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Human well-being and natural infrastructure: assessing opportunities for equitable project planning and implementation

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There is consensus within psychological, physiological, medical, and social science disciplines that active and passive exposure to nature enhances human well-being. Natural infrastructure (NI) includes elements of nature that can deliver these ancillary well-being benefits while serving their infrastructure-related purposes and, as such, offer great promise for agencies including the U.S. Army Corps of Engineers as a means of enhancing economic, environmental, and societal benefits in civil works projects. Yet, to date, NI are typically framed as alternatives to conventional infrastructure but are rarely competitive for project selection because there is no standardized approach to demonstrate their value or justify their cost. The infrastructure projects subsequently selected may not maximize societal well-being or distribute benefits equitably. A framework is needed to capture diverse and holistic benefits of NI. As part of ongoing research, this paper describes the components necessary to construct a framework for well-being benefits accounting and equitable distribution of NI projects and explores how they might be applied within a framework. We conclude with methodological examples of well-being accounting tools for NI that are based on ongoing research and development associated with this project. The findings provide insights and support for both the Engineering with Nature community and the community of NI practitioners at large.

KEYWORDS

well-being, nature-based solutions, equity, benefits accounting, nature-deprived communities, environmental justice

1 Introduction

Natural Infrastructure (NI) refers to an area or system that is naturally occurring, naturalized (i.e., converted from grey infrastructure to natural), or constructed to mimic naturally occurring, ecological or geological features and then intentionally managed to enhance ecosystem value and provide social and economic benefits (DiFrancesco et al., 2015; Roy, 2018). An expanding body of research highlighting the diversity of benefits that can be achieved by NI—such as building coastal resilience (Bridges et al., 2015), mitigating and adapting to climate change (Griscom et al., 2017; Choi et al., 2021), and enhancing biodiversity conservation (Key et al., 2022; McKay et al., 2023; van Rees et al., 2023a, 2023b)—has prompted greater demand for their use to meet traditional engineering objectives (e.g., mitigate flood risk). As such, efforts are underway to facilitate the use of NI because an array of advancements is needed to overcome challenges that accompany implementing as-of-yet unconventional projects. The need for such advancements is confirmed in the U.S. Executive Office of the White House "Roadmap", which calls for federal agencies in the US to update policies and conduct research to fill knowledge gaps and build the evidence base (White House Council on Environmental Quality et al., 2022).

Research and development are progressing to both improve the evidence base for NI and translate that evidence into accounting methods that practitioners can employ in project alternative analysis. Enumeration of benefits is an important task in new project justification, both for formal economic analysis as well as for stakeholder buy-in, and for which a need for greater comprehensiveness has been expressed (e.g., James, 2020, 2021). In essence, planners must build a business case to establish that projects are justified by the public benefit they will yield. This aligns with the economic welfare theory objective of allocating resources in a manner that maximizes the net effect on human well-being (Hicks, 1939). Failure to more completely assess the scope of social and environmental benefits that prospective NI projects may offer leads to undervaluation and an inability to truly compare NI with traditional engineering alternatives. Although US federal policy is evolving to support comprehensive benefits accounting by requiring Federal investments in water resources to evaluate environmental, economic, and social benefits[1], the existing toolbox at the disposal of planners for including the diverse benefits of NI is not yet robust.

NI projects require new and expanded procedures to support benefits accounting because benefits are difficult to quantify or define, particularly as non-overlapping, and can be difficult to aggregate and compare across projects. The diversity of NI benefits to humans, along with the biophysical complexity of nature, necessitates a very multidisciplinary effort to support accounting. Benefits can include water quality improvement, mitigation of floods and droughts, food provision, employment, recreation, educational and cultural values, and many more (Hartig et al., 2014; Sandifer et al., 2015). Tools that bring these benefits into a single framework are important, as is the primary research that underpins our understanding of benefits and subsequent efforts of translate research into information that can be used in analysis (Sharpe et al., 2023). Building on the broad portfolio of work by the U.S. Army Engineer Research and Development Center's Engineering With Nature (EWN) program, the research presented here seeks to expand the range of benefits attributed to NI projects and the ability of agencies to account for them in planning. Specifically, this research focuses on the human well-being benefits of nature and how NI planning and evaluation can include these benefits.

Many of the so-called "co-benefits" of NI (i.e., positive impacts of these features beyond the primary purpose of their use in infrastructure planning) stem from the inclusion of green space and natural elements (Raymond et al., 2017) or existence at the interface of built and natural environments thereby enhancing access to beneficial spaces. Exposure and proximity to nature, urban green space, and, increasingly, blue space are widely recognized to have positive impacts on human well-being and have been proposed as public health measures (Hartig et al., 2014; Nejade et al., 2022; Hunter et al., 2023). Well-being has promise as a category of NI co-benefits because it has been recognized as useful for providing information to policy makers designing policies and regulations to enhance people's lives (Frijters and Krekel, 2021). A report by the United States Congress in the 1970s expressed concern that social well-being has not been given enough attention in federal project analysis (Ehrenwerth et al., 2022), to which a remedy is only now beginning to be developed. As such, the foundation and institutional memory to account for well-being in infrastructure planning is generally lacking.

According to the U.S. Centers for Disease Control and Prevention (CDC), well-being "can be described as judging life positively and feeling good" and includes "the presence of positive emotions and moods, the absence of negative emotions, satisfaction with life, and fulfillment and positive functioning" (Center for Disease Control, 2018), a definition they base on the foundational work on the concept by Diener (e.g., Diener, 1984) and others. Many efforts to define the connections between nature and multi-dimensional well-being exist (as in Figure 1)—for instance, the Millenium Ecosystem Assessment connects the functions of ecosystems to determinants and constituents of well-being (Millennium Ecosystem Assessment, 2005). Well-being dimensions often include health, social cohesion, safety and security, living standards, spiritual and cultural fulfilment, and others (Smith et al., 2013). Researchers have described the pathways through which nature can affect well-being; a 2016 multi-disciplinary workshop "Exploring Potential Pathways Linking Greenness and Green Spaces to Health" developed three paths: reducing harm (e.g., mitigating pollution), building capabilities (e.g., stress recovery), and build capabilities (e.g., facilitating social cohesion) (Markevych et al., 2017). Increasing attention on well-being is related to the recognition that well-being is not only a function of the absence of pathogenic influences, but

1 Principles and Requirements for Federal Investments in Water Resources. Retrieved from: https://obamawhitehouse.archives.gov/sites/default/files/final_principles_and_requirements_march_2013.pdf.

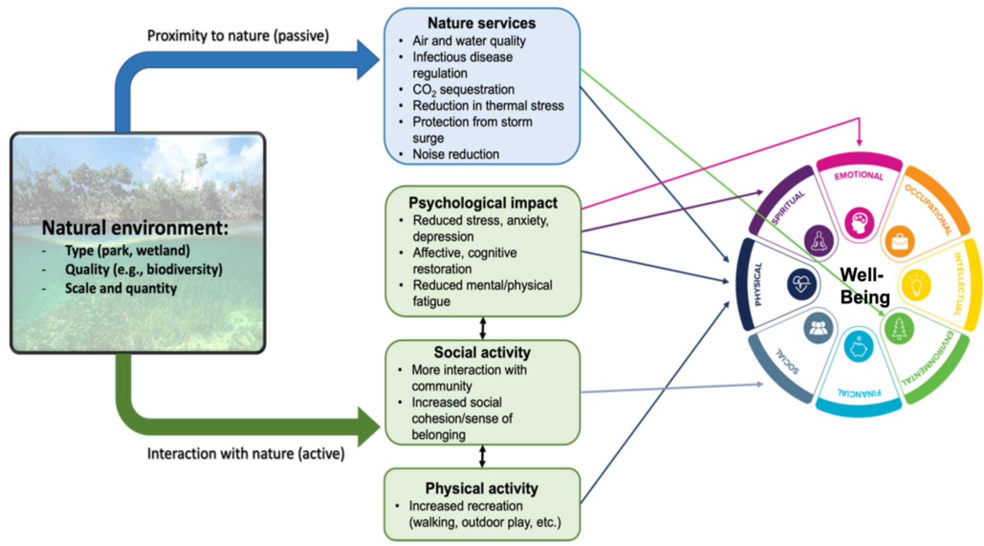

FIGURE 1
Diagram of the nature-well-being relationship (adapted from Hartig et al., 2014).

also the presence of salutogenic ones (Huppert, 2009), which is also captured by "social determinants of health" (Office of Disease Prevention and Health Promotion, n.d.). Given the potential for NI projects to have well-being benefits via these pathways, they should not be overlooked despite the challenge posed by accounting.

Beyond understanding the well-being benefits that are produced by NI projects, efforts to account for them should consider the distributional benefits. Certain communities enjoy a disproportionate share of nature-based amenities, while other communities suffer from a nature deficit (Strife and Downey, 2009; Leong et al., 2018; Flint et al., 2022; Langhans et al., 2023). This gap is recognized in the 2022 Memorandum of Understanding on Promoting Equitable Access to Nature in Nature-Deprived Communities[2], which defines nature-deprived as disadvantaged communities that disproportionately lack access to the climate mitigation and human health benefits of natural areas. Affluent, majority-White jurisdictions have been shown to benefit from higher quality park systems (in terms of acreage, access, facilities and investment) than communities with larger concentrations of low-income, ethnic minority people (Rigolon et al., 2018). Discrepancies in greenspace exposure have similarly been identified at the global scale, with Global North countries experiencing higher levels of exposure than those countries belonging to the Global South (Chen et al., 2022). Inequities in nature access and its benefits have been perpetuated by an array of sociopolitical factors. For example, historic processes of injustice have produced present-day disparities among different demographic groups (Keeler et al., 2020) including discriminatory practices embedded in zoning regulations. Although these inequities in NI benefits are generally recognized, no accounting framework currently exists for incorporating this equity gap within planning processes.

The research reported here advances well-being accounting for NI, rising to the demand for multiple intertwined outcomes: for information and tools to support practitioners in justifying investment in NI, a refocus of public investment on projects to promote well-being, and improvement in equity and environmental justice. To do so, we first compile well-being benefits accounting research—how nature and well-being can be measured and how utility functions can be used to monetize or otherwise quantify the well-being benefits of nature. We then outline a framework for NI well-being benefits accounting informed by the compiled nature-well-being relationships.

2 Framework components: the state of the research

To support the development of a framework to help agencies in meeting federal mandates for comprehensive benefits accounting, institutionalizing equity principles, and enhancing nature access amongst nature-deprived communities, existing research was first compiled. The review was guided by the desired public outcomes described above, each of which informs a component of the framework. The following sections summarize the state of the research for each of the components:

- How to operationalize nature access and exposure in order to measure nature abundance or deprivation;

2 United States Government Interagency Memorandum of Understanding on Promoting Equitable Access to Nature in Nature-Deprived Communities. Retrieved from: https://www.whitehouse.gov/wp-content/uploads/2022/09/Nature-Deprived-Communities-MOU.pdf.

- Existing human well-being indicators;
- Utility functions.

2.1 Operationalizing nature access and exposure

To support efforts to enhance nature access and, more broadly, better account for the social benefits of public infrastructure projects in planning, decision makers must identify the communities to whom well-being benefits are expected to accrue, assess their baseline access and proximity to nature, and quantify relationships between level of benefits and nature exposure/access. Understanding people's baseline access to nature is important for resolving issues of nature-deprivation and distributional equity, which is described as one dimension of equity along with recognitional and procedural dimensions by McDermott et al. (2013). Efforts to improve access to nature point to existing distributional equity, where lack of access to nature is extended to lacking enjoyment of its benefits. In general, this is supported by determining what landcover or land use constitutes nature (or the targeted nature-like space) and who benefits from it.

There is a lack of consensus or uniformity in the literature on the definition of nature, and terms such as "greenspace" or "naturalized area" are often used interchangeably to suggest the same thing. Taylor and Hochuli (2017) found papers that define greenspaces as vegetated areas, urban green spaces such as parks and gardens, recreational areas, undeveloped land, among others and that there is not clarity on whether greenspace is nature. Vilcins et al. (2022) reviewed common indicators of greenspace. They include satellite-imagery-based landcover, e.g., the normalized difference vegetation index (NDVI), fractional cover of vegetated areas, publicly accessible open space based on land use, tree counts, tree canopy cover, biodiversity indicators, and finer resolution methods such as direct observational surveys of land use and quality. Recent research encourages use of multiple measures of greenspace to capture nuance that has been observed in linkages between greenspace and health (Mears et al., 2020).

Access to nature and its benefits is generally defined in terms of geographic proximity. For instance, the Trust for Public Land's ParkServe initiative estimates that 100 million Americans, many of which are low-income, lack access to parks within walkable distances (i.e., 10 minutes or less) (Trust for Public Land, 2024). They assess this by measuring the half-mile walking distance to the closest public access point of a given park polygon and then calculating summary statistics of demographic variables within park access area boundaries. The Climate and Economic Justice Screening Tool provides geospatial data of the burdens that communities experience and identifies those that meet the criteria of being disadvantaged (White House Council on Environmental Quality, 2022). It includes lack of green spaces as a burden, defined as the amount of land in a census tract that is covered by impervious surfaces and crop land as a measure of nature deficit. Jarvis et al. (2020) use different definitions for the area of influence of nature-based solutions to account for benefits of exposure and access. Exposure was defined as the proportion of nature in a specific area around a point (used 100, 250, 500, and 1000m) and access was based on the World Health Organization (2016) recommendation that people should have greenspace should be within 300–500m of their residence. Accessibility measures often set a minimum size space (Van Den Bosch et al., 2016). Proximity is often used as a proxy for accessibility, although it is known to be imperfect because it does not account for a myriad of challenges that can exist to accessing nearby nature (Wolch et al., 2014).

2.2 Human well-being indices

Measuring trends and patterns in human well-being is a way of gauging societal progress and quality of life. Indices comprise variables assumed to influence well-being, such that improvement in a variable (e.g., air quality) should improve overall well-being scores. Index-based approaches can be advantageous because they afford researchers the flexibility to identify the aspects of a concept that are important to their specific contexts and the values of end users. For instance, a planner in Hawai'i who must allocate coastal protection infrastructure to communities within their jurisdiction based on community vulnerability may use indicators of vulnerability in his/her prioritization scheme that differ from those conceived by a planner in Florida who wishes to do the same. Further, human well-being indices provide planners with variables that they can track over time and target with policies and programs to improve well-being. Human well-being index development can support environmental management: extant indices inform sustainable development (e.g., Summers et al., 2017), conservation (e.g., Mascia et al., 2010), ecosystem recovery (e.g., Biedenweg et al., 2014; Dillard et al., 2013), and integrated ecosystem assessments (e.g., Breslow et al., 2018). Conceptualizations of well-being are diverse (Linton et al., 2016) and how it is defined will determine what is measured and whose needs are served.

Indices often disaggregate well-being into domains—understood here as the defining, theoretical components of a construct—their associated indicators—which specify measurable aspects of domains—and metrics—the concrete measurements of the construct—to organize the multi-faceted concept. For example, King et al. (2014) describe the evolution of well-being indices from a more narrow focus on economic conditions to more multi-dimensional conceptualizations that account for "material and social attributes of people's life circumstances" (p. 683) as well as psychological components. Domains comprised within various indices included: education; health; leisure time; life satisfaction and happiness; living standards; safety and security; social cohesion; and spiritual and cultural fulfillment (Smith et al., 2013). Leisher et al. (2013) found that indices most frequently employ living standards indicators followed by health indicators.

Measures of well-being range from subjective or qualitative questionnaires that gauge individuals' satisfaction (Kahneman and Deaton, 2010), to objective and quantitative, multidimensional indices that compile observable data (such as income) and calculate composite scores (e.g., Summers et al., 2014). Often, these include socioeconomic and demographic metrics found in the U.S. Census, health metrics such as levels of obesity and asthma offered by the CDC, and metrics of environmental quality such as surrounding levels of air pollution, proximity to parks, or levels of greenness. Some indices, such as the Environmental Protection Agency's Human Well-Being Index, incorporate indicators for more abstract dimensions of well-being, such as social cohesion, biophilia, cultural fulfillment, data that must often come from survey-based questionnaires (Summers et al., 2017). Despite improvements in the measurement of intangible concepts like well-being, contemporary, narrowly focused cost-benefit analysis frameworks fail to promote projects that maximize an array of socially-desirable impacts (Wegner and Pascual, 2011). The benefits associated with a natural space can arise from the activities they facilitate but also the spatial patterns of people and environment. The development of human well-being indices is constrained by data at is available to fulfill the desired variables, at the scale of the inquiry.

2.3 Utility functions

To operationalize well-being-nature relationships in a way that supports decision-making, planners must understand how incremental changes in the design of an NI project alternative will yield changes to well-being in the surrounding community. This necessitates the use of utility functions. Utility functions, used by economists to measure the value that an individual or group places on unit goods and services, are usually constructed with an assumed set of canonical properties. The principal of diminishing marginal utility is prominent among these properties. It states that the utility, or satisfaction an individual receives from the consumption of a good or service decreases with increasing consumption of that good or service. This generally implies that, all else being equal, an additional unit of income is less meaningful as the wealth of an individual increases (Kahneman and Deaton, 2010).

This concept is central to welfare economics and has been applied to public projects and policy evaluations through equity-weighted cost benefit analysis (Johansson-Stenman, 2005; Pearce et al., 2006), which weight the net benefits generated by a project according to the marginal utility of the recipients (Adler, 2016). For a variety of reasons, utility cannot be measured directly and within the context of public policy equity-based weights are at least partly normative, requiring both methodological choices and judgement (Hanley, 1992; Kind et al., 2017). This enables prioritizing benefits received by lower income individuals, since marginal utility is a decreasing function with respect to income, which in many cases is desirable (Fankhauser et al., 1997; Johansson-Stenman, 2005; Stroud et al., 2022). Nature is increasingly understood to be an inequitably provided resource that provides many non-market goods and services with concave marginal utility functions (Kruize et al., 2007; Atkinson and Mourato, 2008). Therefore, equity-weighted, utility-based cost benefit methods are expected to yield benefits when applied to policies and projects that influence access to nature and/or NI. Similarly, benefits of exposure to and accessibility of nature likely do not increase linearly, with increases in nature-deficient communities having a greater impact than nature-abundant.

3 A framework for natural infrastructure well-being benefits accounting

This research seeks to provide planning and research communities an accounting framework to estimate well-being impacts of proposed NI-based projects. The components we showcased in Section 2 can be leveraged to evaluate nature-derived benefits for well-being. We describe this framework while acknowledging that this project is ongoing and project specifics (e.g., data used, results, and so on) are still yet to be determined. The proposed framework envisions the use of an index-based approach to measure well-being as it relates to nature (later called the Nature-Centric Well Being Index) and subsequently evaluate the nature-based well-being gains using a utility function concept. As discussed above, the use of indices for attributing value to social phenomena like well-being or vulnerability is commonplace within the body of work to which this study belongs.

3.1 Development of a nature-centric well-being index

3.1.1 Scoping and design

The initial formulation of this study's scope of work and the later development of the roadmap commenced through an iterative process of setting forth core research questions, reviewing the academic literature, assessing data availability to address research questions, and, in cases where data availability was not sufficient to investigate a particular inquiry, revising and reformulating aspects of the project scope. This research is guided by one central research question and two related sub-questions, as follows:

Research Question: How can social factors, such as human well-being and health, be used alongside traditional planning tools (e.g., benefit–cost analysis) to evaluate NI projects with the goal of promoting equitable distribution of nature benefits?

(a) What are robust indicators of well-being that can be used to assess social dimensions of NI?

(b) To what extent are indicators of well-being related to indicators of nature?

It is important to note the targeted decision that this research aims to support. Whereas many research efforts use similar methods to identify geographic areas to prioritize for the addition of nature or conservation/restoration of natural areas, the research here is intended to account for the well-being impacts of nature as a co-benefit of projects with other primary purposes. Projects that incorporate nature and NI, such as living shorelines used for flood risk management and thin-layer placement of dredged material, are generally constrained to areas where they can be implemented.

Therefore, the open-ended question of where to increase nature access and proximity for people is different. Methods are needed to compare how much co-benefit can be achieved by alternative project formulations, including based on their location as well as by their form (e.g., NI versus conventional infrastructure).

3.1.2 Identifying human well-being benefits from nature as prospective indicators

Prospective indicators can be derived from the well-being benefits of nature that have been reported in the literature. These indicators are similar to those described in the ecosystem goods and services literature, as benefit-relevant indicators or indicators that measure the outcomes of ecosystem functions that are relevant to human welfare (Olander et al., 2018). Conditions of nature that impact well-being should form the basis of a nature-centric well-being index, so that a change in nature access or proximity can be expected to change well-being. Research results about the impact of nature on aspects of well-being help to strengthen the evidence that a causal relationship exists between the condition of nature and well-being, thus they have been explored in this work to inform the selection of indicators for a well-being index.

As noted previously, many researchers have defined the pathways through which humans derive well-being benefits from nature. Active benefits result from direct human interaction with a natural setting (e.g., sitting in a park or hiking on a nature trail), whereas passive benefits refer to the biological or physical functions of natural features that serve the well-being of communities in proximity to them (e.g., trees enhancing air quality or a living shoreline providing coastal protection). Both categories of benefits have been studied in a variety of natural environments and through myriad methodological approaches.

3.1.2.1 Active benefits

Research on the active well-being benefits of nature (Table 1) comes from the fields of psychology, physiology, social science, environmental justice, epidemiology, and more. The psychological benefits of nature access have received the most academic attention, with research dating back to the late 20th Century (Keniger et al., 2013; Hartig et al., 2014; Sandifer et al., 2015; Bratman et al., 2019). Such benefits include enhanced attention restoration, reduced mental fatigue, and improved academic performance, education, learning opportunities, mood, and emotional regulation. Psychological benefits of nature are often accompanied by physiological impacts. For instance, those who experience increases in positive mood states and stress reduction may also experience improvements in various health measures, such as blood pressure reduction. Table 1 summarizes benefits of active engagement with nature.

TABLE 1 Active well-being benefits of nature.

Category	Benefit	References*
Active benefits (derived from interaction with nature)		
Psychological	*Attention restoration*	Keniger et al., 2013; Kaplan, 1995; Berman et al., 2008; Hartig et al., 1991; Wells, 2000.
	Reduced mental fatigue	Kuo and Sullivan, 2001.
	Improved academic performance, education, and learning opportunities	Li & Sullivan, 2016; Wu et al., 2014; Kweon et al., 2017.
	Improved mood and emotional regulation	Keniger et al., 2013; Sandifer et al., 2015; Frumkin et al., 2017; Bratman et al., 2019; Wells and Evans, 2003; Astell-Burt et al., 2013; Kuo and Sullivan, 2001; van den Bosch and Meyer-Lindenberg, 2019; Ward Thompson et al., 2016; Catanzaro and Ekanem, 2004; Van Den Berg and Custers, 2011; Curtin, 2009; Barton and Pretty, 2010; Bowler et al., 2010; Lahart et al., 2019.
Social	*Opportunities for social cohesion*	Osmond, 1957; Peters et al., 2010; Schiefer and Van der Noll, 2017; Jennings and Bamkole, 2019; Kawachi et al., 2008; Maller, 2009; Kingsley and Townsend, 2006; Kondo et al., 2015; Francis et al., 2012; Fan et al., 2011; MacKerron and Mourato, 2013.
Physiological	*Reduced physical fatigue*	Park et al., 2011.
	Improved physical health outcomes	Douglas et al., 2017; Keniger et al., 2013; Sandifer et al., 2015; Sleurs et al., 2024
	Facilitation of active lifestyles	Hartig et al., 2014; Lahart et al., 2019.
	Enhanced immunity and reduced chronic and inflammatory diseases	Hanski et al., 2012; Rook, 2013; Lynch et al., 2014; Naik et al., 2012; Su et al., 2013; Clarke et al., 2010; Nicolaou et al., 2005; Hou et al., 2009; Beebe et al., 1967.
	Improved birth outcomes	Douglas et al., 2017; Dadvand et al., 2014; Grazuleviciene et al., 2015.

*The references listed provide evidence of each benefit. This table omits studies that do not document evidence of a given benefit.

3.1.2.2 Passive benefits

Connections between ecosystem services (i.e., the passive benefits of nature) and human health are well-established—in particular, the regulating services that mitigate natural and man-made hazards to human safety and health (Sandifer et al., 2015; Frumkin et al., 2017; Marselle et al., 2021). These benefits (summarized in Table 2) accrue to people by virtue of proximity (passively) instead of by actively spending time in natural spaces. In smaller-scale, urbanized environments, green spaces such as parks have been shown to have significant attenuative impacts on heat stress, noise, and air quality. More recent demand for nature-based flood risk management infrastructure has incited research showcasing the abilities of coastal and inland wetlands in mitigating erosion, storm surge, and heavy rainfall events. Larger-scale studies have probed the passive benefits to human health

TABLE 2 Passive well-being benefits of nature.

Category	Benefit	References*
Passive benefits (derived from proximity to nature)		
Physiological	*Lowered mortality from physiological diseases*	Mitchell and Popham, 2008; Maas et al., 2009; Wilker et al., 2014.
Protection from natural/man-made hazards	*Biodiversity and infectious disease regulation*	Blaikie and Jeanrenaud, 1996; Hough, 2014; Rudolf and Antonovics, 2005; Ezenwa et al., 2006; Mills, 2006; Ostfeld and Keesing, 2000; Wood et al., 2017.
	Air pollution reduction	Landrigan, 2017; Beckett et al., 1998; Janhäll, 2015; Namin et al., 2020; Nowak et al., 2006; Nowak and Crane, 2002; Takahashi et al., 2005; Jia et al., 2021; Leung et al., 2011; Ferrini et al., 2020; Nowak, 1994.
	Noise reduction – hearing loss	Flamme et al., 2012; Mayes, 2021; Van Renterghem et al., 2012; Van Renterghem et al., 2015; Van Renterghem and Botteldooren, 2008; Wong et al., 2010; Van Renterghem, 2019.
	Heat reduction	Environmental Protection Agency, 2008; Debbage and Shepherd, 2015; Fini et al., 2017; Sarrat et al., 2006; Rosenfeld et al., 1998; Cedeño Laurent et al., 2018; Buguet, 2007; Stone, 2012; Gillner et al., 2015; Lehmann et al., 2014; Liu et al., 2020; Ferrini et al., 2020; Brown et al., 2018; Dimoudi and Nikolopoulou, 2003; Hsieh et al., 2018.
	Flood hazard mitigation and resilience	Mason et al., 2010; Chakraborty et al., 2014; Gourevitch et al., 2022; Messager et al., 2021; Brokamp et al., 2017; Ferrini et al., 2020.
Psychological	*Noise reduction – stress*	Münzel et al., 2018; Van Renterghem et al., 2012; Van Renterghem et al., 2015; Van Renterghem and Botteldooren, 2008; Wong et al., 2010; Van Renterghem, 2019.
	Flood hazard mitigation and resilience	Brokamp et al., 2017; Chakraborty et al., 2014; Ferrini et al., 2020; Gourevitch et al., 2022; Mason et al., 2010; Messager et al., 2021; Spalding et al., 2014

*The references listed provide evidence of each benefit. This table omits studies that do not document evidence of a given benefit.

resulting from maintaining biodiverse habitats. Such studies often stem from pathological research, and in several instances, evidence points to a correlation between more biodiversity and increased disease regulation.

3.1.2.3 Takeaways from literature and caveats

Many of the studies reviewed cite the challenges of studying human well-being and attributing well-being to nature. This is because well-being is complex, being comprised of multiple domains, and nature is not a single amenity. Observed relationships between nature and well-being varied by country, gender, socioeconomic position, and, importantly, by the measure of well-being used, which vary from self-reported experiences to objective indicators like health outcomes. Furthermore, most studies demonstrate statistical relationships between the presence of nature and a well-being variable without establishing mechanisms of causality, though more recent work (e.g., Sudimac et al., 2022) is beginning to do so.

Individuals have different circumstantial requirements of nature to derive well-being benefits. Whether an individual benefits from a natural setting (or engages with it in the first place) depend on features such as accessibility (Hartig et al., 2014), perceived safety (Day, 2006; Groff and McCord, 2012; McCord and Houser, 2017; Harris et al., 2018), and the types of nature included (Fuller et al., 2007; Kweon et al., 2017; McKinney and VerBerkmoes, 2020). These research findings can be informative for the design of NI so that human well-being benefits can be explicitly sought and claimed. It is important also to note that community involvement in design, a key tenet of procedural justice and equity theories (Seigerman et al., 2022) ensures that the design reflects communities' needs (such as a sports field) and interests (such as gardening) (Nesbitt et al., 2018).

3.1.3 Selection of indicators

The development of actionable indices for well-being and ambiguous concepts alike is limited to the use of publicly available data with national coverage. Efforts to develop indicators with objective data can utilize statistical methods to aid selection and have scientific rigor (e.g., Gu et al., 2023). The general approach for selecting indicators commences with defining goals for the assessment and operationalizing these goals through a conceptual framework (Breslow et al., 2016). The process then transitions to collecting and developing candidate indicators based on data availability, defining screening criteria for selecting indicators, evaluating the candidate indicators according to these screening criteria, and selecting a suite of complementary indicators that delivers useful information toward achieving the overall goals (Breslow et al., 2016). In some instances, smaller, geographically focused efforts have used a community-driven approach for this step. For example, Biedenweg et al. (2014) solicited concerns and values of residents of a Puget Sound watershed through social science methods to develop a set of screening criteria. Once indicators are selected, the set of indicators can be evaluated empirically through statistical methods associated with external validity and internal consistency assessments, such as Cronbach's alpha, correlation analysis, cluster analysis, and classification trees (Gu et al., 2023). Following Gu et al. (2023), Cronbach's alpha analysis can be used to check the overall consistency of selected indicators and consistency within each indicator for those with multiple measures; correlation analysis allows researchers to compare relationships between each pair of measures; cluster analysis identifies expected differences between the estimations of the measured phenomenon; and, finally, a classification tree indicates the key drivers of cluster outcomes. This research follows this generalized approach in the collection of data and selection of indicators of well-being and nature described below.

3.1.3.1 Nature access and exposure indicators

As noted in the state of the research on operationalizing nature above, there are various metrics of nature abundance and access available. In this research, several nature-related datasets were gathered, including landcover data from the U.S. Geological Survey and park location data from the Trust for Public Land's ParkServe initiative, with the goal of investigating and comparing several metrics of nature. How nature (or lack thereof) is measured can be determined by, for example, grouping landcover classifications that satisfy a definition of nature, or, by contrast, grouping classifications that satisfy a definition of nature deprivation. The use of park data can serve as a complementary measure of nature access and add nuance to analyses of how well-being is impacted by the presence or lack of a natural space. To develop a nature-informed well-being index, this study proposes the use of correlation analysis to investigate statistical relationships between composite well-being scores or individual metrics with measures of nature, contingent on the assumptions of a given correlation analysis method (e.g., data are normally distributed) can be reasonably met by the available data and scope of work.

3.1.3.2 Well-being indicators

The benefits of nature on human well-being found in the literature serve to guide the selection of indicators that can be included in a nature-centric well-being index. There are significant challenges with acquiring nationwide data to serve as metrics of many of the prospective indicators, however. The research team screened multiple indices pertaining to well-being and their associated data sources based on their geographic extent (we sought nationwide data available at the census tract level, where possible) and relation to the pertinent constructs of well-being. While specific metrics have yet to be chosen, paramount among the compiled indices are the CDC PLACES dataset, which provides yearly modeled estimates of various health outcome, health risk behavior, disabilities, prevention, and health status metrics from CDC's Behavioral Risk Factor Surveillance System (see Zhang et al., 2015 for more on modeling approach). We also compiled socioeconomic and demographic data from the CDC's Social Vulnerability Index, which come from the U.S. Census Bureau's American Community Survey estimates for years 2016-2020.

3.2 Translating nature-focused well-being into benefit with utility functions

Public projects providing access to nature offer benefits to individuals and communities, including enhanced well-being and quality of life. Although these benefits are expected to have a larger impact on the well-being of individuals with lower *a priori* access, traditional evaluation methods do not capture these distributional impacts. To address this, we propose using utility functions and equity weighted cost benefit analysis to better capture these projects well-being benefits and address social equity concerns.

Utility functions are used to represent individual's preferences and well-being. These functions are usually constructed with a set of canonical properties (Moscati, 2016). The principal of diminishing marginal utility is prominent among these. It captures the idea that increased access to a good or service improves the well-being of those with limited access more than those with abundant access (Kahneman and Deaton, 2010); when applied to projects that enhance access to nature it implies that an additional unit of access to nature provides more utility to those with limited exposure, making the evaluation more sensitive to the needs of nature-deprived communities. A prototypical function with this property is the isoelastic utility function, in Equation 1.

$$u(c) = \begin{cases} \frac{c^{\{1-\eta\}}}{1-\eta} & \eta \geq 0, \eta \neq 1 \\ \ln(c) & \eta = 1 \end{cases} \quad (1)$$

Where, $u(c)$ represents the utility from consumption; c is the level of consumption, including benefits provided through access to nature; and η is the coefficient of relative risk aversion, the parameterization of which modifies the impact of inequality on risk aversion. For $\eta = 1$, the function exhibits constant relative risk aversion, meaning individuals' preference for increased nature-based benefits is invariant given their initial wealth or *a priori* access to nature. This formulation of the utility function can help isolate the degree to which increases in social welfare are driven by initial inequities, changes in access to nature, and risk aversion (Arrow, 1951; Hakansson, 1974; Kahneman and Tversky, 1979). Kind et al. (2017) analyzed the risk aversion and equity-weights used in cost benefit analysis for flood risk management projects and provides a range of plausible values for η based on previous studies. The application of utility functions further enhances the evaluation of public projects by quantifying non-market values for access to nature, which is a long standing issue in the evaluation of environmental projects (Hanley, 1992; Pearce et al., 2006). In the case of projects that enhance access to nature, we propose registering project benefits with an index derived from well-being index and measure of nature abundance or deficit. Alternative methods can use revealed preferences, contingent valuation, and proxy variables. In sum, the inclusion of utility functions enhances the evaluation of public projects by facilitating the quantification of non-market values associated with improved access to nature. It also helps to ensure that public resources are directed toward individuals and groups in society that benefit the most, through the principal of diminishing marginal utility.

A social welfare function is constructed as the sum of individuals or groups utility functions, and may be used in equity weighted cost benefit analyses (Atkinson, 1970; Duclos and Araar, 2001). Equity weighting complements the use of utility functions by addressing social preferences for more equality and, in particular, more equitable access to nature. Under this approach the social welfare function, $U(C)$ is weighted, as shown in Equation 2.

$$W = \sum \omega_i U_i \quad (2)$$

Where, U_i represents the utility or well-being of the ith individual or group; ω_i represents the weight assigned to that individual, and W is the overall social welfare or utility that incorporates equity weighting. A common weighting scheme uses income-based weights, shown in Equation 3.

$$\omega_i = \frac{1}{Y_i^{\epsilon}} \tag{3}$$

Where, Y_i is the income of the ith individual or group and ϵ is Atkinson social welfare parameter that describes aversion to inequality. For $\epsilon = 0$ there is no aversion to inequality, e.g., the income-based weights have no impact. On the other hand, larger values for ϵ increase the importance assigned to the marginal utility the lowest income individuals or groups in society. This formulation is desirable because it facilitates a sensitivity analysis, evaluating the impact of aversion to inequality of project or plan selection (Johansson-Stenman, 2005; Adler, 2016). A study by Drupp et al. (2015) provides values for ϵ acquired through expert elicitation. These values were recently applied in the analysis of a nature-based flood risk reduction project in Boston (Stroud et al., 2022). This approach addresses social and environmental justice concerns by incorporating preference for a more equitable provision of nature-based benefits, helping to ensure access to nature is provided in a manner that benefits marginalized groups and contributes toward a more inclusive and fair allocation of resources.

Formulations for a utility function will experiment with separate and combined well-being and nature indicators. Ideally, a utility function will result that can be used by project planners to evaluate the utility of a project alternative according to the context of the added nature it provides.

4 Conclusion

The fact that nature is essential for human well-being is generally known, and the inclusion of nature benefits in economic analysis of public investment, particularly in infrastructure, is relatively new and still developing. The benefits found in a limited review of existing research span many dimensions of human well-being but specific causal relationships between parameters of nature access and proximity are difficult to prove. Although research on the benefits of nature, including that presented here, is relatively utilitarian, elsewhere the value of nature conservation and restoration for more ecocentric objectives such as biodiversity is recognized. Methods to account for the inherent value of nature in project planning may also be warranted.

Research and development associated with the operationalization of intangible benefits like human well-being is paramount to influencing socially desirable decision-making surrounding the use of NI. Here, we present a roadmap for a methodology that builds on the research that has developed and applied its components: nature proximity and access, indices of human well-being, and use of utility functions to translate goods and services into quantitative benefits. In doing so, we hope to contribute to solutions that rise to the calls for both comprehensive benefit accounting for public projects and more equitable provision of nature-based benefits and fair allocation of resources. The methodology, as presented, is flexible to future advances in indicator-based definitions of nature abundance and access, as well as that of human well-being.

Importantly, the proposed methodology takes the surrounding context and community characteristics into consideration in quantification of prospective project benefits. In doing so, it can account for equity by capturing the diminishing rate of return between the level of well-being benefits and exposure to or accessibility of nature. We contend that our roadmap is well-suited to accounting for well-being benefits in NI project evaluations, particularly for government agency decision-making, and advantageous in the flexibility it offers for a variety of decision-making contexts.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

EK: Writing – review & editing, Writing – original draft, Investigation, Conceptualization. MK: Writing – review & editing, Writing – original draft, Project administration, Investigation, Conceptualization. JK: Writing – original draft, Conceptualization. SG: Writing – review & editing, Conceptualization. EY: Writing – review & editing, Project administration, Conceptualization.

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