Temporal and spatial drivers of urban regulatory ecosystem service provision

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# Introduction

Urban landscapes are a complex combination of natural, physical, social, and built elements (see Table 1 for our definition of natural, (Pickett et al. 2017)). The integration of natural with social and built elements results in a diverse and unique array of ecosystems within the urban landscape. Globally, urban populations continue to increase in part due to the nature of a city’s centralized design, which allows residents to fulfill many basic needs and access better services (United Nations, Department of Economic and Social Affairs, and Population Division 2019). For example, living in a city can vastly increase the quality and quantity of services accessible to you, such as waste management, water treatment, and higher quality education (United Nations, Department of Economic and Social Affairs, and Population Division 2019). Many benefits of cities are due to the social and built elements that are implemented. However, in addition to the benefits of built and social elements, the natural and physical elements of a city provide many benefits to urban dwellers. Contact with urban nature by residents results in greater overall well-being, more happiness, reduced mortality, and other mental and physical health benefits (Frumkin et al. 2017). All nature, urban and non-urban, provides specific gifts and benefits to humans that we cannot receive from built elements. However, urban nature differs in an important way, management.

Everything in our cities is managed by humans, including nature. Across cities, management occurs on vastly different scales with municipal governments attempting to manage at a city or landscape scale and private land owners often managing at a parcel level. Because of disparate interests and scales, attempting to manage urban nature in a holistic way that meets everyone’s needs and benefits all stakeholders has been referred to as a “wicked” problem (Gaston, Avila-Jim Enez, and Edmondson 2013). Maximizing human benefit can look very different depending on the stakeholder (Salmond et al. 2016). For example, when managing the urban forest, municipal planners may want to have low levels of maintenance and are often guided by ecologically determined “best practices” for planting, whereas individual residents may be trying to maximize benefits such as food production or aesthetic beauty.

Despite being a commonly reiterated goal, cities in the Global North are not being designed or managed to maximize benefits to all stakeholders. Currently, we build and manage our cities under capitalist and settler-colonial systems. The prioritization of maximizing financial benefit to private businesses and individuals in combination with the legacy of settler-colonial ideals, most notably racism, has led to a deeply skewed and inequitable distribution of urban benefits (Ernstson 2013). Despite the hard and relentless work of many municipal government employees, activists, and NGOs to address the long-standing inequities of urban nature’s benefits, there are still extremely harmful disparities in how the distribution, production, and delivery of urban nature’s benefits occurs (Schell et al. 2020). For example, the “luxury effect” is a well supported theory in urban ecology where a large amount of variation in urban nature quantity and quality can be explained by the socioeconomic status of the neighbourhoods in question (Gerrish and Watkins 2018; Wu 2014). For example, the benefits received by urban parks, including but not limited to alleviating public health issues, is negatively correlated with the proportion of Black, Indigenous, and other racialized residents in the census tract in the United States (Hoover and Lim 2020). To maximize urban nature’s benefits to the entire urban population, we must think critically about the prioritization of economic benefits and shift our decision-making priorities to values that benefit our communities as a whole, such as equity, compassion, and justice.

The urban landscape is a complex and dynamic system that is made up of many interactions between humans and nature. Nature bestows many benefits and gifts on humans that interact with it, consciously and unconsciously. Often, the gifts that nature gives to humans are defined as “nature’s contributions to people” or “ecosystem services” (Millennium Ecosystem Assessment 2005; Díaz et al. 2015). Ecosystem services improve the quality of life for people who receive them. Depending on the particular service, humans often rely on ecosystem services for our survival (Millennium Ecosystem Assessment 2005). For example, crop production is an ecosystem service that most humans rely on as our source of food. Ecosystem services can also enhance our lives by providing benefits that we don’t need to survive but are still important to our health and allow us to thrive. For example, in China, living in a community with access to clean water can improve elderly individuals’ mental health and aid in stress recovery (Chen and Yuan 2020). Thus, managing urban nature for the production and delivery of ecosystem services is a common municipal goal. However, nature’s impacts are not always beneficial (Roman et al. 2020; Salmond et al. 2016). For example, urban greening can provide services such as air pollution and heat mitigation but it can also cause gentrification and resident displacement, ultimately acting as a disservice to the community (Roman et al. 2020). The negative impacts of nature on human lives are often referred to as ecosystem disservices. Managing urban nature to maximize benefits to all urban dwellers is a daunting task, however, an ecosystem services framework may allow us to attempt it (Bennett 2017).

Regulating ecosystem services are particularly critical when managing cities (Villamagna, Angermeier, and Bennett 2013). Regulating services are defined as benefits that are provided through the regulation of the ecosystem, such as temperature regulation from tree canopies (Millennium Ecosystem Assessment 2005) The ecological footprint of a city often extends far beyond its borders, with many of the ecosystem services required by the high population being provided from elsewhere (Gaston, Avila-Jim Enez, and Edmondson 2013). For example, many of the provisioning ecosystem services that urban residents need and enjoy are outsourced to surrounding agricultural areas. Similarly, cultural ecosystem services can be provided by nature found outside the city limits, such as National Parks. However, regulating services must be produced *in situ* (Sutherland et al. 2018). The cooling benefits provided by tree canopies cannot be imported, nor can the clean water provided by the city’s watershed. The nature of regulating services requires them to be built into the city’s landscape. Thus, designing and managing urban nature to provide regulating ecosystem services is a key part of having a just and equitable city.

Ecosystem service management includes four different processes, capacity, pressure, demand, and flow (Villamagna, Angermeier, and Bennett 2013). Capacity is the easiest to quantify ecologically, and is often focused on by urban ecology studies. For example, stocking a river with fish will increase the population and improve that ecosystem’s capacity for fishing yields. However, the provision of ecosystem services is not only dependent on the capacity of the ecosystem. We also must consider pressures, which include biophysical influences that change the ability of the ecosystem to provide the service. Pressures can change the capacity of an ecosystem to provide services. For example, overfishing is a pressure that can reduce population levels to a level where stable reproduction levels are no longer possible, thus changing the capacity of the river’s provisioning services. Demand is the level of service that is required by society, and is notoriously difficult to quantify ecologically (Haase et al. 2014). Demand can increase due to increased population, for example, higher population density in turn requires more food. However, demand also changes with individual values and culture. For example, if two neighbourhoods have the same population density but the culture of one values and requires fish as part of their more than the other, then the demand can differ even when the population density doesn’t. Finally, flow is the amount of ecosystem services actually received by people. Flow is an integration of capacity, pressures, and demand. To truly deliver ecosystem services in a meaningful way in cities, we must take each process into account.

The heterogeneity of cities lends another level of complexity to managing ecosystem services. Cities are highly dynamic and heterogeneous, varying on a uniquely fine-scale (Knapp et al. 2020; C. Ziter and Turner 2018). Delivery of ecosystem services changes across space and time, at multiple scales (Pickett et al. 2017). The effective and just delivery of ecosystem services requires an approach that can shift depending on the scale of interest. The capacity of the urban landscape to deliver ecosystem services is highly spatially heterogeneous. For example, ecosystem service capacity of the urban forest is often dependent on the species of trees planted. However, different stakeholders will plant different species, which can occur on a small scale, e.g. different homeowners planting different species in their yards. Spatial heterogeneity can also occur on larger scales, e.g. variation in species composition across different neighbourhoods (Ossola et al. 2019) or cities (Lin et al. 2019). Temporal variation is also an important driver of present ecosystem service capacity, demand, and flow and occurs on multiple scales (Roman et al. 2018; Renard, Rhemtulla, and Bennett 2015; C. Ziter, Graves, and Turner 2017). The nature of development in cities results in current ecosystem service delivery being significantly influenced by legacy effects and time lags. Legacy effects occur when a historical event carries over its effects to all subsequent events (Ossola, Cadenasso, and Meineke 2021; Tappeiner et al. 2020). For example, someone planting a tree in their backyard does not only affect them at the time of planting, but continues to impact them and all subsequent home owners. Time lags add to the legacy effect, when historical actions do not immediately show an effect and instead have a lag between the cause and effect (Tappeiner et al. 2020). Similar to spatial heterogeneity, temporal heterogeneity in ecosystem services can happen on various scales. Thus, uncovering drivers behind ecosystem service capacity, demand, and flow requires a multi-scale spatiotemporal approach.

My proposed thesis will investigate spatial and temporal variation in the delivery of regulating ecosystem services by the urban forest. My first chapter will use a multi-city, multi-service approach to uncovering the drivers of regulating ecosystem service capacity of the urban forest. Three ecosystem services, air pollution mitigation, temperature regulation, and carbon sequestration will be included by modelling their current capacities across major Canadian cities at a street scale, neighbourhood scale, and city scale. We will then determine which drivers are common across cities and scales, and which are unique. The second chapter will investigate the legacy effects of different land cover origins on ecosystem capacity of trees found in urban parks and how time-lags and capacity shifts over time post-development impact current levels of ecosystem services. My third chapter will investigate how urban densification and the associated legacy effects impact the ecosystem service capacity of urban trees found in residential areas. Lastly, my fourth chapter will use the knowledge obtained from chapters 1-3 to create scenarios for development in the Montréal that result in an equitable flow of ecosystem services.

# Study Area

My work will take place on the unceded and traditional lands of the Haudenosaunee and Mohawk peoples (“NativeLand.ca” 2021). Before outlining my data collection and analysis methods, I believe it is important to acknowledge and outline my positionality. One’s positionality refers to the space they occupy in relation to their research (Alcoff 1988). Discussing and acknowledging positionality is a widely accepted and encouraged part of scholarship for many disciplines, mainly in the social sciences (England 1994). Natural science has so far gotten away without this important practice because of the belief that our research is “objective.” However, my training and approach to the natural sciences is directly informed by my privilege, worldview, and experiences. As such, I believe that by outlining my biases and approach, I give context and credibility to the work I will do and provide a critical step in reproducible and transparent research. I am approaching this research as a descendent of white settler-colonial Europeans who grew up on the traditional and unceded homelands of the Haudenosaunee, Anishinaabe, and Attiwonderonk Peoples. My privilege as a cisgender, white, settler researcher directly informs the questions I ask and the science I produce. My training and approach to natural science is informed by a Eurocentric worldview, which means that I have been trained to view humans and nature as distinct entities and use a reductionist approach. My approach is not better or worse than others, however, it does inform how I will ask and answer questions in this system.

The urban forest provides critical ecosystem services to urban residents. All of the trees found in a city contribute to the urban forest and provide regulatory, provisioning, supporting, and cultural ecosystem services (Millennium Ecosystem Assessment 2005). The urban forest is unique in the number and magnitude of regulating ecosystem services it provides which improve the quality of life and health of urban residents. The requirement of regulating services being provided *in situ* means that the management, production, and provision of regulating ecosystem services is a key part of effective city planning and management. One of the most well-known examples of the urban forest’s contribution to regulating the urban ecosystem is the ability of urban trees to buffer against the urban heat island effect (Livesley, McPherson, and Calfapietra 2016; C. D. Ziter et al. 2019; Wang et al. 2021). The shade and evapotranspiration provided by urban trees can reduce urban temperatures by several degrees, potentially reducing air temperatures from levels that are dangerous to human health (Livesley, McPherson, and Calfapietra 2016). The urban forest also reduces air pollution, sequesters carbon, provides flood control, and promotes noise reduction (Andersson et al. 2015). However, the provision of regulating services by the urban forest is dependent on several factors including the scale of analysis and species composition (C. Ziter, Bennett, and Gonzalez 2013; Qiu et al. 2018). Thus, the ability of the urban forest to provide regulating ecosystem services is dependent on its management.

# Proposed Research

## Chapter 1: Cross-city drivers of urban forest regulatory ecosystem services

Ecosystem service capacity is determined by many factors, hereafter referred to as drivers. For example, an urban tree’s capacity to provide temperature regulation to its citizens is partially driven by its leaf area (Rahman et al. 2020). Quantifying and understanding drivers of ecosystem services is an important strategy for planning cities that are healthy and equitable. If the magnitude and direction of the drivers’ influences are known, governments, NGOs, and other interested parties can begin planning for maximum ecosystem service delivery before ever planting a tree. Most ecosystem studies to date assess ecosystem services in one city (C. Ziter 2016). Although a single city approach is extremely useful for understanding fine-scale intricacies of ecosystem services, it does not allow for the identification of common drivers of ecosystem service capacity.

To test the roles of different drivers of urban forest ecosystem service capacity, we propose a framework of “cross-city” and “location-specific” drivers. We would expect location-specific drivers to be unique to individual places and influence ecosystem services on a specific spatial scale. We would expect different cities to have various location-specific drivers that influence one city’s provision of ecosystem services but not another. For example, different management practices in different municipalities may lead to different tree sizes, and thus result in a location-specific driver of aboveground carbon storage. Conversely, cross-city drivers are drivers that influence ecosystem services in multiple locations and across spatial scales. These are processes that consistently influence the provision of ecosystem services, although the magnitude may shift depending on spatial context. For example, biodiversity of the urban forest may influence the provision of ecosystem services, regardless of which city or at what scale you are investigating. Our study’s goals are to identify and differentiate between cross-city and location-specific drivers of urban forest ecosystem services using a cross-city, multi-scale, multi-service approach. Specifically, we will ask:

What are the cross-city drivers of regulatory ecosystem services provided by the urban forest in Canadian temperate cities?

All ecosystem processes are influenced by scale. The highly heterogeneous nature of cities requires a multi-scale approach. The drivers and capacity of ecosystem services by the urban forest are all dependent on the spatial scale of analysis. Factors such as biodiversity, parcel size, spatial distribution of trees, density, soil type and more determine the production and subsequent delivery of ecosystem services by the urban forest (C. Ziter, Bennett, and Gonzalez 2013; Pham et al. 2017; Qiu et al. 2018; Zhang, Middel, and Turner 2019; Wang et al. 2021). Further, relevant scales may differ depending on the driver or service being examined. For example, the relevant scales of urban heat island mitigation by trees, e.g., extremely fine-scale measurements under tree canopies and very large scale measurements at the whole-city level, may differ from the relevant scales for air pollution mitigation, e.g., the combined effect of trees at the neighbourhood scale. Thus, to gain a comprehensive understanding of how ecosystem services and their drivers are operating, we must take a multi-scale approach. To date, there have been few studies that take a multi-scale and multi-service approach (but see [Graves, Pearson, and Turner (2019); zwierzchowska2018] for examples). Further, most multi-scale studies take place in a single city, which provides valuable information for that specific location but limits the ability to extrapolate the trends in services and drivers examined.

*Approach*  
We will use existing, publicly available data to test ecosystem services and their drivers in seven major temperate Canadian cities: Vancouver, Calgary, Winnipeg, Toronto, Ottawa, Montreal, Halifax. We will test drivers of ecosystem services at three scales within the cities, fine-scale (street level), medium-scale (neighbourhood level), and large scale (city level). Using remotely sensed data we will measure proxies for three regulatory ecosystem services, temperature regulation, carbon sequestration, and air pollution mitigation. Using a combination of urban tree inventories, land cover maps, and census data we will have three groups of independent variables: natural, built infrastructure, and human demographics. Our natural variables will include biodiversity, tree size, and tree density. Built infrastructure variables will include road width and building density. Finally, our human demographics will include population density and socioeconomic status. The goal of this study is to determine common drivers of urban forest ecosystem services in Canadian cities.

*Status*  
We are currently in the data collection stage.

## Chapter 2 - Legacy effects of land-use types on regulatory ecosystem service capacity of park trees

The present-day effects of past land-use types, also known as legacy effects, have been demonstrated to influence various ecological processes and functioning. One factor that has legacy effects on the urban environment is past land use type (C. Ziter and Turner 2018). Past land use can change the structure of the current urban environment in many ways, from differences in soil nutrient levels (C. Ziter and Turner 2018) to levels of recreational use by humans (Dallimer et al. 2015). Because cities are cultural landscapes, they often have histories with high rates of land use change due to management by humans (C. Ziter, Graves, and Turner 2017). The high intensity of management paired with a rapid rate of development in cities often results in rapid rates of land use change with little to no landscape-scale planning with respect to proportions and placement of different land cover types.

The rapid rates of land use change in cities is driven by new development and redevelopment, both of which are designed to meet the needs of new residents. The expansion of cities in North America specifically results in large swaths of of agricultural land and forested area being developed to grow the city (Alig, Kline, and Lichtenstein 2004). However, due to intensification within the city’s borders, urban expansion can also result in the redevelopment of industrial, commercial, and residential land use types (Koebel 1996). The mix of new development and redevelopment results in a wide array of past land use legacies within urban areas.

Intrinsically tied to urban expansion is the increased need for regulatory ecosystem services within the city’s borders. Urban parks are a crucial provider of ecosystem services to urban residents and are developed throughout city borders to improve the quality of life of residents. The complex nature of urban development results in park development occurring on many different land use types, which begs the question:

What are the legacy effects of past land-use types on our current parks’ ecosystem service capacities?

Our parks and the urban trees therein provide many ecosystem services to the surrounding urban residents (Wright Wendel, Zarger, and Mihelcic 2012; Fischer et al. 2018). But do the type or quantity of services being delivered change depending on the land-use type the park was developed on? And how does that scale over time? We hypothesize that the previous land-use type will influence the type and quantity of ecosystem services currently being delivered by urban trees in Montreal’s parks. We also hypothesize that the relationship between time since development and quantity/type of ecosystem services will change across time depending on the previous land use type.

*Approach*  
We will investigate the land-use legacies on today’s parks in Montreal, Quebec. Using the city’s historical archives, we will determine the year of establishment for parks in the city and the type of land they were developed on. Using a subset of Montreal’s parks that span age and previous land-use types, we will measure ecosystem service capacity for a group of regulating ecosystem services: temperature regulation, soil type, and flood mitigation.

## Chapter 3 - Legacy effects of development on regulatory ecosystem service capacity of street trees

Following the industrial revolution in North America there has been an influx of people moving to urban centers (United Nations, Department of Economic and Social Affairs, and Population Division 2019). Widespread immigration to cities has resulted in increased human and building density in urban centers across the continent. The legacy of historical downtown cores paired with high-density development occurring consistently across several decades has resulted in a staggered sequence of development in many Canadian cities, including Montréal.

The nature of urban development in Canada results in high-density populations near the city center, with low-density sprawl occurring on the city’s edges (REF). As people have continued to migrate to cities, high-density urban centers stay high-density, low-density sprawl becomes higher density, and surrounding agricultural and natural land is developed into low-density sprawl (REFS). The nature of urban growth in Canada results in areas of the city’s core having been high-density for many decades while areas in the outer suburbs only becoming high-density in recent years. Thus, the structure of Canadian cities is a chronosequence, showing several different states of development at the same time. The chronosequence of development found across Canadian cities, such as Montréal, can then be used to effectively test the legacy effects of development on ecosystem service capacity. Our research question asks:

What are the legacy effects of densification impact street trees’ ecosystem service capacities?

Urban centers have long been recognized as environments that are hostile and difficult for trees to grow in, due to factors such as space constraints, compacted soils, and warmer temperatures (Cavender and Donnelly 2019). Nonetheless, street trees have been planted and managed in contemporary Canadian cities for many decades (Lawrence 2008). We hypothesize that street tree ecosystem service capacity is negatively related to densification, with street trees in low-density areas having the highest capacities for ecosystem services and street trees in high-density areas having the lowest capacities. We would expect low-density areas will have less of the stressors that make tree growth difficult in an urban setting, such as warmer temperatures, and thus the trees will have a greater capacity for ecosystem services due to better health and growth. We also hypothesize that the differences in ecosystem service capacity of street trees in different density areas will increase over time. Due to the legacy effects of living in high-density areas over a long period of time, such as continually declining soil quality, we predict that street tree ecosystem service capacity in high-density areas will not increase at the same rate as street trees in low-density areas due to increased turnover and decreased tree health, resulting in a higher disparity in capacity over time.

*Approach*  
We will sample ecosystem service capacity of street trees in low-density, medium-density, and high-density areas that vary in years since development. We will sample the same regulatory ecosystem services as in Chapter 2, temperature regulation, soil type, and flood mitigation to maximize our knowledge of legacy effects in different areas of the city.

## Chapter 4 - Predictive modelling for equitable ecosystem service flow in Montréal

The city of Montréal is expected to continue its population growth into the coming decades (Canada and Government of Canada 2019). Due to the continued increase in population, Montréal will develop new land and redevelop current municipal land as required. The planning and implementation of development will determine how ecosystem services flow throughout the city well into the future. Considering the current disparity in the flow of ecosystem services on the island of Montréal (Pham et al. 2017), it is critical that we consider ecosystem service capacity, delivery, and flow in future development if we want to prioritize an equitable and sustainable city.

Using the results from chapters 1-3, I will produce multiple modelling scenarios of the future ecosystem service flow in Montreal. Chapter 1-3 focus on determining common drivers,legacy effects of land-use types, and legacy effects of densification of ecosystem service capacity. Using this information of how ecosystem service capacity is affected over time, I will develop a series of modelling scenarios for the City of Montréal. I will incorporate predicted demand of ecosystem services, as well as capacity, to develop models of flow for each scenario.

*Approach*  
Work in progress.

# Significance

Most of the world’s population currently lives in an urban area (United Nations, Department of Economic and Social Affairs, and Population Division 2019), meaning that the majority of people experience nature through the lens of the urban landscape. Close proximity to urban nature means that benefits from urban trees to city residents exceed benefits from forest trees (Larouche et al. 2021). As cities continue to increase in population and size, their ability to effectively produce and deliver ecosystem services is critical for sustainable and equitable development. My research will provide insight into the ecological drivers and legacy effects impacting the capacity of urban forest regulating ecosystem services in a dynamic and heterogeneous landscape. Historically, the scope of our inferences on ecosystem services has been limited due to individual studies being conducted in a single city (Haase et al. 2014). My multi-service, multi-city approach will make significant contributions to the theoretical and applied understanding of the ecology underlying urban ecosystem services. My research will also contribute to quantifying the legacy effects of management decisions such as land-use development and densification. Relating common and distinct drivers across cities and legacy effects of development decisions will promote optimal and equitable distribution of urban forest ecosystem services. Within cities, inequities exist in the access to ecosystem services by urban residents (Schell et al. 2020). Ecological patterns of ecosystem service distribution and access can be predicted by elements of structural racism and other mechanisms of inequality (Pham et al. 2013; Schell et al. 2020). Critically, some factors that impact ecosystem services, such as past acts of racial segregation across neighbourhoods, are set by history and are therefore irrevocable.20,42 However, clearly defining current drivers and legacy effects of ecosystem services, and integrating those effects into future scenario modelling to predict and improve levels of ecosystem services on multiple scales will provide us with the ability to shape current and future urban landscapes to meet the needs of all city residents and stakeholders in an equitable way.

# Glossary

Table 1. Glossary of terms used.

| Term | Definition | Reference |
| --- | --- | --- |
| Urban ecosystem/city | An ecosystem whose biological and physical characteristics are primarily engineered, modified, and constructed by humans. In urban ecosystems, human society influences the relationships among organisms and between organisms and the physical environment. | Des Roches et al. 2020 |
| Natural | The biotic, organic factors that are in a biome or ecosystem | Tansley 1935 |
| Built | All human-generated land modifications, buildings, infrastructure, and other artifacts | Pickett & Grove 2009 |
| Physical | Physical, inorganic factors that form the environment of the biome, habitat factors | Tansley 1935 |
| Social | Human generated social structures and interactions that are crucial to the functioning of ecosystems (e.g. government) | Pickett & Grove 2009 |
| Ecosystem services | The benefits that people derive from ecosystems | Millennium Ecosystem Assessment 2005 |
| Nature’s contribution to people | All the benefits that humanity – individuals, communities, societies, nations or humanity as a whole – in rural and urban settings – obtains from nature | Dìaz et al. 2015 |
| Ecosystem disservices | Ecosystem generated functions, processes and attributes that result in perceived or actual negative impacts on human wellbeing | Shackleton et al. 2016 |
| Regulating services | Benefits obtained from the regulation of ecosystems | Millennium Ecosystem Assessment 2005 |
| Ecosystem service capacity | An ecosystem’s potential to deliver services based on biophysical and social properties and functions | Villamagna et al. 2013 |
| Ecosystem service demand | The amount of a service required or desired by society | Villamagna et al. 2013 |
| Ecosystem service flow | The actual production or use of the service, incorporates biophysical and beneficiary components | Villamagna et al. 2013 |
| Urban forest | Contains all trees, shrubs, lawns, and pervious soils in urban areas | Escobedo et al. 2011 |
| Legacy effects | Manifestation of temporal autocorrelation within and across urban ecosystems. Carry-over effects on subsequent events in ecosystems. | Ossola et al. 2021 |
| Chronosequence | Space-for-time substitutions compiled by measuring ecosystem properties at ecologically similar sites with differing time-since-disturbance and/or successional gradients | Tomscha et al. 2016 |

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