irrigation and winter road salting practices, and that offer food and shelter for butterflies and birds.

Selected species must also meet soil type and soil pH conditions. Over the short term, it is unlikely that soil pH would experience rapid shift from climate change (see Brinkman and Sombroek 1996).

Presented below are two designs, which both address all design criteria. Design A (Figure 3) includes six plant species, is easier to install and maintain but does not implement adaptation strategies and biodiversity goals as fully as Design B (Figure 4). Design B includes 15 plant species—six from Design A plus nine new ones (Table 2; complete trait data for these species in supplemental Table S1). A comparison of aesthetic presence and the spatial location of resources also illustrated for summer (Figure S1) and winter (Figure S2).

RESULTS

The following discussions evaluate the two case demonstrations using the criteria of temperature plasticity, functional redundancy, response diversity, and structural diversity.

Temperature Plasticity

Plants chosen for both designs exhibit high temperature plasticity with overwintering hardiness spanning a minimum of 5 zones and an average of 6.7 zones. For all species but one, the most southerly acceptable growing area is Florida—zones 9 to 10 (Table 2). Use of plants with this type of plasticity serves as an adaptation strategy for climate change because each species can persist under temperatures typical of the recent past and under the warmer temperatures predicted in Michigan under climate change.

Functional Redundancy

In both designs, biodiversity is supported by the simultaneous flowering of multiple plant species that provide butterfly resources (nectar, pollen, and habitat) throughout the summer (Figure 5). For Design A, the period of functional redundancy lasts from July (three species flower in unison) through August (three species) and September (three species). By contrast, Design B expresses greater functional redundancy beginning in June (four species flower in unison) followed by July (eight species), August (nine species), and September (eight species). Greater functional redundancy for bird resources exists in Design B compared to Design A, based on availability of food and year round habitat from multiple sources (see "totals" for each design in Figure 5).

Response Diversity

The occurrence of abnormally high rainfall over several consecutive years is a likely outcome of climate change, and it serves to illustrate the capacity of response diversity to protect ecosystem function under a typical outcome of climate change. Design B is better equipped to

Table 2. Plant list for Designs A and B with traits used for plasticity, functional redundancy, and response diversity; ID = identity in Figures 3 & 4.

Design	Design Plan ID	Common Name	Botanical Name	Hardiness	*Temp Plasticity	Soil Moisture	*Soil Moisture plasticity	Bloom Time
A+B	CB	Coral Bells	*Heuchera americana* 'Ring of Fire'	4–9	6	MD	2	Jn–Ag
A+B	GF	Gayfeather	*Liatris spicata* 'Alba'	3–8	6	MD	2	Jl–Ag
A+B	PC	Purple Coneflower	*Echinacea purpurea*	3–10	8	DMW	3	Jl–S
A+B	RJ	Grey Owl Red Juniper	*Juniperus virginiana* 'Grey Owl'	3–9	7	DM	2	Mr
A+B	SU	Gro-Low Fragrant Sumac	*Rhus aromatica* 'Gro Low'	3–9	7	MD	2	A–My
A+B	WO	White Oak	*Quercus alba*	3–9	7	DMW	3	My
B	BS	Black Eyed Susan	*Rudbeckia hirta* 'Indian Summer'	3–7	5	MD	2	Jn–S
B	BW	Butterfly Weed	*Asclepias tuberosa*	3–9	7	DM	2	Jn–Ag
B	IB	Indian Blanket	*Gaillardia aristata*	3–10	8	DM	2	Jl–S
B	IBB	Indian Blanket-Bijou	*Gaillardia aristata* 'Bijou'	3–8	6	DM	2	Jl–S
B	MG	Pink Muhly Grass	*Sporobolus capillaris / Muhlenbergia capillaris*	5–9	5	DMW	3	Jl–S
B	SA	Stokes Aster	*Stokesia laevis* 'Blue Danube'	5–9	5	MD	2	Jn–S
B	SG	Switchgrass	*Panicum virgatum* 'Shenandoah'	3–9	7	DMW	3	Ag–S
B	TC	Threadleaf coreopsis	*Coreopsis verticillata* 'Moonbeam'	3–9	7	MD	2	Jn–S
B	WC	White Coneflower	*Echinacea purpurea*	3–10	8	DMW	3	Jl–S

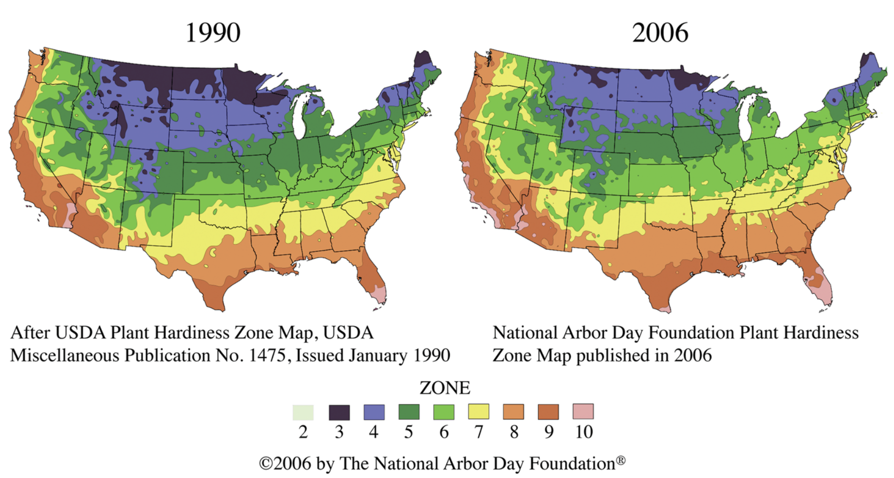

Figure 1. Shift in plant cold-hardiness zones between 1990 and 2006. Color coding relates minimum winter temperatures in increments of 12.2°C where minimum winter temperature for Zone 5 = −23.4°C to −26.1°C and Zone 9 = −1.2°C to −3.8°C. (Reprinted from National Arbor Day Foundation 2006; updating based on data from 5,000 National Climatic Data Center cooperative stations across the continental United States)

provide pollinator and bird resources despite wet conditions (see "totals" for each design in Figure 6). However, neither design will reliably provide resources for pollinators from April through June. The iterative design process would proceed to add at least one pollinator resource species that flowers in each of these early months, is able to grow in wet soils, and fulfills other criteria for height, drought, and salt tolerance. For example, Showy Evening Primrose (*Oenothera speciosa*) fulfills these criteria during June. A general rule of thumb for providing response diversity is to choose species at the outset with the greatest soil moisture plasticity.

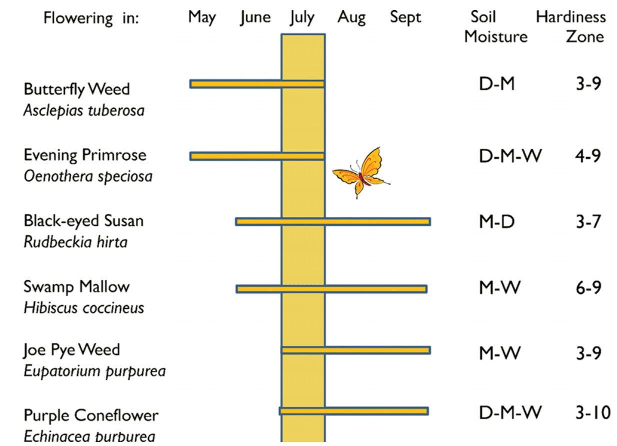

Figure 2. Graphical representations of functional redundancy and response diversity for pollinator resources throughout the growing season with greatest insurance of nectar in July. Bars indicate blooming period. Moisture requirements range from D=dry, to M=moist to W=wet soils.

Structural Diversity

Both designs fulfill criteria for structural diversity by including the architectural form and collective complexity of a tree, several shrubs, and herbaceous perennials. The spatial complexity persists year round for both designs, although Design B offers greater structural diversity in winter with five species compared to Design A with three species. In summer, Design B has more structural diversity owing to a greater range of architectural form provided by seven additional flowering perennial species. Because all species fulfill criteria for temperature plasticity, the reliability of each architectural contribution to habitat complexity is greater.

DISCUSSION

Implementation of an adaptation strategy that focuses on flexibility rather than accommodation of a specific predicted outcome of climate change is more likely to be successful (Hallegatte 2009). The adaptive strategy for climate change presented here provides an approach to planting design for building resilience of urban ecosystems in the face of climate change and other disturbance, whether natural or anthropogenic. The strategy emphasizes the creation of planting designs that provide functional redundancy, response diversity, and structural diversity. It also emphasizes the inclusion of plant species that exhibit plasticity, particularly in response to temperature and rainfall variation. The ecological framework for planting design can be applied equally well to new development or to "adaptive" retrofits of existing gardens. The adaptation strategy can be used at many scales—from larger scale projects such as planting plans for a regional park system or a citywide pollinator support program, to smaller scale designs for subdivisions, urban pocket parks, and small residential gardens.

Benefits and Challenges of the Proposed Strategy

Application of this strategy brings distinct benefits and some manageable challenges described below:

Ecosystem health. Resilience in, or restoration of, even one ecosystem service, like pollinator habitat, can have multiplicative effects on ecosystem health owing to the high degree of dependencies among ecosystem members. The adaptation strategy for climate change serves equally well as a prescription for ecological restoration because it supports diversity and buffers urban ecosystems from the effects of disturbance. Creating many small gardens provides the benefit of enhancing biodiversity and ecosystem function citywide or regionally (Goddard, Dougill, and Benton 2010; Kendal, Williams, and Williams 2010). With application of the adaptation strategy to a collective of small spaces, there is potential to safeguard and enhance a network of urban linked green space. Greening of cities creates links across otherwise impermeable barriers to plant and animal dispersal, thereby supporting both local and regional environmental health (Angold et al. 2006; Arendt 2004; Hunter and Hunter 2008; Oprea et al. 2009; Snep et al. 2006; Van Rossum and Triest 2010).

Collective application of the adaptation strategy to many small gardens across a metropolis also has the capacity to provide a low cost version of assisted migration. Assisted migration involves the manual relocation of species by humans to portions of their expected, expanded geographic range as predicted by climate change models. The intervention is valuable because natural dispersal may not occur with sufficient speed or frequency to keep organisms in suitable habitat. Arguments against assisted migration, based on interference with natural plant communities (McLachlan, Hellmann,

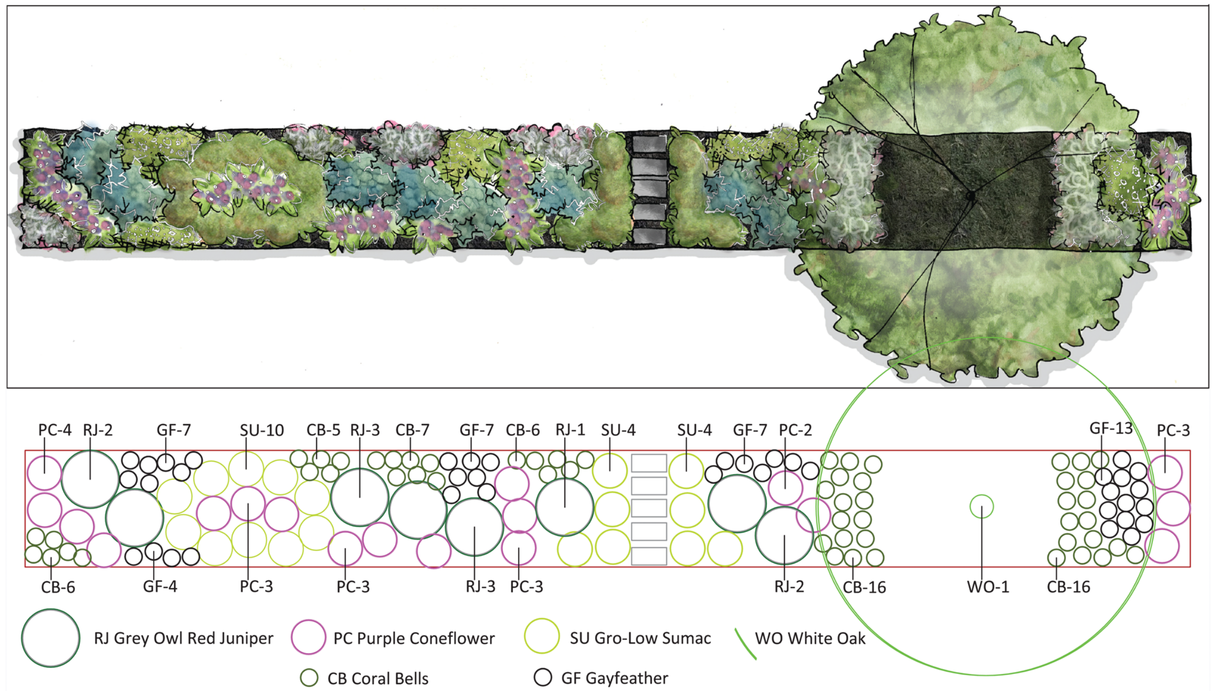

Figure 3. Design A for support of birds and butterflies using 5 plant species. The illustrative plan view conveys the aesthetic intent and the diagrammatic plan view gives species identity (key to abbreviations in Table 2) and the number of individuals that occupy each delineated space. The planting strip is approximately 30 m × 3 m.

and Schwartz 2007), may not be as relevant in urban settings where ecosystem processes are already modified. For example, horticultural introduction of species that can sustain urban conditions typically bypasses or enhances their natural dispersal capacity. Horticultural plantings in urban areas have already assisted plant migration to more northerly reaches (Van der Veken et al. 2008; Woodall et al. 2010). Therefore, urban areas may be suitable locations to assess the value of assisted migration using the adaptation strategy for planting design. Implementation would require help from the horticulture industry (Dehnen-Schmutz et al. 2010) and cooperation from local nursery suppliers.

Biodiversity constraints. The extensive use of highly plastic species can inadvertently result in lower biodiversity in several ways. First, as requirements for plasticity on multiple traits increases, the list of potential plant species drops. Second, as the use of highly plastic species increases, there is a drop in the number of species available to maintain ecosystem function across a wide range of environmental variation. Consequently, biodiversity is best served by choosing plant species for a given ecosystem function that include a mixture of highly plastic species and those that contribute to response diversity by differing in their capacities to withstand climate extremes. Program goals of a design project can also result in lower biodiversity. For example, site conditions required that all plants for Designs A and B are drought and salt tolerant. This caused a significant reduction in the list of potential plant species to meet ecological and aesthetic goals. Competing demands call for pragmatism, greater creativity to meet aesthetic goals, and ongoing expansion of the plant database.

Aesthetic consideration. It is important to keep aesthetic goals in sharp focus if an ecological planting design is to be culturally accepted and supported (in other words, sustainable) over the long term (Hunter 2006; Nassauer 1995; Parsons and Daniel 2002). The adaptive strategy presented here allows aesthetic and ecological considerations to remain on equal footing. The approach does not require a modification of the creative design process, leaving a designer free to create spatial form, color and texture palettes, and a temporal sequence of sensory experience. However, the designer must be willing to put more consideration into the choice of plant species in order to fulfill ecological criteria.

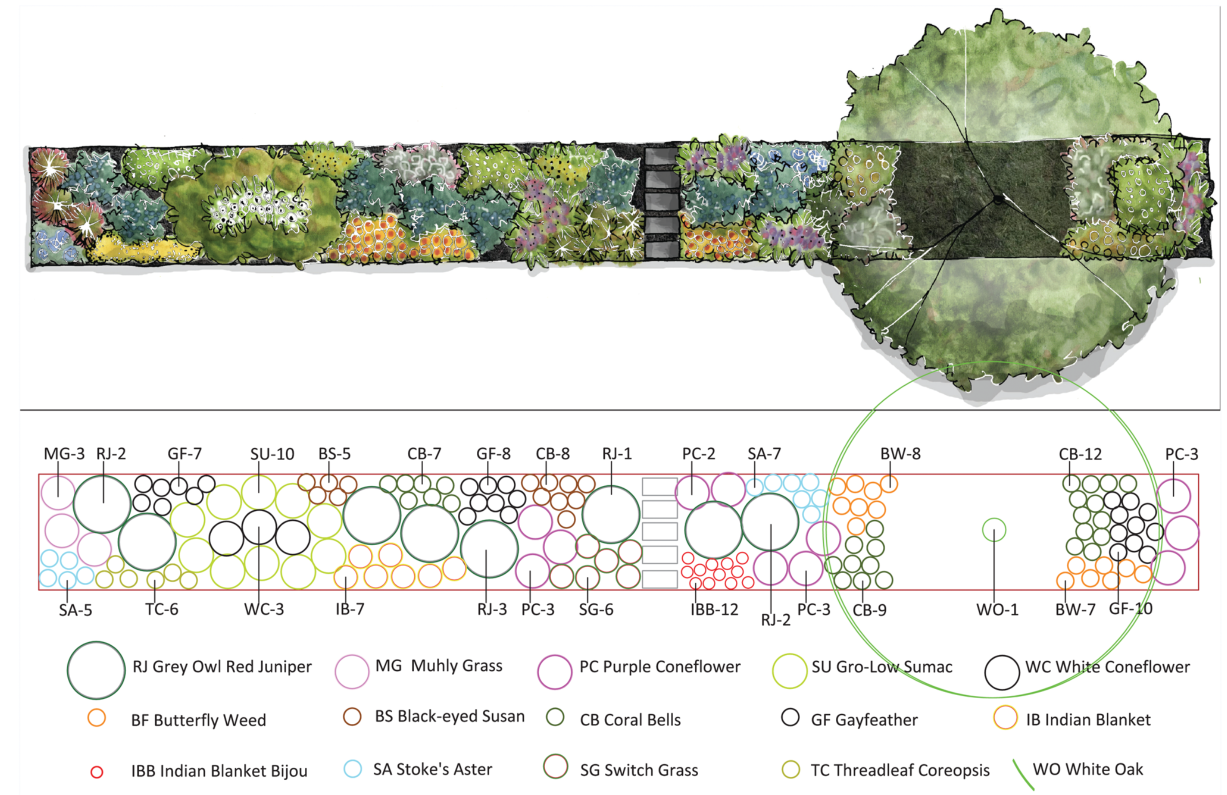

Figure 4. Design B for support of birds and butterflies using 15 plant species including 2 cultivars of same species. The illustrative plan view conveys the aesthetic intent and the diagrammatic plan view gives species identity (key to abbreviations in Table 2) and the number of individuals that occupy each delineated space. The planting strip is approximately 30 m × 3 m.

Long term management. Unlike buildings, plants grow. Consequently, a planting design should include a management plan to guide future form and function (Koningen 2004). The potential of climate change to adjust plant performance makes the provision of management more critical. Written documentation should include directives on how to replace a plant species that does poorly, how to control a plant that begins to outcompete companion species, and how to add new plant species as the needs of other ecosystem members (for example, pollinators, people) become known.

Research Collaboration between Designers and Ecologists

The work presented here is an example of translational research, wherein solutions for complex environmental problems come from connecting scientific theory, concepts, and principles to the design and planning of the built environment (Musacchio 2008; Hunter and Hunter 2008). The adaptation strategy for planting design under climate change offers a foundation for collaborative work with ecologists to expand our understanding of urban ecosystem processes and performance. Implementation of the strategy will produce experimental plots in the form of garden spaces to test hypotheses about urban landscape ecological processes at multiple spatial scales. Collaboration between designers and ecologists would constitute an example of "designed experiments" (Felson and Pickett 2005), wherein designers create a product that balances ecological, aesthetic, and urban functional goals and is amenable to criteria for hypothesis testing as set forth by scientists. "Designed experiments" aim to balance realistic complexity with experimental control. This is an ideal approach for evaluating the ability of the adaptation strategy presented here to support resilience of ecosystems impacted by climate change. Post-occupancy evaluation, a method used by designers and permitting agencies to evaluate the success of installed designs, could be used to evaluate the effectiveness of implementing the climate change adapted planting design strategy. Collection of scientific data will enable evaluation of hypotheses about the success of the adaptation strategy relative to ecological and management

			BUTTERFLY RESOURCES						BIRD RESOURCES		
			food and habitat						habitat	food	
design	ID	Common Name	April	May	June	July	Aug	Sept	year round	summer & fall	winter
A+B	CB	Coral Bells									
A+B	GF	Gayfeather									
A+B	PC	Purple Coneflower									
A+B	RJ	Grey Owl Red Juniper									
A+B	SU	Gro-Low Sumac									
A+B	WO	White Oak									
		Totals for Design A	1	1	1	3	2	2	3	4	3
B	BS	Black-eyed Susan									
B	BW	Butterfly Weed									
B	IB	Indian Blanket									
B	IBB	Indian Blanket-Bijou									
B	MG	Pink Muhly Grass									
B	SA	Stoke's Aster									
B	SG	Switch Grass									
B	TC	Threadleaf coreopsis									
B	WC	White Coneflower									
		additional in design B			4	8	9	8	2	5	
		Totals for Design B	1	1	5	11	11	10	5	9	3

Figure 5. Seasonal resource and aesthetic presence chart for species in Designs A and B. Bloom time and flower color are shown for butterfly resources; flower and fruit/seed color and availability are shown for bird resources. Totals indicate the number of species/varieties contributing to functional redundancy in resource provisioning by month (pollinators) or season (birds).

goals, the success of biodiversity enhancement in support of ecosystem functions (like pollination), the capacity of small linked gardens to serve as vital corridors for the natural community, etc. Collaborative effort will reduce the burden of data collection. Adaptive collaborative landscape management (Duff et al. 2009) and citizen science (Bonney et al. 2009) offer approaches for engaging other user groups and the public at large in scientific data collection.

Prescribing Adaptation Strategies for Uncertain Climate Projections

Models that predict the impact of climate change on global weather patterns provide an enormously useful premise for mitigation and adaptation planning (Kling et al. 2005; Wilby et al. 2009). However, predictions from these models exhibit greater uncertainty as variables related to soil moisture, such as precipitation, cloud cover, and wind are included (Crimmins et al. 2011; Troccoli 2010) and as the geographic scale for prediction becomes finer (Praskievicz and Chang 2009).

One approach for understanding the nature of future climates at finer geographic scales (like a state or city) is to find a climate analog, a present day geographic location whose weather matches that of the projected weather patterns in the place of interest. For example, climate projections were used to identify climate analogs for the states of Michigan and Illinois (Hayhoe et al. 2010). The results show that under a low greenhouse gas emissions scenario, weather in southeastern Michigan will be like that of present-day southern Ohio in the near future (2010 to 2039), like that of West Virginia by

				BUTTERFLY RESOURCES						BIRD RESOURCES		
				food & habitat						habitat	food	
design	ID	Common Name	soil moisture	April	May	June	July	Aug	Sept	year round	summer & fall	winter
A+B	CB	Coral Bells	M,D									
A+B	GF	Gayfeather	M,D									
A+B	PC	Purple Coneflower	D,M,W									
A+B	RJ	Grey Owl Red Cedar	D,M									
A+B	SU	Gro-Low Sumac	M,D									
A+B	WO	White Oak	D,M,W									
		Totals for Design A		0	0	0	1	1	1	1	1	1
B	BS	Black-eyed Susan	M,D									
B	BW	Butterfly Weed	D,M									
B	IB	Indian Blanket	D,M									
B	IBB	Indian Blanket-Bijou	D,M									
B	MG	Pink Muhly Grass	D,M,W									
B	SA	Stoke's Aster	M,D									
B	SG	Switch Grass	D,M,W									
B	TC	Threadleaf coreopsis	M,D									
B	WC	White Coneflower	D,M,W									
		additional in design B					2	3	3	2	1	
		Totals for Design B		0	0	0	3	4	4	3	2	1

Figure 6. Evaluation of response diversity in Designs A and B for year(s) of abnormally high rainfall. Shaded squares indicate the species able to provide ecosystem services owing to their ability to sustain themselves through extended periods with wet soil. Empty boxes indicate lost ecosystem function for species that cannot function when soils remain wet. Soil moisture capacity for D=dry, M=moist, W=wet soils.

mid-century, and like that of Tennessee by the end of the century. Under a high emissions scenario, the climate analogs are even further south and west. These predictions provide additional criteria for creating adaptive plant palettes. For example, a climate adaptation plant list for southeastern Michigan could include native species that are currently successful in urban areas of southern Ohio.

This approach to adaptation while promising has several limitations. First, the application of model predictions can be used only where downscaled climate projections are available. Second, the simulation models, even with downscaling, are insensitive to the impact of topography and land cover on microclimate at any given location (Praskievicz and Chang 2009). Since skillful planting designers always account for microclimate during plant choice, it is conceivable that designers will be able to customize plant lists based on projected climate scenarios and knowledge of current microclimatic relationships with the land. Third, as forecasting models are improved and predictions modified, the constitution of the protective plant palette must be reevaluated. While the reliability and local specificity of forecasting models improve, planting designers and city planners need immediate guidance in how to plan for ecosystem resilience in the face of uncertainty about the local impact of climate change. For these reasons, it is efficient to use plant overwinter hardiness as the starting point for selecting an adaptive plant palette. Hardiness data is universally available and easy to interpret by both expert and layman.

Despite the perils of using climate predictions to develop adaptation strategies, countries and communities are developing place-specific strategies. For

Figure S1. Summer comparison of aesthetic presence and spatial location of butterfly and bird resources between Design A (above) and Design B (below).

example, policy makers and citizens from the City of Chicago developed an elegant climate change action plan based on feasibility and cost/benefit ratio over the short and long term (Coffee et al. 2010). At least a half dozen of the adaptation actions require careful choice of plant species if they are to be successful. These include city tree planting, development of a performance-based landscape ordinance and a single-lot storm ordinance, green alley design, updating of a recommended plant list, and urban forest and wetland management plans. The adaptation strategy for plant selection presented in this paper offers guidance to help meet these goals.

Such visioning still leaves the problem of what future to design for. For the Great Lakes region there are climate projections at three future time periods and under two emissions scenarios (Hayhoe et al. 2010). Projections emerged from coupled atmosphere-ocean general circulation models (AOGCM) to which statistical downscaling was applied to capture the nuances of regional-scale change. Descriptions of a few of their results show how climate change projections might be used in the development of plant palettes that offer protection for urban ecosystems in southeast Michigan. For the near future (2010 to 2039), simulation models predict that average winter and summer temperatures in southeastern Michigan will be 2°C warmer compared to average temperatures from 1961 to 1990. Over this time frame, precipitation is projected to increase 5 to 10 percent (spring) and 0 to 5 percent (summer). In combination with warmer temperatures, the net effect will be drier summer weather.

Figure S2. Winter comparison of aesthetic presence and spatial location of butterfly and bird resources between Design A (above) and Design B (below).

These specific predictions suggest that an adaptive plant palette for southeast Michigan should be biased toward species that have greater capacity for spring flooding yet higher drought tolerance. Demonstrations of how to apply the urban planting adaptation strategy presented earlier show how to plan for this forecast. The selected plant palette shown in Table 2 will produce a garden able to handle drier summer weather (owing to the criterion for drought resistant species) and wetter springs (owing to high plasticity for moisture availability). Moreover, species plasticity will buffer the garden from greater year round extreme temperature and rainfall events, the types of fluctuation that accompany the more gradual shift in average climate parameters (CCSP 2008). For geographic areas with different projected futures (for example, increased summer flooding), plant selection can be adjusted accordingly within the framework of local predictions and in light of the general goals of the adaptation strategy.

As an antidote to the imprecision of climate change projections, adaptation strategies should be designed with built-in flexibility features for managed ecosystems that combine multiple options for enhancing ecosystem resistance, resilience, and response capacity to changing conditions (Millar, Stephenson, and Stephens 2007). The adaptation strategy for urban planting design embraces all of these goals. Resistance (forestalling the undesired effects of change) is facilitated by designing gardens with season-long diversity in pollinator resources with the collective capacity to protect

Table S1. Complete trait data for plants used on Designs A and B in spreadsheet format, ready for sorting

Plant type	Common Name	Botanical Name	Persistence	Nativity	Hardiness	*Temp Plasticity	Light Type	*Light Plasticity	Light preference	Soil Type	*Soils Plasticity	Soil pH	Soil Moisture	*Soil Moisture plasticity	Details on soil moisture needs	*Drought tolerance	*Salt tolerance
3	Butterfly Weed	*Asclepias tuberosa*	1	2	3–9	7	F–PSh	2		L,S,C	3	AC	DM	2	Does well in poor, dry soils	4	ST
3	Threadleaf coreopsis	*Coreopsis verticillata* 'Moonbeam'	1	1	3–9	7	F	1	full sun	S,L	2	AC	MD	2	Thrives in poor soil w/ good drainage	4	ST
3	Purple Coneflower	*Echinacea purpurea*	1	2	3–10	8	F	1	best in full sun	L,S	2	ALK	DMW	3	Tolerates poor soil	4	ST
3	Indian Blanket	*Gaillardia aristata*	1	1	3–10	8	F	1	full sun	S,L	2	AC	DM	2	Prefers well-drained soils	4	ST
3	Indian Blanket-Bijou	*Gaillardia aristata* 'Bijou'	1	1	3–8	6	F	1	full sun	S,L	2	AC	DM	2	Prefers well-drained soils	4	ST
3	Rock Geranium	*Heuchera americana* 'Ring of Fire'	1	2	4–9	6	F–PSh	2	prefers afternoon shade	L,S	2	Neutral	MD	2	medium moisture, well-drained	4	ST
2	Grey Owl Red Juniper	*Juniperus virginiana* 'Grey Owl'	2	2	3–9	7	F–PSh	2		L,S,C	3	sl AC- ALK	DM	2	Intolerant of wet soils	4	ST
3	Blazing Star	*Liatris spicata* 'Alba'	1	2	3–8	6	F	1		L	1	Neutral	MD	2	Intolerant of wet soils in winter	4	ST
4	Switchgrass	*Panicum virgatum* 'Shenandoah'	1	2	5–9	5	F	1	slumps in shade	L,S,C	3	Neutral	DMW	3	Flops in rich soils, prefers moist	2	ST
1	White Oak	*Quercus alba*	1	2	3–9	7	F–PSh	2	full sun	L,S,C	3	AC	DMW	3	Prefers moist, acidic soil	4	ST
2	Gro-Low Fragrant Sumac	*Rhus aromatica* 'Gro Low'	1	2	3–9	7	F–PSh	2		L,S,C	3	sl AC-Neutral	MD	2	Not tolerant of poor drainage	4	ST
3	Black Eyed Susan	*Rudbeckia hirta* 'Indian Summer'	1	2	3–7	5	F	1		L,S	2	Neutral	MD	2	Best in moist but not wet soils	2	ST
4	Pink Muhly Grass	*Sporobolus capillaris / Muhlenbergia capillaris*	1	1	5–9	5	F	1		L,S,C	3	Neutral-ALK	DMW	3	Tolerates poorly drained soils	4	ST
3	Stokes Aster	*Stokesia laevis* 'Blue Danube'	1	1	5–9	5	F–PSh	2		S,L	2	AC	MD	2	Prefers well-drained soils	4	ST

Table S1 (*cont.*). Complete trait data for plants used on Designs A and B in spreadsheet format, ready for sorting

Common Name	*Heat tolerance	Typical Height	Typical Width	Plant Form	Plant Texture	Foliage Color	Fall Color	Bloom Time	* Bloom Plasticity	Bloom Color	Fruit Type	Fruit Color	Winter Form	Wildlife Value	Notes
Butterfly Weed		1–2.5′	1–1.5′	E	M, C	MG		Jn–Ag	3	Y, O		G		Bf	architectural pods in fall
Threadleaf coreopsis	HT	1.5–2′	1.5–2′	M	F	MG		Jn–S	4	Y				Bf	adundant pale yellow flowers, needle-like foliage
Purple Coneflower		2–5′	1.5–2′	E	M	DG		Jl–S	3	P-Pr			S	Bd, Bf	many cultivars with great petal-cone color combos
Indian Blanket	HT	2–3′	2′	E–CL	M	GrG		Jl–S	3	R				B, Bd, Bf	forms dense clumps; bright red petals with yellow tips
Indian Blanket-Bijou	HT	1′	1′	E–CL	M	GrG		Jl–S	3	R+O				B, Bd, Bf	forms dense clumps; dwarf; orange-red petals with yellow tips
Rock Geranium		1–2′	1′	E–CL	M	BG–Si		Jn–Ag	3	pP				Bf	pale pink bloom on airy stems; silvery leaf -bright coral edge in fall
Grey Owl Red Juniper		2–3′	4–6′	S	M	GrG–Si		Mr	1	i	F	B-G	A	Bd, Ma	silvery green, fragrant foliage gives texture, showy bark
Blazing Star	HT	2–4′	2′	E	F	MG		Jl–Ag	2	W				Bd, Bf	flowers as feathery spikes, grass-like foliage on upright stems
Switchgrass		3–6′	2–3′	E–CL	F	MG–P	O, R, Y	Ag–S	2	P			A, S	Bd, Ma	lovely winter form
White Oak		50–80′	50–80′	Py	C	BG	R	My	1	i	S	Br	A, B	Bd, Ma	handsome brown acorns, architectural form
Gro-Low Fragrant Sumac		1.5–2′	6–8′	R, S	M	MG	O, R	A–My	2	i	F	R	F	Bd, Bf	
Black Eyed Susan		2–3′	1–3′	E	M	MG, DG		Jn–S	4	Y			S	B, Bd, Bf	
Pink Muhly Grass	HT	2–3′	2–3′	E–CL	F	MG	O, B	Jl–S	3	P			A, S	Bd, Ma	
Stokes Aster	HT	1–2′	1.5–2′	M	F	DG		Jn–S	4	B				Bf	

ecosystem function. Resilience (supporting the ability of an urban ecosystem to return to a desired state after disturbance) is facilitated by using plants that exhibit high phenotypic plasticity and can withstand fluctuations in temperature and moisture. Response capacity (accommodating rather than resisting change thereby supporting the ecosystem in its transition to new conditions) is facilitated by populating gardens with native species that also do well in warmer climates, based on winter hardiness ratings.

The adaptation strategy for planting design produces several opportunities for climate change mitigation. As planting strategy implementation increases across a city, the likelihood of producing functional urban habitat corridors increases because the repetition of appropriately composed gardens across an urban area better supports the migration of plants and animals (Doody et al. 2010; Goddard, Dougill, and Benton 2010). Planting designs that substitute trees and flowering shrubs in lieu of herbaceous perennials will increase carbon sequestration, and the transformation of lawns to low-input native species gardens will reduce greenhouse gas-emissions. Finally, the adaptation strategy for urban planting design is in line with "no regret" options, adaptation tactics that deliver benefits greater than their costs, regardless of the extent of future climate change (Heltberg, Siegel, and Jorgensen 2009).

CONCLUDING REMARKS

Adaptive strategies for climate change that include resistance, resilience, and facilitation actions offer a productive method to protect biodiversity during climate change (Galatowitsch, Frelich, and Phillips-Mao 2009). The strategy delineated here directly addresses two of these three recommendations. Resistance is indirectly addressed because this type of ecological planting design is a proxy for ecological restoration. The adaptation strategy is also practical, for it requires no policy change, no bureaucratic support, is relatively inexpensive, and affords a low-cost approach to research on its effectiveness. Climate change is not waiting, so neither should we.

ACKNOWLEDGMENTS

Research was supported with a grant from the US Forest Service and University of Michigan's School of Natural Resources and Environment. Sara Turner, Allison Krueger, Cara Kappler, Brooke Nanna, and Miranda Mumford assisted with database development. Lauren De Silva illustrated the planting designs.

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