

## Emerging Landscapes

# Using Ecological Theory to Guide Urban Planting Design:

## An adaptation strategy for climate change

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**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

### 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 (Ros-

siter 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 re-

sources 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 (Godard, 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; Bjercknes 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.

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**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., greener 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

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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 (non-

selfing 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).

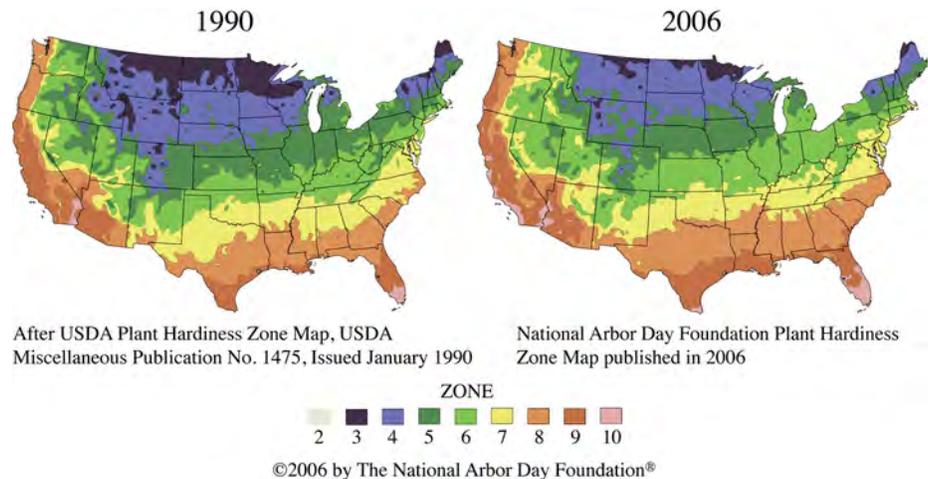
### Response Diversity

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 = id entity 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	<i>Heuchera americana</i> 'Ring of Fire'	4-9	6	MD	2	Jn-Ag
A+B	GF	Gayfeather	<i>Liatrix spicata</i> 'Alba'	3-8	6	MD	2	Jl-Ag
A+B	PC	Purple Coneflower	<i>Echinacea purpurea</i>	3-10	8	DMW	3	Jl-S
A+B	RJ	Grey Owl Red Juniper	<i>Juniperus virginiana</i> 'Grey Owl'	3-9	7	DM	2	Mr
A+B	SU	Gro-Low Fragrant Sumac	<i>Rhus aromatica</i> 'Gro Low'	3-9	7	MD	2	A-My
A+B	WO	White Oak	<i>Quercus alba</i>	3-9	7	DMW	3	My
B	BS	Black Eyed Susan	<i>Rudbeckia hirta</i> 'Indian Summer'	3-7	5	MD	2	Jn-S
B	BW	Butterfly Weed	<i>Asclepias tuberosa</i>	3-9	7	DM	2	Jn-Ag
B	IB	Indian Blanket	<i>Gaillardia aristata</i>	3-10	8	DM	2	Jl-S
B	IBB	Indian Blanket-Bijou	<i>Gaillardia aristata</i> 'Bijou'	3-8	6	DM	2	Jl-S
B	MG	Pink Muhly Grass	<i>Sporobolus capillaris</i> / <i>Muhlenbergia capillaris</i>	5-9	5	DMW	3	Jl-S
B	SA	Stokes Aster	<i>Stokesia laevis</i> 'Blue Danube'	5-9	5	MD	2	Jn-S
B	SG	Switchgrass	<i>Panicum virgatum</i> 'Shenandoah'	3-9	7	DMW	3	Ag-S
B	TC	Threadleaf coreopsis	<i>Coreopsis verticillata</i> 'Moonbeam'	3-9	7	MD	2	Jn-S
B	WC	White Coneflower	<i>Echinacea purpurea</i>	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.

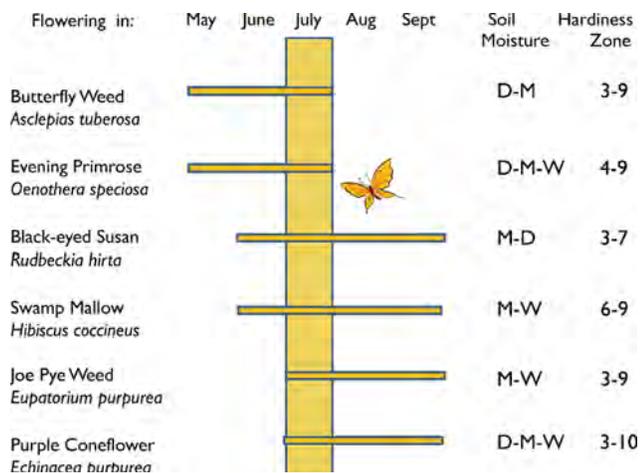


Figure 2. Graphical representations of functional redundancy and response diversity for pollinator resources throughout the growing season with greatest insurance of nectar in July. Bars indicate blooming period. Moisture requirements range from D = dry, to M = moist to W = wet soils.

### 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,

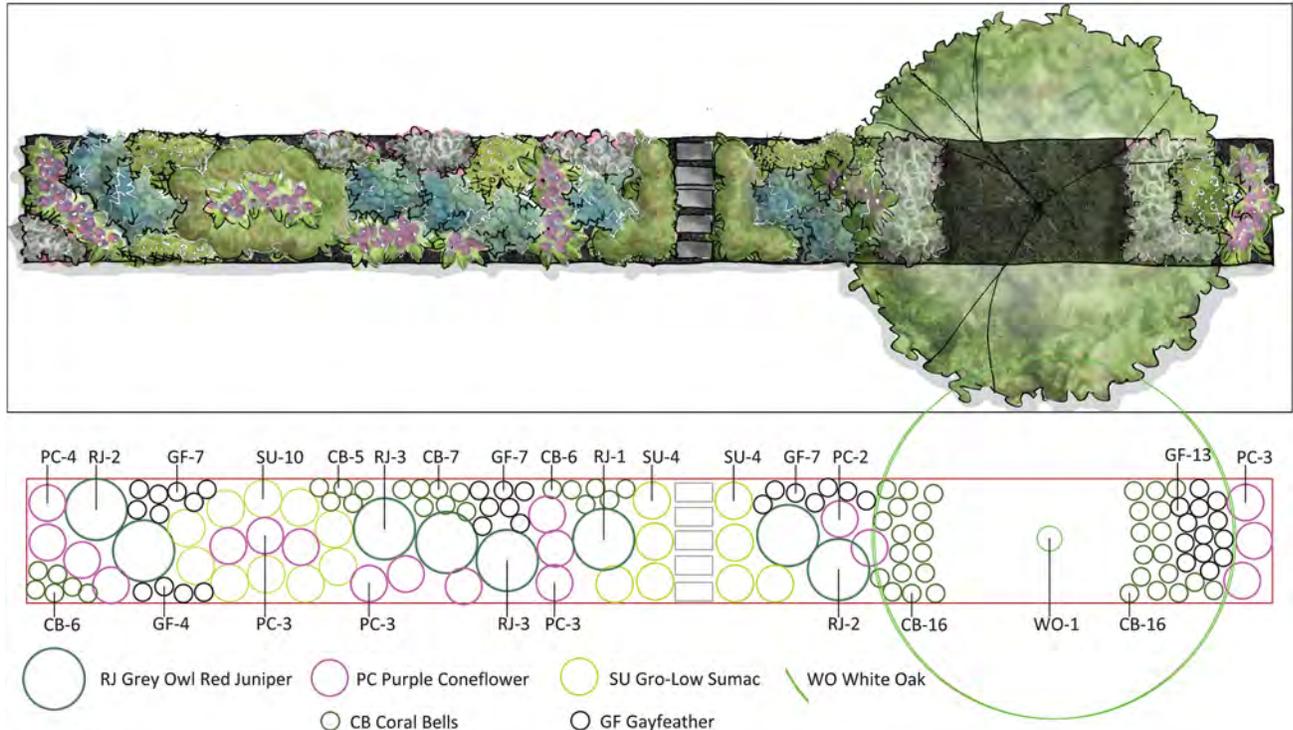


Figure 3. Design A for support of birds and butterflies using 5 plant species. The illustrative plan view conveys the aesthetic intent and the diagrammatic plan view gives species identity (key to abbreviations in Table 2) and the number of individuals that occupy each delineated space. The planting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

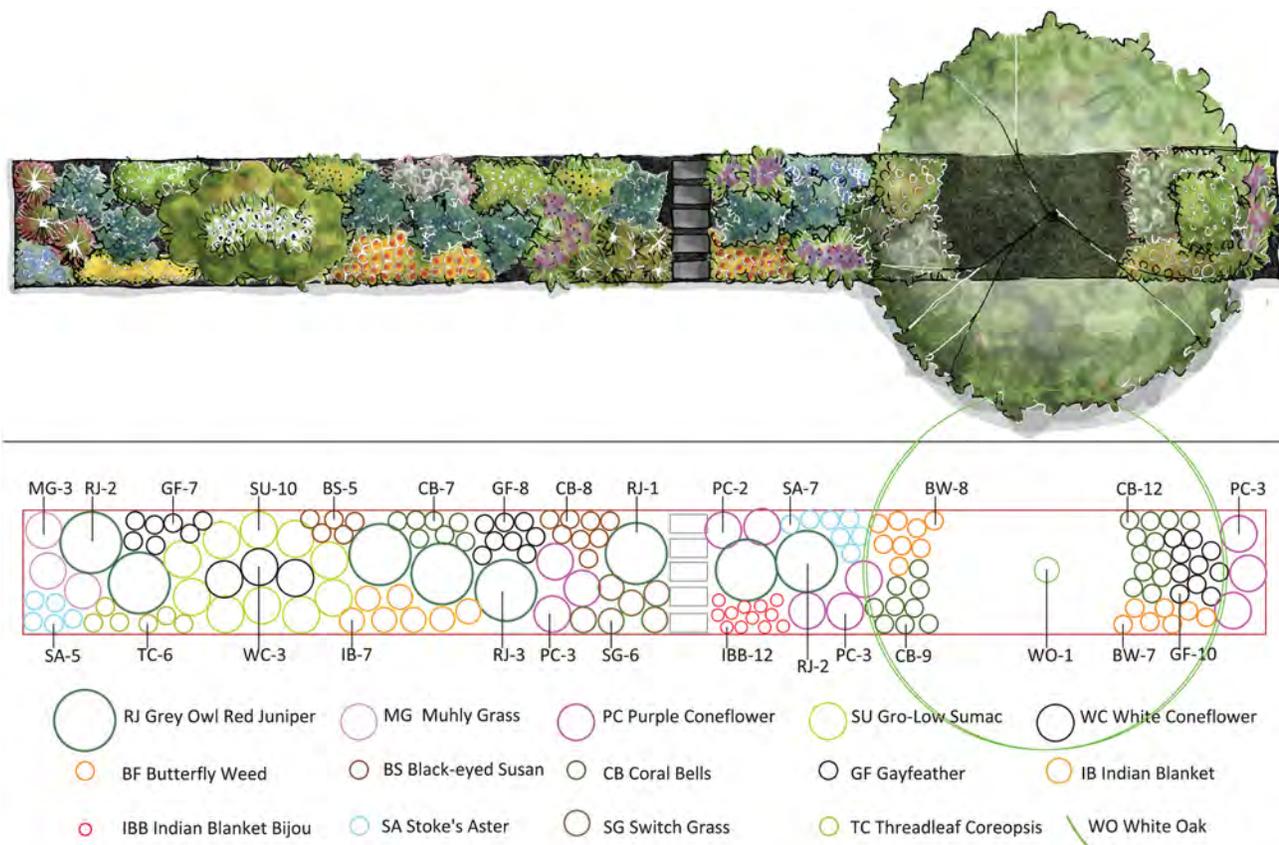


Figure 4. Design B for support of birds and butterflies using 15 plant species including 2 cultivars of same species. The illustrative plan view conveys the aesthetic intent and the diagrammatic plan view gives species identity (key to abbreviations in Table 2) and the number of individuals that occupy 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 out-compete 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

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).

design	ID	Common Name	BUTTERFLY RESOURCES						BIRD RESOURCES		
			food and habitat						habitat	food	
			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

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

design	ID	Common Name	soil moisture	BUTTERFLY RESOURCES					BIRD RESOURCES			
				food & habitat					habitat	food		
				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 for mat, 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	<i>Asclepias tuberosa</i>	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	<i>Coreopsis verticillata</i> '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	<i>Echinacea purpurea</i>	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	<i>Gaillardia aristata</i>	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	<i>Gaillardia aristata</i> '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	<i>Heuchera americana</i> '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	<i>Juniperus virginiana</i> '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	<i>Liatris spicata</i> 'Alba'	1	2	3-8	6	F	1		L	1	Neutral	MD	2	Intolerant of wet soils in winter	4	ST
4	Switchgrass	<i>Panicum virgatum</i> '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	<i>Quercus alba</i>	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	<i>Rhus aromatica</i> '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	<i>Rudbeckia hirta</i> '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	<i>Sporobolus capillaris</i> / <i>Muhlenbergia capillaris</i>	1	1	5-9	5	F	1		L,S,C	3	Neutral-ALK	DMW	3	Tolerates poorly drained soils	4	ST
3	Stokes Aster	<i>Stokesia laevis</i> '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 for material 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	abundant 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 f; 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.

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## REFERENCES

- Aitken, Sally N., Sam Yeaman, Jason A. Holliday, Tongli Wang, Sierra Curtis-McLane. 2008. Adaptation, migration or extirpation: climate change outcomes for tree populations. *Evolutionary Applications* 1 (1): 95–111
- Alberti, Marina. 2005. The effects of urban patterns on ecosystem function. *International Regional Science Review* 28 (2): 168–192.
- Angold, Penny, Jon P. Sadler, Mark O. Hill, Andrew Pullin, Steven Rushton, K. Austin, Emma Small, B. Wood, Richard Wadsworth, Roy Sanderson, and Ken Thompson. 2006. Biodiversity in urban habitat patches. *Science of the Total Environment* 360 (1–3): 196–204.
- Aniski, Tomasz. 2008. *When Perennials Bloom: An Almanac for Planning and Planting*. Portland, OR: Timber Press.
- Arendt, Randall. 2004. Linked landscapes: Creating greenway corridors through conservation subdivision design strategies in the northeastern and central United States. *Landscape and Urban Planning* 68 (2–3): 241–269.
- Bardsley, Douglas, and Gareth Edwards-Jones. 2007. Invasive species policy and climate change: social perceptions of environmental change in the Mediterranean. *Environmental Science and Policy* 10 (3): 230–242.
- Baschak, Lawrence A., and Robert D. Brown. 1995. An ecological framework for the planning, design, and management of urban river greenways. *Landscape and Urban Planning* 33 (1–3): 211–225.
- Bergerot, Benjamin, Benoit Fontaine, Mathilde Renard, Antoine Cadi, and Romain Julliard. 2010. Preferences for exotic flowers do not promote urban life in butterflies. *Landscape and Urban Planning* 96 (2): 98–107.
- Bjerknes, Anne-Line, Ørjan Totland, Stein Joar Hegland, and Anders Nielsen. 2007. Do alien plant invasions really affect pollination success in native plant species? *Biological Conservation* 138 (1–2): 1–12.

- Blanco, Hilda, Marina Alberti, Ann Forsyth, Kevin Krizek, Daniel A. Rodriguez, Emily Talen, and Cliff Ellis. 2009. Hot, congested, crowded, and diverse: Emerging research agendas in planning. *Progress in Planning* 71 (4): 153–205.
- Boland, Timothy, Laura Coit, and Marty Hart. 2002. *Michigan Gardener's Guide*, 2nd ed. Nashville, TN: Cool Springs Press.
- Bonney, Rick, Caren Cooper, Janis Dickinson, Steve Kelling, Tina Phillips, Kenneth V. Rosenberg, and Jennifer Shirk. 2009. Citizen science: A developing tool for expanding science knowledge and scientific literacy. *Bioscience* 59 (11): 977–984.
- Botequilha-Leitão, André, and Jack Ahern. 2002. Applying landscape ecological concepts and metrics in sustainable landscape planning. *Landscape and Urban Planning* 59 (2): 65–93.
- Brinkman, Robert, and Wim Sombroek. 1996. The effects of global change on soil conditions in relation to plant growth and food production. In *Global Climate Change and Agricultural Production: Direct and Indirect Effects of Changing Hydrological, Pedological, and Plant Physiological Processes*, ed. Fakhri Bazzaz and Wim Sombroek, 49–64. New York: John Wiley and Sons and The Food and Agriculture Organization of the United Nations.
- Brooker, Rob W., Justin M. J. Travis, Ewen J. Clark, and Calvin Dytham. 2007. Modelling species' range shifts in a changing climate: The impacts of biotic interactions, dispersal distance, and the rate of climate change. *Journal of Theoretical Biology* 245 (1): 59–65.
- Brooklyn Botanic Garden. 2006. *Native Alternatives to Invasive Plants*, Handbook #185. New York: Brooklyn Botanic Garden.
- Burghardt, Karin, Douglas Tallamy, and W. Gregory Shriver. 2009. Impact of native plants on bird and butterfly biodiversity in suburban landscapes. *Conservation Biology* 23 (1): 219–224.
- Calkins, Meg. 2005. Strategy use and challenges of ecological design in landscape architecture. *Landscape and Urban Planning* 73 (1): 29–48.
- CCSP. 2008. Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, ed. Thomas R. Karl, Gerald A. Meehl, Christopher Miller, Susan J. Hassol, Anne M. Waple and William L. Murray. Washington DC: US Department of Commerce, NOAA's National Climatic Data Center.
- Charmantier, Anne, Robin McCleery, Lionel R. Cole, Chris Perrins, Loeske E. B. Kruuk, and Ben C. Sheldon. 2008. Adaptive phenotypic plasticity in response to climate change in a wild bird population. *Science* 320 (5877): 800–803.
- Chown, Steven, Sarette Slabber, Melodie A. McGeoch, Charlene Janion, and Hans Petter Leinaas. 2007. Phenotypic plasticity mediates climate change responses among invasive and indigenous arthropods. *Proceedings of the Royal Society B: Biological Sciences* 274 (1625): 2531–537.
- Coffee, Joyce E., Julia Parzen, Mark Wagstaff, and Richard S. Lewis. 2010. Preparing for a changing climate: The Chicago climate action plan's adaptation strategy. *Journal of Great Lakes Research* 36 (Supplement 2, Special Issue SI): 115–117.
- Colding, Johan. 2007. Ecological land-use complementation for building resilience in urban ecosystems. *Landscape and Urban Planning* 81 (1–2): 46–55.
- Crimmins, Shawn M., Solomon Z. Dobrowski, Jonathan A. Greenberg, John T. Abatzoglou, and Alison R. Mynsberge. 2011. Changes in climatic water balance drive downhill shifts in plant species' optimum elevations. *Science* 331 (6015): 324–327.
- Daniels, Grant, and Jamie Kirkpatrick. 2006. Does variation in garden characteristics influence the conservation of birds in suburbia? *Biological Conservation* 133 (3): 326–335.
- Darke, Richard. 2007. *Encyclopedia of Ornamental Grasses for Livable Landscapes*. Portland, OR: Timber Press.
- Dehnen-Schmutz, Katharina, Ottmar Holdenrieder, Michael Jeger, and Marco Pautasso. 2010. Structural change in the international horticultural industry: Some implications for plant health. *Scientia Horticulturae* 125 (1): 1–15.
- Dirr, Michael. 1998. *Manual of Woody Landscape Plants: Their Identification, Ornamental Characteristics, Culture, Propagation, and Uses*, 5th ed. Champaign, IL: Stipes Publishing.
- Doody, Brendan J., Jon J. Sullivan, Colin D. Meurk, Glenn H. Stewart, and Harvey C. Perkins. 2010. Urban realities: the contribution of residential gardens to the conservation of urban forest remnants. *Biodiversity and Conservation* 19 (5): 1385–1400.
- Duff, Gordon, David Garnett, Peter Jacklyn, Jill Landsberg, John Ludwig, Joe Morrison, Paul Novelly, Dan Walker, and Peter Whitehead. 2009. A collaborative design to adaptively manage for landscape sustainability in north Australia: Lessons from a decade of cooperative research. *Landscape Ecology* 24 (8): 1135–1143.

- Elmqvist, Thomas, Carl Folke, Magnus Nystrom, Garry Peterson, Jan Bengtsson, Brian Walker, and Jon Norberg. 2003. Response diversity, ecosystem change, and resilience. *Frontiers in Ecology and the Environment* 1 (9): 488–494.
- Felson, Alex J., and Steward T.A. Pickett. 2005. Designed experiments: New approaches to studying urban ecosystems. *Frontiers in Ecology and Environment* 3 (10): 549–556.
- Galatowitsch, Susan, Lee Frelich, and Laura Phillips-Mao. 2009. Regional climate change adaptation strategies for biodiversity conservation in a midcontinental region of North America. *Biological Conservation* 142 (10): 2012–2022.
- Gilman, Sarah E., Mark C. Urban, Joshua Tewksbury, George W. Gilchrist, and Robert D. Holt. 2010. A framework for community interactions under climate change. *Trends in Ecology and Evolution* 25 (6): 325–331.
- Goddard, Mark A., Andrew J. Dougill, and Tim G. Benton. 2010. Scaling up from gardens: Biodiversity conservation in urban environments. *Trends in Ecology and Evolution* 25 (2): 90–98.
- Gould, Stephen Jay. 1997. An evolutionary perspective on strengths, fallacies, and confusions in the concept of native plants. In *Nature and Ideology: Nature and Garden Design in the Twentieth Century*, ed. Joachim Wolschke-Bulmahn, 11–19. Washington DC: Dumbarton Oaks.
- Hahs, Amy K., Mark J. McDonnell, Michael A. McCarthy, Peter A. Vesik, Richard T. Corlett, Briony A. Norton, Steven E. Clemants, Richard P. Duncan, Ken Thompson, Mark W. Schwartz, and Nicholas S. G. Williams. 2009. A global synthesis of plant extinction rates in urban areas. *Ecology Letters* 12 (11): 1165–1173.
- Hallegatte, Stéphane. 2009. Strategies to adapt to an uncertain climate change. *Global Environmental Change-Human and Policy Dimensions* 19 (2): 240–247.
- Hamlet, Alan F., Philip W. Mote, Martyn P. Clark, and Dennis P. Lettenmaier. 2007. Twentieth-century trends in runoff, evapotranspiration, and soil moisture in the Western United States. *Journal of Climate* 20 (8): 1468–1486.
- Hansen, Andrew J., Thomas A. Spies, Frederick J. Swanson, and Janet L. Ohmann. 1991. Conserving biodiversity in managed forests—Lessons from natural forests. *Bioscience* 41 (6): 382–92.
- Hayhoe, Katharine, Jeff VanDorn, Thomas Croley II, Nicole Schlegel, and Donald Wuebbles. 2010. Regional climate change projections for Chicago and the US Great Lakes. *Journal of Great Lakes Research* 36 (Supplement 2, Special Issue SI): 7–21.
- Heltberg, Rasmus, Paul B. Siegel, and Steen L. Jorgensen. 2009. Addressing human vulnerability to climate change: Toward a ‘no-regrets’ approach. *Global Environmental Change-Human and Policy Dimensions* 19 (1): 89–99.
- Heneghan, Liam, and Mary Carol Hunter. 2004. Biodiversity. In *Landscaping with Native Plants: Exploring the Environmental, Social, and Economic Benefits Conference*. Chicago, IL. [http://www.epa.gov/greenacres/conf12\\_04/conf\\_knowledge.html](http://www.epa.gov/greenacres/conf12_04/conf_knowledge.html) [August 2010].
- Horwitz, Pierre, Michael Lindsay, and Moira O’Connor. 2001. Biodiversity, endemism, sense of place, and public health: Inter-relationships for Australian inland aquatic systems. *Ecosystem Health* 7 (4): 253–265.
- Hull, R. Bruce, Mark Lam, and Gabriela Vigo. 1994. Place identity: Symbols of self and the urban fabric. *Landscape and Urban Planning* 28 (2–3): 109–120.
- Hunter, MaryCarol R. 2008. Managing Sense of Place in Transition: Coping with Climate Change. *Places* 20 (2): 20–25.
- Hunter, MaryCarol R., and Mark D. Hunter. 2008. Designing for conservation of insects in the built environment. *Insect Conservation and Diversity* 1 (4): 189–196.
- Hunter, MaryCarol. 2006. Ecological Community Restoration In *Landscape Architectural Graphics Standards; Professional Edition*, ed. L. J. Hopper, 792–798. New York: John Wiley and Sons.
- Hunter, MaryCarol. 2009. *Nature for Cities*. <http://natureforcities.snre.umich.edu/nature-in-the-city/urban-biodiversity-in-your-yard/> [August 2010].
- IPCC. 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. New York: Cambridge University Press.
- Iverson, Louis R., and Anantha M. Prasad. 1998. Predicting abundance of 80 tree species following climate change in the Eastern United States. *Ecological Monographs* 68 (4): 465–485.
- Jarvis, Peter J. 1973. North American plants and horticultural innovation in England, 1550–1700. *Geographical Review* 63 (4): 477–499.
- Kendal, David, Nicholas S. G. Williams, and Kathryn J. H. Williams. 2010. Harnessing diversity in gardens through individual decision makers. *Trends in Ecology and Evolution* 25 (4): 201–202.
- Kendle, Anthony D., and Juliet E. Rose. 2000. The aliens have landed! What are the justifications for ‘native only’ policies in landscape plantings? *Landscape and Urban Planning* 47 (1–2): 19–31.

- Kling, George W, Katharine Hayhoe, Lucinda B. Johnson, John Magnuson, Stephen Polasky, Scott K. Robinson, Brian Shuter, Michelle M. Wander, Donald Wuebbles, and Donald R. Zak. 2005. *Confronting Climate Change in the Great Lakes Region: Impacts on Our Communities and Ecosystems*, Executive Summary. Cambridge, MA: UCS Publications, The Union of Concerned Scientists, and The Ecological Society of America.
- Koningen, Hein 2004. Creative Management. In *The dynamic landscape: naturalistic planting in an urban context*, ed. Nigel Dunnett and James D. Hitchmough, 368–415. New York: Taylor and Francis.
- Lawton, John H., and Valerie K. Brown. 1993. Redundancy in ecosystems. In *Biodiversity and Ecosystem Function*, ed. Eernst-Detlef Schulze and Harold A. Mooney, 255–270. New York: Springer.
- Li, Feng, Rusong S. Wang, Juergen Paulussen, and Xusheng S. Liu. 2005. Comprehensive concept planning of urban greening based on ecological principles: A case study in Beijing, China. *Landscape and Urban Planning* 72 (4): 325–336.
- Lovell, Sarah T., and Douglas M. Johnston. 2009. Designing landscapes for performance based on emerging principles in landscape ecology. *Ecology and Society* 14 (1): 1–24.
- Marris, Emma. 2007. A garden for all climates. *Nature* 450 (13): 937–939.
- McKinney, Michael L. 2006. Urbanization as a major cause of biotic homogenization. *Biological Conservation* 127 (3): 247–260.
- McLachlan, Jason S., Jessica J. Hellmann, and Mark W. Schwartz. 2007. A framework for debate of assisted migration in an era of climate change. *Conservation Biology* 21 (2): 297–302.
- Millar, Constance I., Nathan L. Stephenson, and Scott L. Stephens. 2007. Climate change and forests of the future: Managing in the face of uncertainty. *Ecological Applications* 17 (8): 2145–2151.
- Missouri Botanical Garden. 2011. Kemper Center Plant Finder. St. Louis, MO: Missouri Botanical Garden. <http://www.mobot.org/gardeninghelp/plantfinder/alpha.asp> [April 16, 2011].
- Monrovia. 2011. Plant Catalog. Azusa, CA: Monrovia. <http://www.monrovia.com/plant-catalog/> [16 April 2011].
- Musacchio, Laura R. 2008. Using Translational Research to Increase Sustainability, Resilience, and Regeneration. *Landscape Journal* 27 (1): 1–8.
- Musacchio, Laura R. 2009. The scientific basis for the design of landscape sustainability: A conceptual framework for translational landscape research and practice of designed landscapes and the six Es of landscape sustainability. *Landscape Ecology* 24 (8): 993–1013.
- Nassauer, Joan. 1995. Messy ecosystems, orderly frames. *Landscape Journal* 14 (2): 161–170.
- Oprea, Monik, Poliona Mendes, Thiago B. Vieira, and Albert D. Ditchfield. 2009. Do wooded streets provide connectivity for bats in an urban landscape? *Biodiversity and Conservation* 18 (9): 2361–2371.
- Parmesan, Camille. 2006. Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology, Evolution, and Systematics* 37 (1): 637–669.
- Parmesan, Camille, and Gary Yohe. 2003. A globally coherent fingerprint of climate change impacts across natural systems. *Nature* 421 (6918): 37–42.
- Parsons, Russ, and Terry C. Daniel. 2002. Good looking: In defense of scenic landscape aesthetics. *Landscape and Urban Planning* 60 (1): 43–56.
- Pickett, Steward T. A., and Mary L. Cadenasso. 2008. Linking ecological and built components of urban mosaics: An open cycle of ecological design. *Journal of Ecology* 96 (1): 8–12.
- Pielke, Roger A. 1998. Rethinking the role of adaptation in climate policy. *Global Environmental Change* 8 (2): 159–170.
- Praskievicz, Sarah, and Heejun J. Chang. 2009. A review of hydrological modeling of basin-scale climate change and urban development impacts. *Progress in Physical Geography* 33 (5): 650–671.
- Primack, Richard B., and Abraham J. Miller-Rushing. 2009. The role of botanical gardens in climate change research. *New Phytologist* 182 (2): 303–313.
- Rapport, David J. 1998. Biodiversity and saving the earth. *Environmental Monitoring and Assessment* 49 (2–3): 169–175.
- Rossiter, MaryCarol. 1996. The incidence and consequences of inherited environmental effects. *Annual Review of Ecology and Systematics* 27: 451–476.
- Shaw, Daniel, Rusty Schmidt, Brian Ashman, Hugh Johnson, and Tony Randazzo. 2007. *Plants for Stormwater Design: Species Selection for the Upper Midwest*, vol. 2. St. Paul, MN: Great River Greening.
- Snep, Robbert, Paul Opdam, Johannes Baveco, Michiel Wallis-DeVries, Wim Timmermans, R. G. M. Kwak, and Vincent Kuypers. 2006. How peri-urban areas can strengthen animal populations within cities: A modeling approach. *Biological Conservation* 127 (3): 345–355.

- Tallamy, Douglas W., and Kimberley J. Shropshire. 2009. Ranking Lepidopteran use of native versus introduced plants. *Conservation Biology* 23 (4): 941–947.
- Tallamy, Douglas W. 2009. *Bringing Nature Home: How You Can Sustain Wildlife with Native Plants*. Portland, OR: Timber Press.
- Tratalos, Jamie, Richard A. Fuller, Philip H. Warren, Richard G. Davies, and Kevin J. Gaston. 2007. Urban form, biodiversity potential, and ecosystem services. *Landscape and Urban Planning* 83 (4): 308–317.
- Troccoli, Alberto 2010. Seasonal climate forecasting. *Meteorological Applications* 17 (3): 251–268.
- USDA-NRCS. 2011. The PLANTS Database. Baton Rouge, LA: National Plant Data Center. <http://plants.usda.gov> [16 April 2011].
- USDA-NISC. 2010. National Invasive Species Information Center. Beltsville, MD: National Agricultural Library. <http://www.invasivespeciesinfo.gov/plants/main.shtml> [August 2010].
- Van der Veken, Sebastiaan, Martin Hermy, Mark Vellend, Anne Knapen, and Kris Verheyen. 2008. Garden plants get a head start on climate change. *Frontiers in Ecology and the Environment* 6 (4): 212–216.
- Van Rossum, Fabienne, and Ludwig Triest. 2010. Pollen dispersal in an insect-pollinated wet meadow herb along an urban river. *Landscape and Urban Planning* 95 (4): 201–208.
- Visser, Marcel E., and Christiaan Both. 2005. Shifts in phenology due to global climate change: The need for a yardstick. *Proceedings of the Royal Society B: Biological Sciences* 272 (1581): 2561–2569.
- Walther, Gian-Reto, Alain Roques, Philip E. Hulme, Martin T. Sykes, Petr Pysek, Ingolf Kuhn, Martin Zobel, Sven Bacher, Zoltan Botta-Dukat, Harald Bugmann, Bálint Czucz, Jens Dauber, Thomas Hickler, Vojtech Jarosik, Marc Kenis, Stefan Klotz, Dan Minchin, Mari Moora, Wolfgang Nentwig, Jürgen Ott, Vadim E. Panov, Björn Reineking, Christelle Robinet, Vitaliy Semenchenko, Wojciech Solarz, Wilfried Thuiller, Montserrat Vila, Katrin Vohland, and Josef Settele. 2009. Alien species in a warmer world: risks and opportunities. *Trends in Ecology and Evolution* 24 (12): 686–693.
- Warren, Charles R. 2007. Perspectives on the ‘alien’ versus ‘native’ species debate: a critique of concepts, language, and practice. *Progress in Human Geography* 31 (4): 427–446.
- Wilby, Robert L., J. Troni, Yvan Biot, Lennard Tedd, Bruce C. Hewitson, Doug M. Smith, and Rowan T. Sutton. 2009. A review of climate risk information for adaptation and development planning. *International Journal of Climatology* 29 (9): 1193–1215.
- Wilson, Robert J., David Gutierrez, Javier Gutierrez, and Victor J. Monserrat. 2007. An elevational shift in butterfly species richness and composition accompanying recent climate change. *Global Change Biology* 13 (9): 1873–1887.
- Wolfe, David W.; Mark D. Schwartz, Alan N. Lakso, Yuka Otsuki, Robert M. Pool and Nelson J. Shaulis. 2004. Climate change and shifts in spring phenology of three horticultural woody perennials in northeastern USA. *International Journal of Biometeorology* 49 (5): 303–309.
- Woodall, Christopher W., David Nowak, Greg C. Liknes, and Jim Westfall. 2010. Assessing the potential for urban trees to facilitate forest tree migration in the eastern United States. *Forest Ecology and Management* 259 (8): 1447–1454.
- Yachi, Shigeo, and Michel Loreau. 1999. Biodiversity and ecosystem productivity in a fluctuating environment: The insurance hypothesis. *Proceedings of the National Academy of Sciences of the United States of America* 96 (4): 1463–1468.
- Zhang, Lingxian, Quing Liu, Nigel Hall, and Zetian Fu. 2007. An environmental accounting framework applied to green space ecosystem planning for small towns in China as a case study. *Ecological Economics* 60 (3): 533–542.

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