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Research

Ecosystem Connectivity for Livable Cities: a Connectivity Benefits Framework for Urban Planning

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ABSTRACT. Urbanization disrupts landscapes and ecosystem functions, which poses threats to biodiversity, social systems, and human health, particularly among vulnerable populations. Urban land-use planners are faced with competing demands for housing, safety, transportation, and economic development and often lack tools to integrate these with protecting environmental functions. We identify three major barriers to integrating the benefits that flow with connected, functioning ecosystems into land-use planning. The lack of a shared language among planners and stakeholders poses a barrier to the restoration and preservation of ecological features. Methods of incorporating the benefits from connectivity are not standardized because values are not readily available or lack credibility. Ecological restoration tends to be poorly coordinated at broad scales, and thus often fails to achieve landscape-level objectives. To address these challenges, we developed a novel integrated framework, the Connectivity Benefits Framework (CBF), which combines the benefits from three categories of ecosystem connectivity with benefit- and risk-relevant indicators, enabling both monetary and non-monetary valuation of benefits. Moreover, it provides a method to identify and visualize the multiple and overlapping benefits from management actions to aid in prioritizing initiatives that support ecosystem functions. Unlike software tools that incorporate generalized values of ecosystem services at a landscape level, the CBF guides a systematic approach to community-engaged land-use planning that prioritizes localized societal needs while protecting biodiversity and ecosystem function for more equitable, resilient cities. We demonstrate the potential for multiple overlapping benefits from actions that restore and protect ecosystem connectivity by applying the framework to a transit planning project in Portland, Oregon.

Key Words: *benefit-relevant indicators; eco-social connectivity; ecosystem multifunctionality; resilient cities; risk-relevant indicators; urban resilience*

INTRODUCTION

Urbanization fragments landscapes and disrupts ecosystem functions, jeopardizing the seemingly disparate areas of biodiversity, human health, and ecological and social systems (Biondi et al. 2003, Yli-Pelkonen and Niemelä 2005). Decisions about land use that fail to reconnect or that further fragment ecosystems contribute to continued loss of biodiversity, along with other impacts. The loss and fragmentation of ecosystems, which occurs in part due to the built environment, is a major driver of species decline (Zambrano et al. 2019, Pimm and Raven 2000). It can lead to local extinctions of pollinators, migrating birds, and amphibians (Vos et al. 2002, Husté and Boulinier 2007, Dornier and Cheptou 2012), and may decrease options for climate-caused range shifts (Keeley et al. 2018). A growing body of research also links urbanization to negative impacts on human health. Expansive impervious surfaces and fragmented tree canopies can result in urban heat islands and lead to heat-related illness and death (Fahy et al. 2019). Urban dwellers experience increased rates of depression, cardiovascular disease, childhood asthma, and other respiratory illnesses, with rates typically higher in underserved neighborhoods (Voelkel et al. 2018, Baro et al. 2019, Turner-Skoff and Cavender 2019). Fragmentation due to the built environment also disrupts geophysical processes, worsening the impact of natural disasters such as storms, floods, wildfires, heat waves, droughts, and sea level rise (Laurance and Williamson 2001, Li et al. 2017). These effects in turn reduce the resilience of communities in urban areas.

Urban planning ideally helps cities mitigate these challenges and regain benefits that flow from improved ecosystem connectivity. However, urban planning lacks a common way to evaluate the diverse benefits of ecosystem connectivity (Mitchell et al. 2015, Butler et al. 2021). Ecosystem connectivity is defined here as the physical and functional links among and within ecosystems that support biodiversity, complexity, and resilience (Beller et al. 2019). Three key factors create barriers to integrating the benefits of ecosystem connectivity into urban planning designs and decisions. First, we identified a lack of a shared language among researchers, planners, decision makers, and communities to describe the myriad features and functions of ecosystem connectivity (Butler et al. 2021). Second, the lack of standardized methods for valuing the benefits of functioning ecosystems when services are not traded on markets reduces the likelihood that connectivity features and functions will be considered in decision making (Costanza et al. 1997, 2014). Finally, there is poor coordination of ecosystem restoration projects at a landscape scale, and piecemeal initiatives fail to achieve ecosystem-level connectivity objectives (Neeson et al. 2015). We aim to overcome these barriers through the design of a framework that guides a systematic approach to community-engaged land-use planning that prioritizes localized societal needs while protecting biodiversity and ecosystem function, resulting in more equitable and resilient cities.

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Table 1. Key features associated with each category of connectivity and the ecological or societal functions provided by those features (based on Butler et al. 2021). This list is not exhaustive, and other features and functions can be added based on regional priorities. These features and functions can be used to populate a Connectivity Planning Matrix.

Connectivity Category	Feature	Function
Habitat connectivity	Connected, contiguous terrestrial wildlife corridors	Gene flow among and across populations. Migration and climate range shifts facilitated
Habitat connectivity	Connected aquatic habitats	Gene flow among and across populations. Migration and climate range shifts facilitated
Habitat connectivity	Vegetated stepping-stone habitat patches	Pollinator and propagule dispersal facilitated; food webs supported across built landscapes
Habitat connectivity	Physical barriers minimized	Reduced hazards to organisms across landscapes and watersheds
Geophysical connectivity	Hydrologic connectivity across landscapes	Filtration and storage of water
Geophysical connectivity	Vegetated strips and patches in erosion-prone areas	Soil and geologic stability
Geophysical connectivity	Connected or extensive floodplains	Physical protection against major disturbances
Geophysical connectivity	Contiguous urban and upland tree canopy and roots	Air filtration, stormwater management, soil retention, shade, carbon storage, nutrient cycling
Geophysical connectivity	Connected riparian areas with resilient trees and vegetation	Interception of pollutants, temperature regulation, mitigation of nutrient and sediment runoff
Eco-social connectivity	Accessible green spaces within walking distance of neighborhoods	Human physical and mental health and safety
Eco-social connectivity	Accessible food production and natural materials gathering areas near neighborhoods	Food and shelter security
Eco-social connectivity	Accessible green jobs within walking distance of disenfranchised communities	Economic stability and equity
Eco-social connectivity	Clean water and clean air accessible in all neighborhoods	Human health and equity
Eco-social connectivity	Regional connected trail systems	Access to active transportation, exercise, nature, and other services
Eco-social connectivity	Access to shade	Human health and equity

Categories of Connectivity

Establishing common terminology and a shared understanding of the multiple benefits provided by connectivity is a first step in considering its importance in urban planning. Therefore, in a companion paper (Butler et al. 2021), we identify and promote the use of four interrelated categories of ecosystem connectivity: habitat, geophysical, eco-social, and landscape connectivity; we use the first three of these to structure our framework. Habitat connectivity characterizes the ability of organisms and/or their genetic materials to move within populations and within potential habitats. Geophysical connectivity describes the permeability or resistance of the landscape to matter and energy flows; it includes the natural processes and the landscape features that regulate them. Like habitat connectivity, these flows can be greatly impaired by land-use change and built environments. Eco-social connectivity captures spatial, infrastructure, and social properties of landscapes that facilitate people's access to nature and its benefits (Butler et al. 2021). Thus, landscape connectivity depicts spatial contiguity or proximity of related landscape elements, which can include human features like land ownership and management units and does not represent ecological functions. Landscape connectivity is pattern based rather than process based so it is not included in our framework. Key features and associated functions of connected ecosystems are summarized in Table 1 and documented in detail in our companion paper (Butler et al. 2021).

Urban planners work at the landscape level, placing them in a unique position to assess the benefits derived from integrating connectivity features across urban landscapes and to communicate these benefits to policy makers, landowners, and communities. Landscape design features and management actions that restore and protect ecological connectivity can be used by planners as a driver to gain support for otherwise disjointed objectives. For example, increasing the urban and upland tree canopy provides shade, air, and water filtration, reducing risks to human health (Turner-Skoff and Cavender 2019). It can provide corridors and habitats for small animals and pollinators (Caryl et al. 2013, Vergnes et al. 2013, Maruyama et al. 2019, Ossola et al. 2019). It can also increase property values (Donovan and Butry 2011) and tourism (Hall et al. 2011), strengthening local economies. Plus, trees stabilize soils, sequester carbon, and increase water storage, helping mitigate and adapt to climate change (Zabret and Sraj 2015). Green infrastructure initiatives such as building bioswales, installing green roofs, and reducing impervious surfaces are often introduced in response to extreme rain events (Zuniga-Teran et al. 2020). Such initiatives can not only increase ecosystem function, but frequently employ local labor and materials (BenDor et al. 2015) resulting in local economic benefits. If tree planting is focused in urban heat-islands, health risks to vulnerable populations can be reduced (Shandas et al. 2019, Turner-Skoff and Cavender 2019.)

Need for Connectivity in Planning

Purchasing land for conservation and dedicating funds to integrate nature into the built environment often fall below other urban priorities such as increased need for housing and safety (Harvey 2004, Kumar 2010, Buscher et al. 2012). Even when funded, urban conservation projects are frequently implemented at small scales based on land-parcel ownership and zoning. This site-based approach disconnects restoration from the areas of highest need, thereby perpetuating racial injustice (Schell et al. 2020). Restoration of forest fragments, planting of street trees, and provision of park lands has historically been concentrated in areas of high income, providing inequitable delivery or services to only those with proximity and access (Shandas et al. 2019, Schell et al. 2020). Without a method of prioritizing the eco-social benefits of reconnecting ecosystems in underserved areas, equity across urban areas cannot be achieved. Initiatives that support connectivity can amend these issues.

Coordination at a large scale is difficult, in part because U.S. urban areas generally encompass multiple counties and cities, which are managed by agencies operating within their own geographic boundaries and under specific policies, missions, and governmental bodies. Resilient land management aimed at restoring ecosystem function requires a holistic approach that includes biotic, abiotic, and human elements, and an understanding of how these elements function and interact across a landscape (Wu 2013). In particular, landscape fragments often lack the intended conservation benefits (Brown et al. 2019). For example, site-based riparian restoration improves salmonid survival (Beechie et al. 2012), but without mitigation of upstream barriers, fish passage is blocked, so the cultural and economic benefits of this initiative are not fully realized (Yeakley et al. 2016). Thus, local land-use plans may inadvertently fragment habitats, disrupt hydrologic flows and other geophysical processes, and disconnect humans from nature. Collaboration among agencies, planners, and developers using tools that promote ecosystem connectivity can help prevent further disruption to ecological and social systems.

Valuing Benefits of Connectivity

Valuation of ecosystem services (ES) has been increasingly used in the past three decades to inform land-use decisions and policies that restore or conserve natural system functions (Costanza et al. 1997, 2014, Kumar 2010, Olander et al. 2018). Ecosystem services can be linked to human well-being (Millenium Ecosystem Assessment (MEA) 2005) and can be used to examine how changes in ecological systems affect people and societies. However, monetary values are not readily available or credible when services are not traded in markets (Costanza et al. 2011). Although assigning monetary value to ES is becoming more common (Deal et al. 2012), critics assert that assigning market values to nature fails to capture the full worth of resources (Harvey 2004, 2005, Buscher et al. 2012), undermines nature's intrinsic value, and creates inequities (Polanyi 1944, Block 2003). Referring to nature as a separate entity that provides services to humans is also contradictory to some cultural views (Chan et al. 2012).

One solution to integrating the benefits of connectivity into planning without relying on monetary values is to use Olander and colleagues' benefit-relevant indicators (BRIs) (2018). Benefit-relevant indicators identify benefits of functioning ecosystems through the use of causal chains that link management actions to changes in ecosystem function and then link those to impacts on society or systems (Olander et al. 2018). Benefit-relevant indicators can be used as values themselves (e.g., reduced exposure to nitrous oxides (NO_x), a category of atmospheric pollutant) or as a method to assign monetary value when possible or desirable. Rao et al. (2014) estimated that every 10 ha of tree canopy in Portland, Oregon, is correlated with a 0.5 parts per billion decrease in NO_2 and, in turn, a decrease in respiratory illness valued at $7 million USD annually. Benefit-relevant indicators can identify which benefits are important to specific communities and specify outcomes that are highly valued even when expressed in non-monetary terms.

Connectivity Framework

We used our categories of connectivity and the BRI causal chain methodology, which we expand to connectivity causal webs, to design a set of tools and processes called the Connectivity Benefits Framework (CBF). The CBF helps planners and practitioners identify values associated with increasing ecosystem function in terms of both ecological and societal benefits. It also provides templates to capture and rank management actions that support connectivity. Other models that assign benefits provided by ecosystem functions typically focus on biophysical systems and have limited ability to identify the benefits provided to people by functional connected ecosystems. Models can also require months of work by experts combined with on-the-ground monitoring that may be impractical, unaffordable, or both (Rieb et al. 2017) and do not necessarily build community support for initiatives. Unlike software tools like InVEST and ARIES that use top-down approaches to incorporate ES values at a landscape level, the CBF guides a systematic approach to community-engaged land-use planning that prioritizes localized societal values and needs and does not require expertise in modeling. Additionally, we observed a lack of tools and methodologies (1) to capture the associated risks and costs associated with connectivity and (2) to assign rank to management actions that restore ecosystem function. Thus, the CBF introduces risk-relevant indicators (RRIs) as a form of a high-level cost–benefit analysis and an optional relative ranked value system (RRVS) for scoring and prioritizing management actions.

Although the CBF is broadly applicable to any geographic area, this approach is particularly relevant to urbanized areas where the impact of fragmentation is most acute and the economic and social benefits of improving connectivity are greatest (McDonald et al. 2009, Kabisch et al. 2018). Here, we apply the CBF to the Portland, Oregon metropolitan area because of the authors' combined experience in working in this region with ecologists and other practitioners from governmental and non-governmental organizations. Portland was recently ranked the 25th-largest metropolitan area in the USA (U.S. Census Bureau 2019) and is growing rapidly (Oregon Metro 2016). The population of the Portland Metro Region in 2021 was reported to be 2.7 million. Located in Northwest Oregon, the Portland Metro Region sits at the confluence of two rivers, the Willamette and Columbia. These major waterways and their associated riparian areas provide wildlife corridors to many aquatic and terrestrial wildlife species. With strict land-use planning regulations and a history of racial housing discrimination and gentrification (Bates 2013), greater Portland faces pressures to provide housing and services to a growing population within limited space without sacrificing its rich natural resources. Thus, it serves as a case study for urban areas facing similar issues. We compiled goals that support ecosystem connectivity from 15 Portland regional, city, and community planning documents, which are listed in Append. 1. Employing the CBF, we illustrate multiple overlapping benefits from actions that support these connectivity goals. To do this, we use current initiatives in Portland directed at protecting water quality and expanding light rail transportation.

Fig. 1. Example management actions that support all three categories of connectivity, usually even supporting multiple features of each connectivity category. These actions paired with features can be modified or expanded and matched with specific goals to populate a Connectivity Planning Matrix.

Management Actions	Habitat Connectivity Features				Geophysical Connectivity Features					Eco-social Connectivity Features					
	Wildlife corridors	Aquatic corridors	Habitat patches	Physical barriers removed	Hydrologic connectivity	Vegetated patches	Functional floodplains	Resilient upland trees	Resilient riparian areas	Access to green space	Accessible food & natural materials	Accessible green jobs	Access to clean air and water	Access to trail system	Access to shade
Increase complexity of vegetation integrating multiple contiguous habitat types within and in natural areas.	x		x		x	x		x	x				x		
Protect and expand urban tree canopy especially into areas that are tree deficient. Retain large trees.	x		x		x	x		x	x	x	x	x	x		x
Construct vegetated overpasses across roads and mass transit lines. Combine with fencing to direct animal passage.	x		x	x	x	x						x			x
Protect and restore riparian areas replacing invasive with native plants and trees.	x	x	x		x	x	x	x	x		x	x	x		x
Reconnect floodplains to water courses.	x	x	x	x	x	x	x		x				x	x	
Reduce and minimize the area of impervious surfaces particularly in urban heat islands.					x	x		x						x	x
Create complex and dense vegetated buffers along transit routes doubling, where feasible, as trail systems.	x				x	x				x			x		x
Remove fencing and walls replacing with hedgerows or trees.	x		x	x	x	x				x		x	x		x
Expand natural areas and parklands.	x		x		x	x	x	x	x	x		x	x	x	x
Modify dams and culverts to allow unhindered fish passage.		x		x	x		x		x		x	x			
Design, build and maintain a continuous network of trails lined with trees and other vegetation.	x		x		x	x		x		x		x	x		x
Through inclusive design processes, create community gardens and green spaces within neighborhoods.			x	x	x	x		x		x	x	x		x	x
Strategic land acquisition to connect watersheds and protect visually and culturally important areas.	x	x	x		x	x	x	x	x		x	x	x	x	x

METHODS

Review of Local Planning Documents

To develop the CBF process and to demonstrate the CBF tools in this paper, we reviewed regional, city, county, and community planning documents published between 2005 and 2018 for the Portland Metro Region and in current use by agencies (Append. 1). Cross-disciplinary organizational teams participated in the development of these published planning documents. Hence, they capture key goals and objectives important to local decision makers and community groups. Such documents provide a relevant source of data to populate CBF tools prior to engaging with stakeholders in planning meetings. We recorded all goals that explicitly called for connectivity or could be achieved through reconnecting ecosystems. We then identified connectivity features and functions supported by the proposed management actions and did this in coordination with a review of literature that linked actions to features and functions. We created a matrix with goals and actions in rows and features and functions for each connectivity category in columns (Fig. 1). We then tallied the goals and objectives across the Portland plans (Append. 2). The community-level plans reviewed did not explicitly reference ecosystem connectivity objectives, so were not included in the tally although they did commonly highlight socio-cultural values tied to ecosystem function and features.

The process of identifying and scanning planning documents aided in the development of the CBF but is not necessary for future use of the framework. However, we found that starting with existing documents was an effective way to build a foundation for collaborative work. Therefore, planners may want to begin populating the CBF using existing current local planning documents.

Planner and Practitioner Input

We presented the CBF to the Portland Metro Regional Habitat Connectivity Work Group. The Work Group incorporated the use of our connectivity categories and included geo-physical and eco-social benefits of actions that reconnect habitats into their draft Strategic Action Plan. In March 2019, we presented the CBF at the Urban Ecology and Conservation Symposium held in Portland, Oregon, which includes many habitat managers. Attendants at a companion workshop expressed a high level of interest in ecosystem connectivity tools, the categories of connectivity, and the CBF. Practitioners from Clean Water Services, Oregon Metro, Urban Greenspace Institute, the Portland Bureau of Environmental Services, and a planner from the Bureau of Planning and Sustainability provided input that helped refine the CBF. We adopted several recommendations that were common among the practitioners, improving the usefulness and accessibility of the tool to multiple types of users. Specifically, we more clearly tied connectivity features and functions to management actions in support of connectivity. Also, in response to practitioner suggestions, we built flexibility into the process describing how and when to use the component tools. For example, ranking the connectivity features and functions early in the planning process may prove difficult across a broad group of stakeholders, but their relative values may become more evident as planning progresses and can be captured later in the process.

From conversations with planners, the greatest perceived value of the CBF was as a communication tool. Planners noted that it will help them identify and communicate the multiple benefits of management actions that support connectivity to developers and decision/policy makers. Similarly, practitioners identified that the tool would help them communicate the multiple benefits of actions that support connectivity to community members and individual landowners. The Connectivity Causal Webs (CCW) were perceived as valuable for conducting and visualizing the cost vs. benefit of actions supporting connectivity. The Connectivity Planning Matrix (CPM) was valued as a tool that aided in the iterative design of management actions so that they support as many features and functions of connectivity as feasible. Examples of management actions that support connectivity features are provided in Fig. 1.

Application of the Connectivity Benefits Framework to Local Project

We applied the CBF to a planned project in the Portland Metro Region, the Southwest Corridor Light Rail Project, to demonstrate workflow and utility. To apply the CBF to this project, potential environmental impacts identified in the Draft Environmental Impact Statement (Federal Transit Administration et al. 2018) were extracted and converted into goals. A set of actions that support multiple aspects of connectivity was developed with a local practitioner familiar with the project.

THE CONNECTIVITY BENEFITS FRAMEWORK

The CBF aims to assist planners with aligning goals across work groups, organizations, landowners, and communities by providing a method of defining and capturing the myriad benefits and associated values of functioning, connected ecosystems. Moreover, it provides a method to identify and visualize multiple and overlapping benefits from connectivity management actions to refine and prioritize connectivity initiatives. The CBF offers a way to synthesize many possible actions linked to societal values and capture co-benefits of specific connectivity actions while also capturing risk and mitigation strategies.

The tools of the CBF include the CPM, the CCWs, and the Relative Ranking System (RRS). Each of these tools and the steps to develop them are discussed below. Links to CBF tools are provided in Append. 3.

Connectivity Benefits Framework Workflow

We provide an example of a CPM (Fig. 2) and follow this example throughout this section, explaining each step to get to this final matrix. A CPM is first populated with goals and actions captured from planning documents or through a participatory method of gathering stakeholder input. In this example workflow, the goals and actions represent those most common in and across Portland area plans.

In this workflow, the features of connectivity that were used to populate the matrix were identified through a literature review and are described in our companion paper (Butler et al. 2021; Table 1). This example only uses features, but the matrix can be expanded to include columns for functions for each connectivity category as well. Alternatively, the matrix can be connected to a table like Table 1 that shows how the features provide specific ecological and social functions.

An overview of the workflow to create a CPM and the associated tools is provided in Fig. 3. Definitions are provided in Table 2.

Step 1: Populate the connectivity planning matrix with goals and actions

The CPM provides the mechanism to capture management actions that support local goals and align them with the features and functions of connectivity (Figs. 2, 4). First, populate the CPM with the goals most important to the region and its communities and any specific actions that have been identified to support ecosystem connectivity, conservation, and restoration of ecosystem function. We recommend first populating the rows of the CPM with the goals and actions common among existing regional and local plans and supplementing that with ample stakeholder input.

Protecting water quality is featured in eight of the 15 Portland plans. We identified five actions from the plans and supported by the literature that advance water quality protection and connectivity. (A) Restore floodplains across the landscape to provide biofiltration (Brauman et al. 2007). (B) Restore riparian area along streams to reduce surface water runoff and sediment in streams. Stream sediments can lower oxygen levels, disrupting aquatic habitats and negatively impacting drinking water quality (Liu et al. 2020, McMahon et al. 2020). (C) Modify culverts to avoid erosion and amplification of sediment loads (Boardman et al. 2019). (D) Restore and reconnect upper watersheds to manage surface flow and groundwater storage (Brauman et al. 2007). (E) Minimize impervious surfaces to decrease runoff from urban roads that typically contain elevated levels of metals, polycyclic aromatic hydrocarbons (PAHs), and organic matter (McIntyre et al. 2015).

Step 2: Populate the connectivity planning matrix with connectivity features and functions

Most plans are organized in terms of goals and actions and do not consider if or how actions support connectivity. As such, plans may inadvertently fragment habitats, disrupt hydrologic and other geophysical processes, and disconnect humans from nature's systems. The CPM captures features and functions of connectivity that may have been overlooked in earlier planning. A CPM can be pre-populated using existing planning documents and then supplemented or refined through stakeholder input. By involving stakeholders with diverse cultural and experiential backgrounds, planners are more likely to include features of connectivity that support biodiversity and equity (Brondizio et al. 2009) in landscape-level design. The CPM captures connectivity features and functions organized by connectivity category across the top rows of the tool, and relative ranked values are assigned through stakeholder input if desired (Figs. 2, 5).

An optional but potentially powerful feature of the CBF tool is the RRVS. This ranking system can be employed to assist in prioritizing connectivity features and management actions that are most important to the stakeholders of a region or specific geographic area. In addition to helping identify which actions create the greatest benefits, the goal to rank the actions and features can catalyze a rich, facilitated community discussion about values and may also help identify additional actions,

Fig. 2. This Connectivity Planning Matrix provides the mechanism to rank management actions that support local goals and align them with the ranked features and functions of connectivity. In the far-left column, goals that support connectivity are captured along with actions that support each goal. In this case, the goals and actions were identified through a review of Portland planning documents. Each action receives a ranked value based on how well it supports connectivity. The ranked values (1–5) are assigned during planning sessions. Features of connectivity are listed across the top of the matrix. These features were identified in our companion paper (Butler et al. 2021) and in this example of the matrix were ranked based on the authors' perceived relative importance of these features based on a review of Portland planning documents. This example only shows features but can be expanded to have columns for functions for each category as well or can be connected to a table like Table 1 that shows how features provide specific ecological and social functions. If an action supports a connectivity feature, the corresponding cell is activated, and the product of ranks assigned to the action and feature are captured. The total value by action is captured in the far-right column providing a mechanism to rank the relative importance of actions based on how well they support connectivity. If a cell is blank, or especially if a whole high-value column is empty, there is opportunity to identify additional actions or modify an action to better support a desired feature of connectivity.

		CONNECTIVITY CATEGORIES & CONNECTIVITY FEATURES															
		HABITAT CONNECTIVITY				GEOPHYSICAL CONNECTIVITY					ECO-SOCIAL CONNECTIVITY						
	Ecosystem Connectivity Goals and Actions	Connected wildlife corridors (3)	Connected aquatic habitats (4)	Vegetated habitat patches (4)	Physical barriers removed (3)	Hydrologic connectivity (5)	Vegetated strips and patches for soil stability (4)	Connected floodplains (4)	Contiguous tree canopy and root systems (4)	Contiguous vegetated riparian areas (5)	Accessible green spaces within neighborhoods (4)	Accessible food production and gathering near neighborhoods (3)	Living wage green jobs within walking distance of targeted communities (5)	Clean water and clean air in neighborhoods (5)	Regional connected trail system (3)	Access to shade (5)	TOTAL
Goal 1: Protect Water Quality	**Action A: (4)** Restore flood plains		16	16	12	20	16	16	16	20	16	12	20	20			200
	Action B: (4) Restore riparian areas		16	16	12	20	16		16	20	16		20	20		20	192
	Action C: (3) Widen/remove culverts		12		9	15		12				9		15			82
	Action D: (5) Restore upper watersheds	15	20	20	15	25	20			25	20			25		25	210
	Action E: (4) Plant in paved areas			16	12	20					16	12	20	20		20	136

Low 1 2 3 4 5 High Value Gap

features, or functions. We recommend that these ranking exercises take place in inclusive meetings with communities impacted by land-use decisions. Any ranking scale can be used. For the purposes of illustration, we use a five-point RRVS of 1–5 with 1 being the lowest rank and 5 the highest. A relative ranking system allows planners and their stakeholders to consider both subjective and objective values, which may vary based on individual and community beliefs and attitudes (Jacoby 2011), in addition to real or perceived monetary benefits and costs if available and desirable.

Relative ranked values may be assigned to each connectivity feature. The assignment of ranked value may be most relevant at smaller scales like community-level planning, where the eco-social features may rank highest, and in areas managed for a specific purpose such as wildlife refuges, where habitat connectivity may rank high. In a wildlife refuge, habitat connectivity features may rank 5, whereas eco-social connectivity features, such as living-wage green jobs within walking distance of communities may rank 1. In an urban community, this ranking may flip. If both are considered equally important, they would receive the same rank. These rankings are assigned during the development of the CPM.

Step 3: Develop connectivity causal webs

Connectivity causal webs provide a mechanism to capture (1) multiple benefits and values from actions that increase ecosystem function, and (2) associated risks and risk mitigation approaches (Fig. 6). Developing CCWs can be a time-intensive process. However, in our experience, developing these CCWs trains people to think in terms of ecosystem functions that are dependent on ecosystem connectivity and to translate functions to the measurable benefits that derive from connectivity. Building these webs with diverse stakeholder groups may also result in unexpected co-benefits, unanticipated risks, and risk mitigation strategies. Planners may wish to partner with researchers or facilitators trained in ecosystem connectivity to build CCWs.

Table 2. Terms and abbreviations used in the Connectivity Benefits Framework

Abbreviation	Title	Description
CBF	Connectivity Benefits Framework	Set of tools and processes to guide connectivity planning
CPM	Connectivity Planning Matrix	Matrix that catalogs goals and actions, connectivity features and functions, and relative ranked values to aid in prioritization of initiatives.
CCC/CCW	Connectivity Causal Chain/Connectivity Causal Web	A method of linking management actions to changes in ecosystem function resulting in benefits and values, plus risks and costs. Using the Relative Ranked Value system, a net value may be assigned to the management actions.
Rank/RRV	Relative Ranked Values	The method used to rank the relative value of connectivity features and functions and the management actions that support them. It is ultimately used to prioritize those actions that support multiple connectivity functions.

For example, in support of the goal to protect water quality, a CCW captures the multiple benefits of increased water filtration and water quantity regulation by increasing vegetation along streams. Measurable BRIs could include helping to meet the Total Daily Maximum Load (TMDL) standards set by the Oregon's Department of Environmental Quality (DEQ) for a particular waterway. The multiple benefits and values of increasing riparian vegetation are: reduced rates of cyanobacteria blooms (Moore et al. 2008); improved salmonid survival rates (McIntyre et al. 2015); reduced cost of flood damage (Yang and Zhang 2011); decreased cost of illness from toxic chemical contaminants like arsenic, mercury, and atrazine (Easter and Konishi 2007); and reduced sediment input that decreases water treatment costs (Green et al. 2016). Each of the benefits could be translated into monetary terms if practical or desirable; however, monetary values of the multiple benefits are not needed for this process if stakeholders can agree on their relative value to the community.

During the development of the CCWs, each BRI/ benefit may be assigned a ranked value. Risk-relevant indicators/risks are also assigned a ranked cost. The net value of each web is decided by discussion. If the RRI can be mitigated without substantial cost, it may not negatively influence the net value. If an RRI cannot be mitigated, it may reduce the rank of the management action from a net 5 to a net of 1 to 4 depending on the significance of the risk and potential cost. The net ranked value of the management action is recorded in the CPM (Fig. 2).

Step 4: Record connectivity features and functions supported by actions, modify actions to support gaps
To visualize how well management actions support the various functions of connectivity, check the box/cell when a management action supports a specific connectivity feature and function. Optionally, as part of the RRVS, the checks in the boxes can be replaced with values by multiplying the ranked value for each connectivity feature or function (from step 2) with the value for each action (from CCWs, from step 3). The values for each action (row) can then be summed and recorded in the last column, which helps identify which actions can create the greatest benefits (Fig. 2).

Step 5: Identify gaps
To identify opportunities to increase connectivity, highlight gaps in the CPM where connectivity features are not supported. In conversation with stakeholders, add or modify actions to address these gaps. For example, planting vegetation in neighborhoods could provide accessible living wage jobs if the action includes this criterion. Check additional boxes as appropriate. This method can be applied at both small and large scales. Through this iterative process, management actions may evolve once stakeholders are able to visualize the multiple and overlapping benefits of actions encouraging design innovation. Collaborative models are a dynamic process, not a fixed result (Parrott 2017). As plans evolve and needs change, management actions may be redesigned to better address multiple facets of connectivity.

APPLYING THE CONNECTIVITY BENEFITS FRAMEWORK TO LIGHT RAIL PROJECT

An expansion of Portland Metro's light rail system into the southwest section of the region aims to reduce passenger vehicle traffic to relieve congestion, decrease air pollution, and meet carbon-reduction targets, among other goals. The expansion extends from downtown Portland to the cities of Tigard and Tualatin 17.7 km southwest. However, the rail network threatens to further disrupt ecosystem connectivity. Here, we show how the CBF can be used to identify opportunities to minimize disruption of connectivity while still meeting all its stated goals. Ideally the CBF would be populated in planning meetings with transdisciplinary teams of transportation experts, engineers, ecologists, natural resource managers, researchers, planners, and community representatives to maximize all types of ecosystem connectivity alongside social connectivity.

For this example, the goals used to populate the CPM were extracted from the Southwest Corridor Draft Environmental Impact Statement (Federal Transit Administration et al. 2018). The matrix can then be brought to planning meetings with the array of stakeholders to stimulate discussion. Action items were developed in a planning meeting with a natural resource and landscape manager with the aim of minimizing disruption of ecosystem function and incorporating nature into the design. Applying the CPM to this project identified management actions

Fig. 3. Connectivity Benefits Framework Workflow. There are five steps to the CBF. (1) Populate the CPM with goals and actions from plans and/or stakeholder interviews. (2) Fill in connectivity features and functions from plans or interviews guided by examples provided in Table 1 and our companion paper (Butler et al. 2021) and, optionally, assign relative ranked values to each feature and function. (3) Develop Connectivity Causal Webs (CCWs) capturing BRIs and RRIs. Connectivity Causal Webs can be pre-developed, then expanded in workshops. Optionally, assign relative ranked values to each BRI/Value and RRI/Cost and assign a relative ranked net value to the action. (4a) Fill in the cells of the matrix when an action supports a feature or function; (4b) Capture the net relative ranked value assigned from the CCWs into the cells of the CPM. (5) Identify gaps where features and functions are not supported. Add and modify actions and adjust relative ranked values of actions accordingly. Populating the matrix can be an iterative process, so after step 5, a planning group may revisit Step 1.

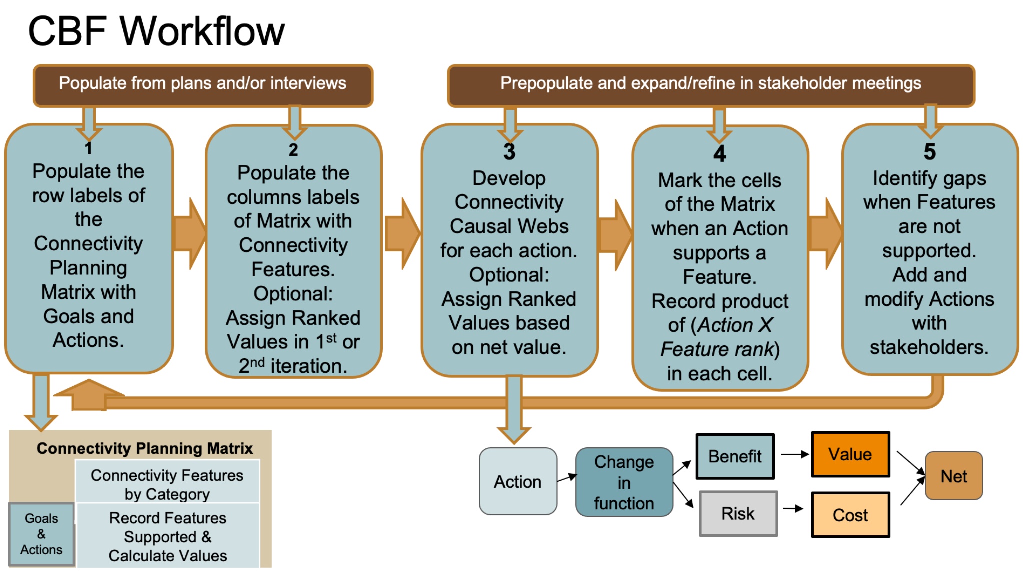


Fig. 4. The Connectivity Planning Matrix (CPM) template lists Connectivity features and functions organized by connectivity category along the top of the template of the CPM. The rows of the CPM display connectivity goals and actions important to the stakeholders of the region. Examples of goals that support healthy, resilient cities extracted from Portland plans, are shown in the lower left box, labeled "Connectivity Goals for Healthy, Resilient Cities." Each goal is supported by a series of actions captured in the CPM. Shown here, in the box on the bottom right, are examples of actions that support Goal 2: Protect Water Quality.

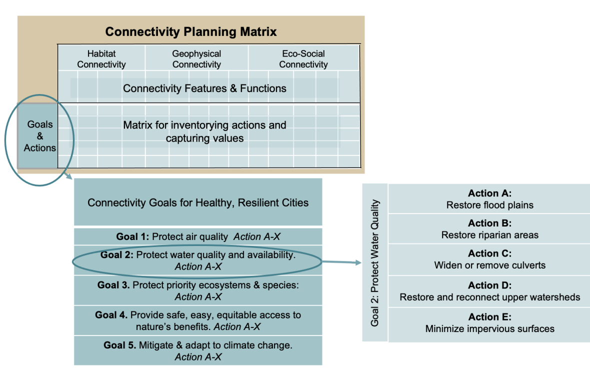


Fig. 5. The Connectivity Planning Matrix captures connectivity features and functions organized by connectivity category in columns across the top of the template. Here, as an example, five connectivity features and functions of geophysical connectivity are captured in the columns below the geophysical connectivity header. Each is assigned a relative ranked value of importance from a low of 1 to a high of 5 based on their relative local importance as identified in planning sessions.

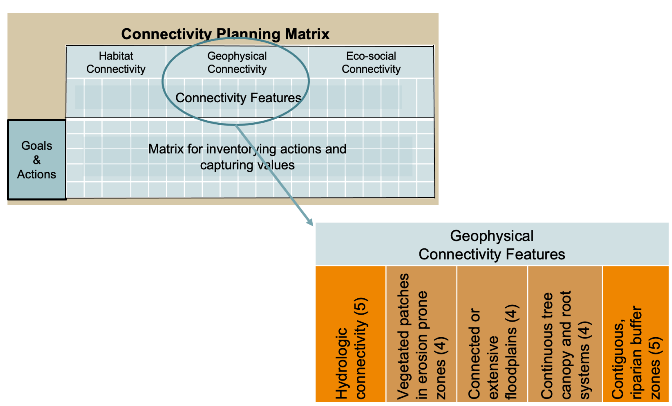
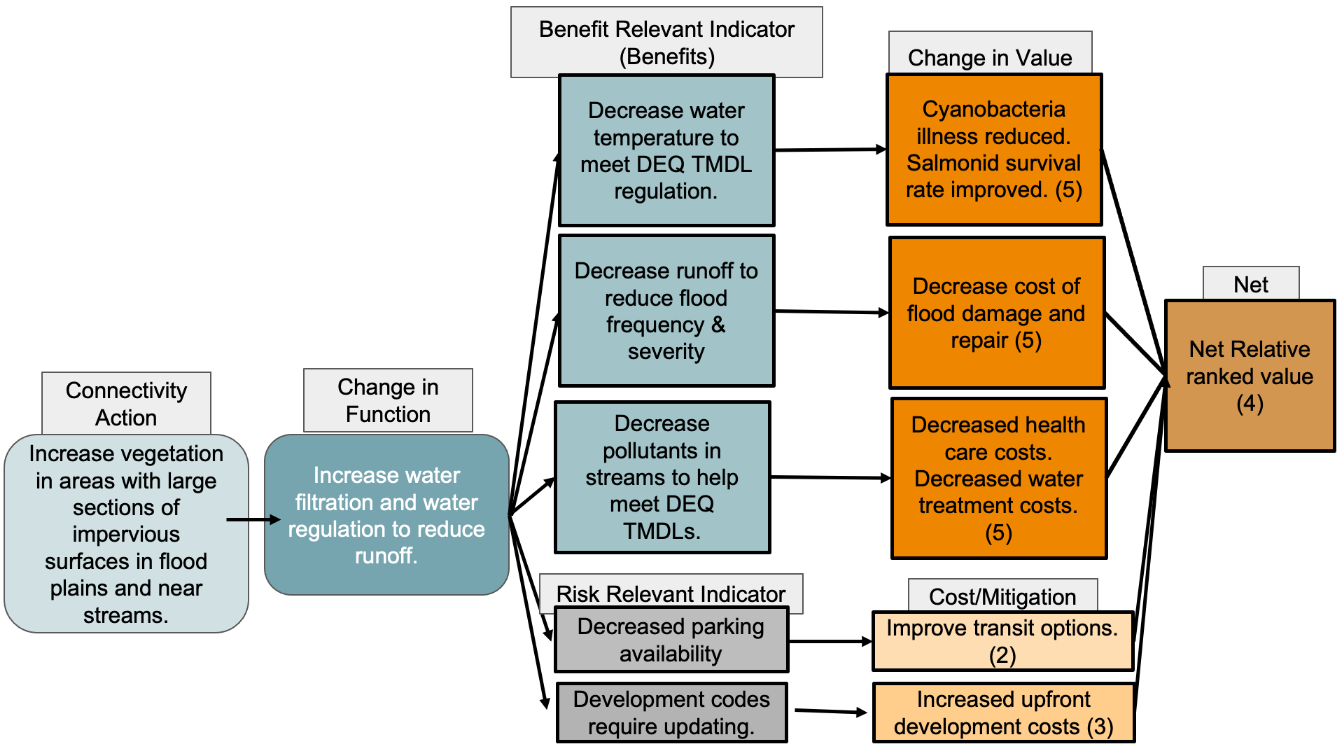


Fig. 6. This example of a Connectivity Causal Web captures the benefits, values, and risks of restoring native vegetation along streams. Here, the action of restoring native vegetation along streams increases water filtration thereby reducing runoff into streams. Three BRIs are identified: (1) decreased water temperatures, (2) decreased runoff thereby flood frequency, and (3) decreased pollutants. Each benefit is assigned a ranked value of 5 based on the relative importance of these initiatives to a region. Two RRIs are identified: (1) decreased parking availability, which could be mitigated by improving transit options to the area so a relative ranked value of 2 is assigned, and (2) updated development codes may result in increased upfront development costs so is assigned rank of 3. When weighed against three ranked values of 5 assigned for each BRIs, the total relative ranked net value assigned is 4 out of a possible 5. Here, these are relative ranked values, so the values are not added together. There is subjectivity involved in assigning ranks based on the stakeholders' beliefs and perceptions.

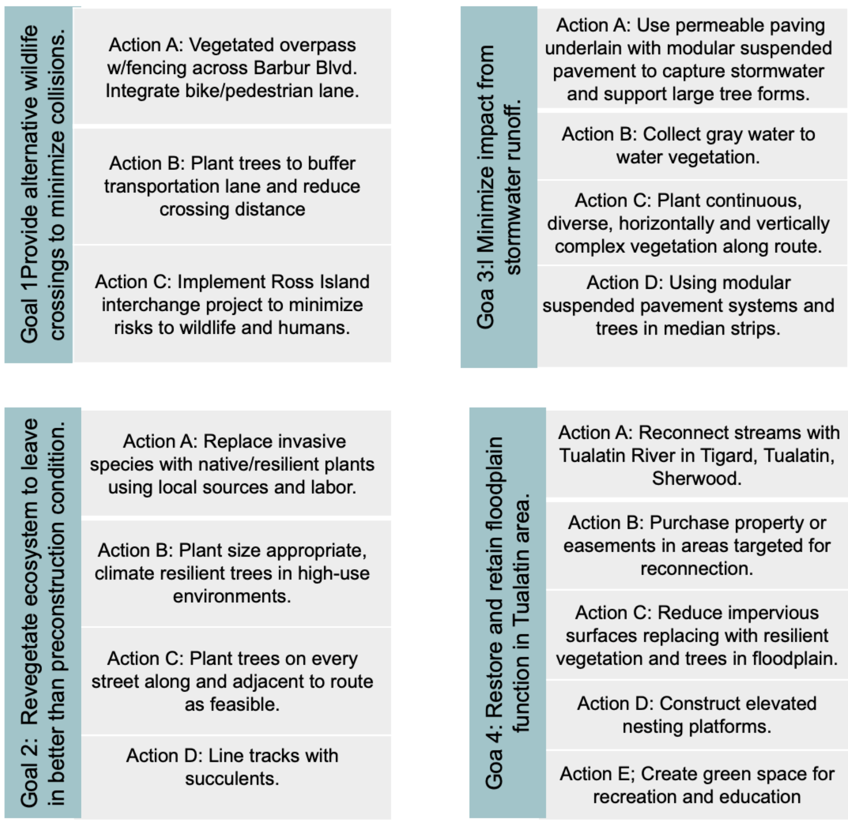


designed to support as many aspects of connectivity as feasible. Examples of goals and actions that support multiple connectivity features and functions are shown in Fig. 7. An example of a CCW with relative ranked values assigned, is provided in Fig. 8. These values were assigned based on the authors' perception of values based on planning documents and discussions with practitioners. An abbreviated version of the CPM that captures the connectivity features supported (and not supported) by actions that correspond with the four goals for this project is provided in Fig. 9. For ease of reading Fig. 9, the actions identified in support of these four goals are not listed in Fig. 9 but can be found in Fig. 7.

In this example of a CCW (Fig. 8), Goal 4 calls for restoring and retaining flood plains in the Tualatin River area. Sample management actions that support this goal include: (1) Reconnect streams with the Tualatin River in Tigard, Tualatin, and Sherwood; (2) Purchase property for easements in areas targeted for reconnection; (3) Reduce impervious surfaces, replacing them with resilient vegetation, including trees; (4) Build elevated nesting platforms to support local raptor populations; and (5) Create green space for recreation and education. Although these latter two actions might not immediately come to mind, especially if considering this goal only with a geophysical connectivity lens, it is important to think broadly here to capture as many of the connectivity categories or associated features and functions as possible when creating a CCW and CPM.

The CCW illustrates the multiple benefits that were identified for the variety of actions that together would increase water filtration and water regulation (Fig. 8). Decreased water temperatures should reduce cyanobacteria and rates of illness and improve salmonid survival rates. Decreased runoff reduces flood frequency and severity, reducing damage and repair costs and potentially reducing insurance rates. Decreased pollutants in waterways would help meet water quality standards, decrease health care costs, and water treatment costs. Increased wildlife habitats in strips and patches would protect biodiversity and

Fig. 7. Four goals gathered from the Southwest Corridor Light Rail Environmental Impact Statement (Federal Transit Administration et al. 2018) are used to populate the left-hand column of the Connectivity Planning Matrix. Actions that support multiple connectivity features are listed for each goal and are captured in the rows of the CPM. For ease of reading, the goals and actions are presented as snapshots from the CPM in this figure.

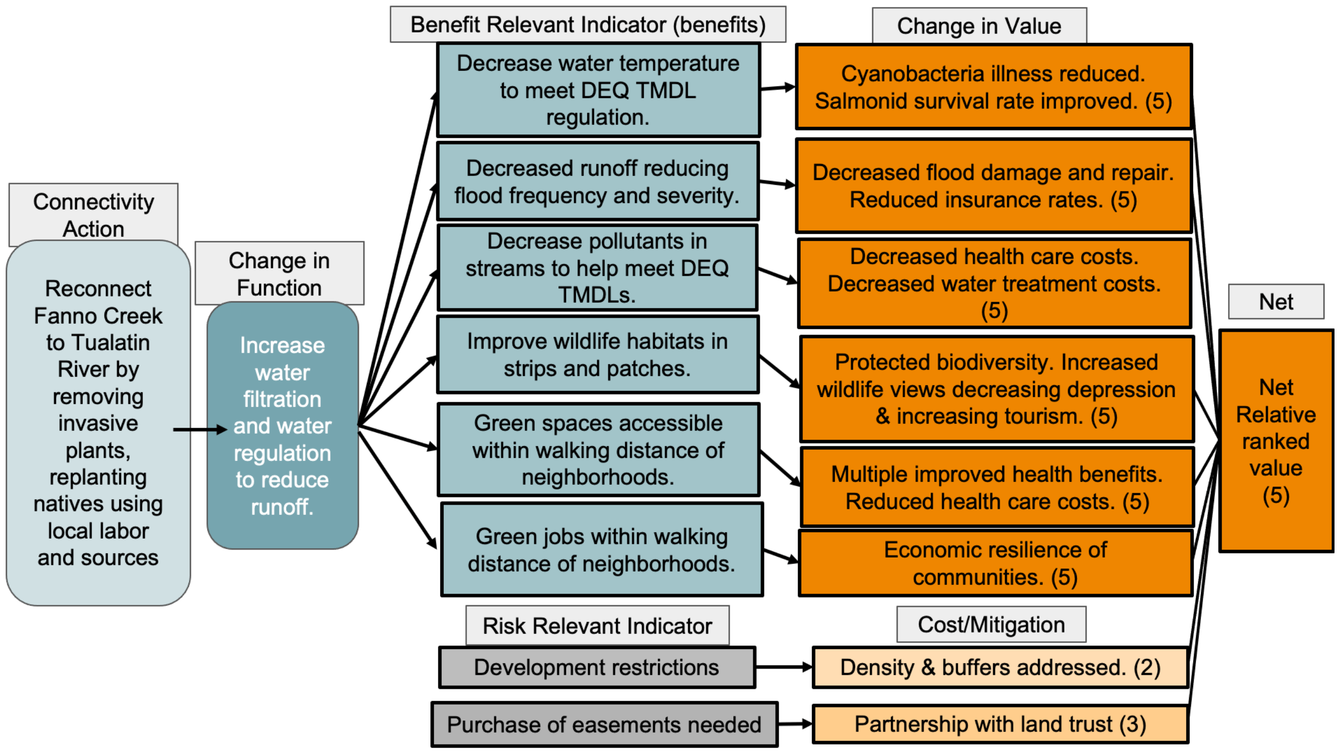


increase wildlife views, which can decrease rates of depression and increase tourism. Green spaces would be accessible within walking distance of neighborhoods, improving human health. Green jobs may even be made available supporting local economies and economically resilient communities. Two potential risks were identified: (1) the need to update development restrictions and resistance to such restrictions from businesses and residents; and (2) the cost of purchasing easements. The cost to local taxpayers of easements could be mitigated by developing partnerships with a land trust that has a local presence such as The Nature Conservancy. Each value was given the highest relative ranked value (RRV) of 5 based on the high perceived importance of each of the six BRIs. The costs associated with both risks were assigned a relative low rank and can be addressed through mitigation. Therefore, the overall net ranked value (NRV) was given the RRV of 5.

During the process of developing and refining the CCWs, one action (Action A in support of Goal 4) was further modified so that it could better support multiple features and functions of connectivity: Reconnect Fanno Creek to Tualatin River could align with Action A of Goal 2, removing invasive plants and replanting native species, because having a more diverse set of plant roots can decrease runoff and subsequent flood severity. A further associated action that could be added to support eco-social connectivity would be to hire local labor and nurseries to alter the vegetation. Indeed, in reviewing current actions, it is useful to look for complementary actions that can support other types of connectivity so the most co-benefits are realized.

Additionally, vegetated overpasses and underpasses can facilitate wildlife movement across the city. Such movement would reduce genetic isolation and animal–vehicle collisions, thereby protecting wildlife species and human safety (Corlatti et al. 2009). Relative risk indicators to consider included building and maintenance costs, risk of attracting houseless camps, which could increase safety concerns. These risks and costs would require mitigation strategies. Preserving connections among multiple habitat types by planting diverse tree species and vegetation along the route can increase pollinator and bird habitats and provide migration paths (Husté and Boulinier 2007, Dornier and Cheptou 2012). Construction of route-adjacent biking and walking trails with diverse vegetation provides recreation opportunities and views of green spaces. These paths reduce runoff of contaminants into

Fig. 8. This example of a Connectivity Causal Web captures benefits (BRIs) resulting from reconnecting Fanno Creek to the Tualatin River (Connectivity Action) and their associated values (Change in Value), risks (RRIs) and associated costs and/or mitigation approaches (Cost/Mitigation). This example of a Connectivity Action supports Goal 4: Restore and Retain Flood Plain function in the Tualatin area. Each value was given the highest relative ranked value of 5. The costs associated with the risk both have a relative low rank and can be addressed through mitigation, therefore the overall net ranked value assigned is 5.



waterways (McIntyre et al. 2015) and can double as wildlife corridors. Risk-relevant indicators include potential damage to the systems from tree roots and tree maintenance cost. These costs may be minimized through innovative designs that emerge through connectivity planning discussions.

Integrating connectivity features across the network can also result in system-wide benefits. For example, increasing the tree canopy can increase carbon sequestration, offsetting greenhouse gas emissions (Nowak and Crane 2002). The provision of shade from trees reduces heat-related illness and mortality (Hardin and Jensen 2007, Kravchenko et al. 2013). Increased tree canopy improves air quality by reducing NO_2, resulting in reduced health care costs from pulmonary illness (Rao et al. 2014, Elmqvist et al. 2015).

DISCUSSION

Integration of connectivity features and protecting ecosystem function across broad landscapes is an emerging and important discipline. However, reintegrating nature into and across urban environments typically lacks design standards, regulatory pathways, and financing methods (Zuniga-Teran et al. 2020). Perhaps the biggest challenge is the lack of standardized methods to assign values to the benefits of nature and natural systems and tools to garner support for broader scale projects. Identifying and bundling the values of ecological benefits of large, reconnected ecosystems in terms that are understandable and relevant to local stakeholders from diverse backgrounds and cultures is more likely to result in broadly adopted management actions and land-use choices supporting connectivity (Deal et al. 2012) and equity (Maia et al. 2020).

The CBF not only captures prioritized actions that support connected ecosystems but guides holistic thinking about managing urban lands. The CPM provides a method to identify management actions that meet an array of needs. Through the process of collaborative planning across broad landscapes with diverse and transdisciplinary planning participants, commonality of goals and unexpected partnerships may emerge (Flitcroft et al. 2016).

Highlighting the categories of connectivity can help broaden thinking about ecosystem function and remind ecologists, practitioners, and planners of the importance of including people as part of ecologically focused land-use planning and research. Moreover, such approaches can improve equity and racial justice by facilitating inclusive engagement of communities and developing innovative solutions that meet the needs of the people

Fig. 9. This example of a Connectivity Planning Matrix displays connectivity features supported by actions that help achieve four of the goals from the Southwest Corridors Light Rail Project Environmental Impact Statement (Federal Transit Administration et al. 2018). The actions in support of the four goals that support these features are listed in Fig. 7. The actions were captured during the development of the Connectivity Causal Web exercise. For the purposes of this example, relative ranked values are not assigned.

	CONNECTIVITY CATEGORIES & CONNECTIVITY FEATURES														
	HABITAT CONNECTIVITY				GEOPHYSICAL CONNECTIVITY					ECO-SOCIAL CONNECTIVITY					
Connectivity Goals for Southwest Corridor Light Rail Project	Connected wildlife corridors	Connected aquatic habitats	Vegetated habitat patches	Physical barriers removed	Hydrologic connectivity	Vegetated strips s in erosion prone zones	Connected or extensive floodplains	Contiguous tree canopy and root systems	Contiguous vegetated riparian areas	Green spaces within walking distance of neighborhoods	Accessible food production and material gathering near neighborhoods	Living wage green jobs within walking distance of communities	Clean water and clean air in neighborhoods	Regional connected trail system	Access to shade
Goal 1: Provide wildlife crossings with pedestrian & bike access. (Actions A-C)	x		x	x		x				x				x	
Goal 2: Revegetate to better condition than preconstruction. (Actions A-D)			x	x		x			x	x		x	x		x
Goal 3. Minimize impact from storm water runoff. (Actions A-D)					x	x	x		x				x		x
Goal 4. Restore and retain flood plain function in Tualatin. (Actions A-E)		x	x	x	x	x	x		x	x		x	x	x	

while supporting biodiversity and ecological function (Brondzio et al. 2009, Jennings et al. 2012, Zuniga-Teran et al. 2020). Importantly, the process of identifying synergies among connectivity-related goals, identifying the many benefits of connected ecosystems, and acknowledging risks and costs, can be used to garner support for broad-scale connectivity projects. With the CBF, we provide a common language, tools, and processes that together enable coordination and collaboration across goals and communities to help this holistic thinking and support all types of connectivity.

CONCLUSION

Although it is challenging to address urban land-use planning at a regional scale, there is opportunity to gain broad support for restoring ecosystem function across landscapes. Such support and effort can increase resilience of urban systems that face rising levels of disturbance. As common terminology, tools, and inclusive processes become more widely used, the multiple and overlapping benefits of functional connected ecosystems should be more commonly highlighted and valued. Ecosystem connectivity can become foundational to urban planning. The CBF provides tools and a process to capture design solutions, develop best management practices, and identify policies that support ecosystem connectivity while advancing environmental and racial justice across regions. Through collaborative partnerships across transdisciplinary teams, innovative financing solutions may be developed as communities consider the myriad benefits of restoring functionally connected ecosystems and the incalculable cost of continued loss of biodiversity and human well-being.

Responses to this article can be read online at:
https://www.ecologyandsociety.org/issues/responses.php/13371

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Data Availability:

The data used to prepare this manuscript are available in Appendix 2.

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Appendix 1: List of Portland plans reviewed

To populate the tools of the Connectivity Benefits Framework (CBF), we compiled goals that support ecosystem connectivity from Portland regional, city and community plans. Fifteen plans fit the criteria of still being in use by organizations, and having been published between 2005 and 2018 in the Portland Metro region. Cross disciplinary and multi-organizational teams participated in the development of these plans capturing goals and objectives most important to local decision makers and community groups thereby also serving as a credible way to pre-populate the CBF tools prior to working with stakeholders. Only some of the plans explicitly include connectivity goals, objectives or actions as recorded in Table A1.1. The community level plans reviewed did not explicitly reference ecosystem connectivity objectives although they commonly highlighted socio-cultural values tied to ecosystem function.

Table A1.1 List of Portland Area Plans Reviewed

PLAN NAME	PRODUCED BY	REGION	YEAR PUB.	WHY SELECTED	EXPLICITLY INCLUDES CONNECTIVITY GOALS
2035 Comprehensive Plan	City of Portland	Multnomah County	2016	Guides how and where land is developed and infrastructure projects	Yes
Actions for Watershed Health: 2005 Portland Watershed Management Plan	City of Portland Bureau of Environmental Services (BES)/ Portland Parks and Recreation (PP&R), Bureau of Planning	Columbia Slough, Fanno Creek, Johnson Creek, Tryon Creek, Willamette River	2005	Plan currently used by BES as a system wide technical foundation by which to manage Portland's five watersheds.	Yes
Afro-Ecology Movement: An environmental movement for the Pan-African	NGO: The Portland African American Leadership	Portland Metro region	2018	Addresses environmental and climate justice issues for African Americans	Yes

communities of Portland	Forum (PAALF) & Africa House			residents of Multnomah including immigrants and refugees.	
Portland Urban Forestry Management Plan	City of Portland: Portland Parks and Recreation (PP&R)	Multnomah County	2004	Specifically addresses the management of the flora and fauna within the City of Portland	Yes
Clackamas County Comprehensive Plan	Clackamas County	Clackamas County	2001 with later amend-ments	Identifies land use by individual sites based on regional goals. Covers all of Clackamas County.	No
Clean Water Services Healthy Stream Plans	Clean Water Services - Contracted Utility for Tualatin River	Tualatin River watershed. Primarily Washington County.	2005	Responsible for Tualatin River watershed in Washington County with a focus on in-stream water quality	Yes
Greater Forest Park Conservation Initiative	NGO: Forest Park Conservancy & Forest Park Alliance (government and non-government agency collaborative)	Forest Park and surrounding private lands located in Multnomah County	2013	Sets out conservation initiatives specific to this unique 10,000 acre area of urban forest.	Yes
The Intertwine Regional Conservation Strategy	Intertwine Alliance (partnership of government and	Portland Metro region and Vancouver, Washington.	2012	Conservation initiative covering the Portland and Vancouver region. The only regional	Yes

	non-government agencies)			plan.	
Living Cully Community Energy Plan	NGO Partnership:: Living Cully (Verde, NAYA, Hacienda, Habitat for Humanity)	Cully neighborhood in Multnomah County (NE Portland)	2018	Used as a model for other underserved communities. Addresses displacement and environmental injustice.	No
Metro: Regional Transportation Plan	Metro - Regional Government Bureau	Clackamas, Multnomah & Washington Counties	2018	Regional transportation plan. Guides the individual county transportation plans.	Yes
Metro: Urban Growth Management Functional Plan	Metro - Regional Government Bureau	Clackamas, Multnomah & Washington Counties	2018	Includes 2040 metro growth concept, goals and objectives.	Yes
Multnomah County and the City of Portland: Climate Change Preparation Strategy: Risk and Vulnerability Assessment	City of Portland and Multnomah County	Multnomah County	2014	Establishes long-term adaptation and mitigation strategies including land use planning goals.	Yes
On the Frontlines of Climate Change of Voz	NGO: Voz environmental justice organization representing workers' rights	Portland Metro region	2018	Addresses environmental and climate justice issues for vulnerable day laborers and immigrants.	No
The People's Plan PDX	NGO: PAALF	Multnomah County - NE	2018	Documents Portland's Black	No

		and East Portland		community inequalities and disparate impacts. Addresses policy and law issues.	
Tyee Khunamokwst "Leading Together": Environmental Justice Framework NAYA-CCC-OPAL	NGO: Communities of Color	Portland Metro region	2017	Addresses displacement and gentrification issues for people of color in the Portland metro area.	No
Washington County: Comprehensive Framework Plan for the Urban Area Volume II	Washington County	Washington County	2017	Sets long range land use strategies for one of the three Portland metro counties.	No

Appendix 2 Connectivity goals and objectives supported by Portland plans

To develop the Connectivity Benefits Framework (CBF) process and to demonstrate how to populate the CBF tools, we reviewed regional, city, county, and community planning documents that were published between 2005 and 2018 for the Portland Metro region. Cross disciplinary and organizational teams participating in the development of these published planning documents capturing key goals and objectives most important to local decision makers and community groups. We recorded all goals and objectives that support connectivity features and functions that were documented in these plans in a spreadsheet using the key below (Table A 2.1). We then identified the type of connectivity that could help achieve the objectives and goals and identified the desired change in ecosystem function resulting from potential management actions. We tallied the goals and objectives from each plan (Table A2.2). Those more frequently cited within and across plans were assigned a higher Rank in examples of Connectivity Causal Webs and Connectivity Planning Matrices included in this paper.

Table 2.1

Code	**Name of Plan**	**Publishing Entity**
35CP	2035 Comprehensive Plan	City of Portland
BES	Portland Watershed Plan	Portland Bureau of Environmental Services
FP	Greater Forest Park Conservation Initiative	Forest Park Alliance
HSP	Healthy Streams Plan	Clean Water Services
RCS	Regional Conservation Strategy	The Intertwine Alliance
RVA	Climate Change Preparation Strategy: Risk and Vulnerability Assessment	City of Portland/Multnomah County
TP	Metro Regional Transportation Plan	Metro Regional Government
UFP	Portland Urban Forest Management Plan	Portland Parks and Recreation
UG	Urban Growth Boundary Management Functional Plan (updated)	Metro Regional Government
WC	Washington County Comprehensive Plan	Washington County

Table 2.2. Connectivity goals and objectives support by Portland Plans

		HABITAT CONNECTIVITY FEATURES/FUNCITONS			
		Connected, quality terrestrial habitat	Connected, quality aquatic habitat	Reduced hazards to organisms in urban matrix	Biological functions/services where valuable
Infrastructure	Enable community access to nature and greenspace	BES, FP, HSP, RCS, TP [5]	BES, FP, HSP, RCS, TP [5]	BES, FP, HSP, RCS, TP, UFP [6]	35CP, BES, RCS, (RVA), TP, UFP, UG [7]
Infrastructure	Improve efficiency and effectiveness of transportation	RCS, TP, (UG) [3]	RCS, TP [2]	RCS, TP, UFP [3]	TP [1]
Infrastructure	Maintain greenspace and natural resources in urban landscape	35CP, BES, FP, HSP, RCS, UG [6]	BES, FP, HSP [3]	35CP, BES, FP, HSP, (RVA), UFP, (UG) [7]	35CP, BES, FP, HSP, RCS, (RVA), UFP, WC [8]
Infrastructure	Mitigate negative impacts of infrastructure	RCS [1]	BES, HSP, RCS [3]	BES, FP, RCS, (RVA), TP [5]	35CP, BES, FP, HSP, RCS, (RVA), TP, UFP [8]
Infrastructure	Reduce disaster hazards and increase resilience	[0]	[0]	[0]	35CP, BES, FP, HSP, RCS, (RVA) TP, UFP [8]
Biodiversity	Conserve and restore priority ecosystems in urban landscape	BES, FP, RCS [3]	RCS [1]	BES, FP [2]	35CP, BES, FP, HSP, RCS, (RVA), UFP, UG [8]
Biodiversity	Conserve and recover priority species in urban landscape	BES, FP, HSP, RCS [4]	BES, FP, HSP, RCS [4]	BES, FP, HSP, RVA [4]	35CP, BES, FP, HSP, RCS, (RVA), UFP [7]
Biodiversity	Contain spread and manage impacts of invasive species	[0]	[0]	BES, FP, (RVA) [3]	BES, FP, RCS, (RVA), UFP [5]
Biodiversity	Enable species and ecosystems to adapt to climate change	FP [1]	[0]	BES, FP [2]	35CP, FP, RCS, (RVA), UFP [5]
Water	Meet or exceed water quality and quantity goals	[0]	BES, HSP [2]	RCS, UFP [2]	35CP, BES, HSP, RCS, (RVA), UFP, (UG), WC [8]
Water	Protect usability and function of water resources	FP, RCS [2]	BES, FP, HSP [3]	BES, FP, HSP, RCS, TP [5]	35CP, BES, FP, HSP, RCS, (RVA), UFP, (UG), WC [9]
Society	Equitably improve environmental quality of life in communities	(BES), RCS [2]	(BES), RCS [2]	(BES), RCS [2]	35CP, BES, RCS, RVA, UFP, UG [6]
Society	Equitably include stakeholders in planning	RCS [1]	RCS [1]	RCS [1]	RCS, UFP [2]
Society	Reduce societal barriers to accessing nature and ES	[0]	[0]	FP, RCS, TP [3]	35CP, (BES), RCS, UFP, UG [5]

GEOPHYSICAL CONNECTIVITY FEATURES/FUNCTIONS			
Hydrologic function and water quality	Air quality and climate regulation	Stability of soils and geology	Regulation of disturbance processes
BES, FP, RCS, TP [4]	BES, FP, RCS [3]	FP, RCS [2]	[0]
RCS, TP, UFP [3]	RCS, TP [2]	RCS [1]	[0]
35CP, BES, FP, HSP, RCS, (RVA), TP, UG [8]	35CP, BES, FP, HSP, RCS, RVA, TP, UG [8]	35CP, BES, FP, RCS, UG [5]	35CP, BES, FP, HSP, RCS, (RVA), UG [7]
HSP, RCS, RVA, TP [4]	BES, FP, RCS, (RVA), TP [5]	BES, FP, RCS [3]	35CP, BES, FP, HSP, RCS, (RVA) [6]
UFP [1]	[0]	35CP, (HSP), UG [3]	35CP, BES, FP, HSP, RCS, (RVA), WC [7]
HSP [1]	[0]	[0]	BES, FP, HSP, RCS [4]
BES, FP, HSP, (RVA), UFP, WC [6]	BES [1]	(HSP) [1]	BES, HSP, RCS [3]
BES, HSP [2]	[0]	[0]	BES, FP, HSP, RCS [4]
BES, FP [2]	[0]	[0]	35CP, RCS, RVA [3]
35CP, BES, FP, HSP, RVA, TP, UG [7]	(RVA) [1]	BES, FP, HSP, (RVA) [4]	35CP, BES, HSP, RCS, (RVA), UG [6]
35CP, BES, FP, HSP, UG [5]	WC [1]	BES, FP, HSP [3]	35CP, BES, FP, HSP, RCS, (RVA), UG [7]
35CP, BES, RCS, RVA, UFP [5]	35CP, RCS, RVA, UFP [4]	35CP, (BES), RCS, UFP [4]	35CP, (BES), RCS, RVA, UFP [5]
RCS, RVA, UFP [3]	35CP, RCS, (RVA) [3]	RCS, (RVA) [2]	RCS [1]
TP [1]	TP [1]	[0]	RCS [1]

ECO-SOCIAL CONNECTIVITY FEATURES/FUNCTIONS			
Access to nature	Human health and wellbeing	Community resilience and prosperity	Environmental equity and justice
BES, FP, RCS, TP, UFP, UG, WC [7]	FP, RCS, TP, UFP [4]	(BES), RCS, (RVA), TP, UG [5]	TP, UG [2]
RCS, TP, UFP [3]	RCS, TP, UFP [3]	35CP, (RVA), TP, UG [4]	RCS, TP, UFP, UG [4]
35CP, FP, RCS, UFP, UG [5]	35CP, FP, RCS, RVA, UFP, UG [6]	35CP, (BES), HSP, RCS, (RVA), UG [6]	35CP, RCS, RVA, UG [4]
FP, RCS, TP, UFP [4]	RCS, (RVA), TP, UFP [4]	35CP, (BES), HSP, RCS, (RVA), TP [6]	RCS, (RVA) [2]
[0]	35CP, UG [2]	35CP, (BES), HSP, RCS, (RVA), TP [6]	TP [1]
RCS [1]	RCS [1]	(BES), HSP, RCS [3]	[0]
RCS [1]	RCS [1]	(BES), RCS [2]	[0]
[0]	(RVA) [1]	(BES), RCS [2]	[0]
[0]	[0]	(BES), RCS, (RVA) [3]	[0]
[0]	BES, FP, HSP, RVA [4]	35CP, BES, HSP, RCS, (RVA) [5]	HSP [1]
35CP [1]	BES, FP, HSP, (RVA) [4]	35CP, BES, HSP, RCS, (RVA) [5]	(RVA) [1]
35CP, (BES), RCS, RVA [4]	35CP, (BES), RCS, RVA, UFP [5]	35CP, (BES), RCS, RVA, TP, UFP, UG [7]	35CP, (BES), RCS, RVA, UFP [5]
35CP, RCS, TP, UFP [4]	35CP, RCS, TP, UFP [4]	(BES), RCS, TP, UFP [4]	35CP, (HSP), RCS, TP, UFP [5]
35CP, (HSP), RCS, TP, UFP, UG [6]	35CP, FP, RCS, (RVA), TP, UFP [6]	RCS, RVA. TP, UFP [4]	35CP, RCS, TP, (RVA), UFP [5]

Appendix 3 – CBF Tool Access

Access to the CBF software tool is provided on the website listed below. A PDF of the companion paper (Butler et al. 2021) is also available on this site https://deriveralab.wordpress.com/publications.