Connecting the dots between urban infrastructure, well-being, livability, and equity: a data-driven approach

Kirti Das¹, Anu Ramaswami¹, Yingling Fan² and Jason Cao²

¹ Princeton University, Civil & Environmental Engineering, 41 Olden St., Princeton, NJ 08544, United States of America
² University of Minnesota, Humphrey School of Public Affairs, 301 19th Ave. S., Minneapolis, MN 55455, United States of America

E-mail: anu.ramaswami@princeton.edu

Keywords: well-being, livability, equity, infrastructure, environment

Abstract

Developing sustainable, livable and equitable cities is a major policy goal. However, livability metrics are amorphous, emphasizing different dimensions. This paper develops a novel data-driven approach by directly surveying subjective well-being (SWB) of urban residents, alongside satisfaction with key social–ecological–infrastructural–urban correlates to inform livability and equity priorities. Our survey is novel in quantifying SWB (Cantril ladder) of urban residents and evaluating both household- and neighborhood-level correlates while addressing confounding effects of socio-demographics and personality. We propose a three-way typology of provisioning systems—foundational, consistently important and added-bonus—based on their quantitative relationship with SWB. Implemented in the Twin-Cities USA, among 21 attributes, home heating-cooling, neighborhood greenery, access to public transportation and snow removal emerged as foundational in cold Minnesota climates; home size was consistently important and satisfaction with streets an added-bonus. Assessing inequality in foundational and consistently important categories revealed disparities by income and race, informing local infrastructure priorities for livability and equity. Key insights emerged on sufficiency and sustainability.

1. Urban environmental sustainability, livability, and equity

Sustainability is increasingly defined as advancing human well-being for all within our planetary boundaries [1]. In this context, seven key infrastructure and food provisioning systems play critical roles: energy, housing, transportation and connectivity, water, sanitation and waste management, public spaces, and food systems. These systems collectively contribute >90% greenhouse gas emissions and >90% of water withdrawals, whereas lack of access to and pollution arising from these seven sectors contribute to more than 19 million premature deaths annually [2]. Physical and social provisioning systems, such as access to education, social services, and health care, together contribute to the overarching concept that advances human well-being [1, 3]. Such linkages are often referred to as the nexus relationships between the physical and social provisioning systems and the outcomes of environmental sustainability, health, and well-being. Human well-being is a broad construct rooted in Sen’s concept of human capabilities and measured in different ways, including the human development index (HDI) [4]. More recently, surveys have emerged that directly measure subjective well-being (SWB), defined in simple terms as judging life positively (evaluative), frequently experiencing positive emotions in balance (emotional), and feeling fulfilled (eudemonic) [3, 5, 6]. With more than half of the world’s population living in cities today, understanding how provisioning systems shape inclusive well-being in cities is key to advancing the sustainability goals reflected in the United Nations Sustainable Development Goal 11 (SDG 11) and the New Urban Agenda [7, 8].

Social inequality manifests in cities in many ways, most importantly unequal income, wealth and access to provisioning systems, which in turn contribute to unequal outcomes related to health and well-being [7, 9–13]. Inequality in access to physical and social provisioning systems and pollution arising from the above systems is a physical manifestation of social inequality, particularly in cities. For example, as much
as 30% of the population in many developing world cities lives in slums, lacking access to clean water, sanitation, energy, and safe housing [11]. In many developed cities, including the USA, inequality in access to mobility, healthcare, education, and parks and green spaces has been documented, particularly during the pandemic, all of which have an impact on objective health outcomes and subjective assessments of well-being [10]. These inequalities in physical and social infrastructures are reflected in the SDGs, for example, clean water (SDG 6), clean energy (SDG 7), safe housing (SDG 11), education (SDG 4), and health care (SDG 3) [7].

However, unpacking how physical and social provisioning systems, and the inequality therein, influence well-being—particularly SWB and quality of life—can be challenging because of the complex linkages across social–ecological–infrastructural urban system features of cities (SEIUS) [3, 9]. Figure 1 illustrates the SEIUS framework, with linkages among key physical and social provisioning systems, and multiple final societal outcomes, including well-being and equity, which are the focus of the present work. While much science has developed to quantify the impact of urban provisioning systems on natural resource use and carbon emissions [14], and on objective measures of human health, for example, disease burden [15], their impact on broader concepts of SWB and the notion of quality of life is more complex. Furthermore, the linkages with equity span inequality in SEIUS determinants as well as the outcomes shown in figure 1. In this study, we focus on the distributional aspects of equity, defined as efforts to reduce disparities (or inequalities) among the most disadvantaged social strata [12, 16, 17], addressing disparities in both determinants and outcomes.

Part of the difficulty in understanding the linkages between infrastructure provisioning systems, well-being and equity has been the challenge of measuring well-being. Measures of well-being have evolved from objective measures, such as the population average gross domestic product and the HDI, which by definition do not address inequality, to a more nuanced consideration of SWB that queries entire populations on how they think and feel about their lives. Such SWB measures have been demonstrated in several rounds of the census in the United Kingdom [18]. Increasingly, the science of measuring SWB has converged, and scales have been developed to measure evaluative, emotional, and eudemonic SWB. However, although SWB measures are available across nations, and there are studies of SWB in cities associated with specific provisioning systems, such as green infrastructure, transportation, water supply, and social capital [19–22], few studies have explored how the range of social and physical provisioning systems (such as those illustrated in figure 1) shapes measures of SWB. Such studies will allow us to better comprehend the nexus among multiple urban infrastructures, social systems, the environment, and well-being in a holistic way in cities.

SWB is closely related to the concept of livability, which is on the policy agenda for several cities [23–25]. The concept of livability and its metrics have also evolved over the past two decades. Livability has been
Table 1. Examples of livability indices comprising physical, social, and environmental determinants.

| Mercer index [28] | Economist Intelligence Unit [30] | ISO Standards [31] | Asian Development Bank [32] | World Health Organization [33] | Global livable cities index [34] | CH2M Hill [35] | Melbourne [36] | Victoria Transport Policy Institute [37] |
|------------------|-------------------------------|-------------------|--------------------------|--------------------------------|--------------------------------|----------------|--------------|--------------------------------------|
| **Infrastructural determinants** | | | | | | | | |
| Communication | X | X | X | | | | | |
| Energy/gas | X | X | X | X | X | X | | |
| Food and local goods | X | | | | | | | |
| Housing | X | X | X | X | | | | |
| Sanitation | X | | | | | | | |
| Waste | X | X | | | | | | |
| Water services | X | X | | X | X | | X | |
| Transport | X | X | | X | X | X | | |
| Public open space | X | | | | | | | |
| Urban planning | X | X | | | | | | |
| **Social determinants** | | | | | | | | |
| Education | X | X | X | | X | | | |
| Economics | X | | | | | | | |
| Emergency response | X | | | | | | | |
| Equity/equality | X | | | | | | | |
| Governance | X | X | X | | | X | | |
| Health/social services | X | X | X | | | X | | |
| Physical activity | X | X | | | | | | |
| Crime and safety | X | X | X | | | X | | |
| Leisure and culture | X | X | | | | | | |
| Social cohesion | X | | | | | | | |
| Tourism | X | X | | | | | | |
| **Environmental determinants** | | | | | | | | |
| Environmental sustainability | X | X | | | | | | |
| Natural environment (+air) | X | X | X | | X | X | X | |
| Acoustic environment | X | | | | | | | |

defined as the ‘features of a place that make it desirable to live in’ [26]. It is often measured in a normative fashion, with numerous livability indices, each capturing what different experts or focus groups consider important. Consequently, the indices of livability vary widely, with some focusing on the standard of living (e.g., the Mercer index), while others address the more subjective aspects of quality of life (e.g., the Organisation for Economic Co-operation and Development’s Better Life Index) [27, 28]. Table 1 demonstrates the wide variation among the infrastructural, social, and environmental parameters incorporated in the leading livability indices, highlighting their diversity and lack of consistency [29]. Indeed, with more than 30 livability indices in the market, researchers suggest that the quest for a unified livability framework or a single livability index may not be meaningful [29]. Furthermore, given the high social inequality in cities, a uniform livability index may not address the needs of a specific and often underserved population.

Against this backdrop, the overarching goal of our study is to develop a new survey methodology and data-driven analysis approach to unpack the relationship between key provisioning systems and SWB in ways that inform both livability and distributional equity. To do so, our paper answers the following research questions:

(a) What physical and social provisioning systems, spanning household, neighborhood and city scales, are correlated with an individual’s SWB, after addressing confounding effects related to socio-demographics, income and personality?

(b) How can these correlates be prioritized to improve livability, i.e., overall SWB?

(c) Further, how can these physical and social provisioning systems be prioritized to promote both livability and distributional equity?

We develop new survey and analysis methods to answer these questions, which are described next.
2. Methods

We answer the three research questions developing methods in the following four steps:

1. Developing a new survey instrument. We develop a survey method that queries people on multiple infrastructure provisioning systems (social and physical) at different scales (household, neighborhood, and citywide) along with demographic, interpersonal, and intrapersonal characteristics to unpack the infrastructure correlates of SWB. We focus on evaluative SWB as measured by the Cantril ladder score. To the best of our knowledge, this is the first study to explore both social and physical provisioning system variables spanning multiple scales, from the household to the neighborhood to the city, alongside a number of interpersonal, intrapersonal, and demographic variables, providing a holistic assessment of SWB and its SEIUS correlates.

2. Survey implementation. We conduct a first exploratory application of the survey in the Twin Cities, USA, exploring SWB correlates across six neighborhoods with diverse social, infrastructural and urban form features.

3. Developing the data-driven analysis approach to inform livability. We develop a new analytical approach that yields a typology of household and neighborhood infrastructure to inform their prioritization for advancing livability based on the relationship between infrastructure satisfaction and SWB. Our approach involves multivariate regression with the SEIUS correlates, wherein we classify infrastructure attributes into different types, for example, foundational (addressing basic needs) versus added bonus (e.g., luxuries), based on the nature of their relationship with wellbeing (see figure 2). The classifications developed in our paper are inspired by recent works in sustainability science [38] and consumer satisfaction research [3, 39].

4. Informing infrastructure prioritization at the nexus of livability and equity. We combine the infrastructure typology and the assessment of inequality to inform infrastructure priorities at the nexus of livability and equity. Focusing on the distributional aspects of equity, we identified those infrastructure investments that are associated with SWB for underserved social groups.

Each of the four steps are described in detail below.

1. Developing a new survey instrument. Our survey methodology integrates three key literatures: (a) measurements of SWB [40]; (b) urban SEUIS frameworks to represent interactions among multiple provisioning systems as they shape environmental health, well-being, and equity outcomes [9, 12]; and (c) measures of consumer satisfaction with services [39, 41].

Table 2 shows a comprehensive and interdisciplinary list of 58 SEIUS SWB correlates identified through a detailed review of the literature from public health, psychology, geography, and urban planning [42, 43]. These 58 correlates of SWB were queried in our survey and included social and infrastructural variables on multiple scales. Specifically, infrastructures include household and neighborhood infrastructure and city-wide services.
Table 2. Individual, household, neighborhood, and city scale variables included in the survey instrument.

| Variables | Individual and household scale | Neighborhood and city scale |
|-----------|--------------------------------|-----------------------------|
| Social/demographic variables | (1) Individual characteristics: age ∗ , gender ∗ , education , income, employment ∗ , health , foreign born status ∗ , race/ethnicity ∗ , vehicle ownership ∗ , household composition ∗ , living with spouse or partner ∗ , age of youngest child ∗ , caregiving status ∗ , pet ownership ∗ , leisure time, leisure travel, work, and work commute | (1) Interpersonal: social relationships and three social neighborhood cohesion attributes |
| Infrastructure provisioning systems variables | (1) Physical provisioning systems: home size, electrical supply, heating and cooling, water supply, food supply, and cooking infrastructure | (2) Physical provisioning: parks and playgrounds, streets, parking, sidewalks, bike trails/paths, public transportation, highways, street lighting, drainage, leisure activities, community facilities, grocery stores and farmers markets, other stores, garbage collection, snow removal, street cleaning, and places of worship |
| Social provisioning | (2) Social provisioning: safety, childcare, medical facilities, educational institutions, financial institutions, police and judiciary, and government services |
| Environmental characteristics | (1) Environmental characteristics: noise, air, greenery and cleanliness |

Satisfaction measurements were recorded for all the above variables on a five-point Likert scale except for selected demographic and intrapersonal variables which are marked with a ∗.

In terms of social system variables, the key contribution is the consideration of intrapersonal characteristics, such as optimism, along with interpersonal relationships from the family to the neighborhood level.

The Cantril ladder or Cantril’s self-anchoring striving scale [44] was used as the SWB measure. In this measure, the respondents identify where they stand on a ladder with 11 steps, where the top of the ladder represents the best possible life for them, and the bottom of the ladder represents the worst possible life for them. We focused on the Cantril ladder, given its use in prior landmark sustainability studies that connected well-being with the environment [1]. Satisfaction with SEIUS attributes (see table 2) was measured using a five-point Likert satisfaction scale (1 = very dissatisfied, 2 = dissatisfied, 3 = unsure, 4 = satisfied, 5 = very satisfied). In particular, respondents self-report their satisfaction with 13 individual life domains and interpersonal variables (health, family relationships, social relationships, leisure time, education, income, home, neighborhood, leisure travel, police and judiciary, and government services), satisfaction with 31 neighborhood and city attributes (related to neighborhood characteristics, infrastructure, accessibility, city services, and sense of community), and satisfaction with seven attributes of their home (home quality, home size, home electric supply, home heating and cooling, and home water supply). The intrapersonal variable, personality, was measured using the life orientation test—revised, which assesses individual differences in generalized optimism versus pessimism [45]. Finally, the respondents provide information on individual-level variables, including age, gender, employment, family structure, household structure, race and ethnicity, education, income, home ownership, auto ownership, etc.

2. Survey implementation. In this paper, we present the first exploratory application of the survey instrument in the Twin Cities, USA, evaluating SWB across six neighborhoods with diverse social, infrastructural and urban form to elucidate key insights. For the survey, six neighborhoods were selected based on income, urban form, access to light rail, and site visits. Phillips and near North are urban low-income neighborhoods, Saint Anthony Park and Prospect Park are urban middle-income neighborhoods, Brooklyn Center is a suburban low-income neighborhood, and Blaine is a suburban middle-income neighborhood. The study participants were selected using random population sampling. To collect a random sample, the study team used block data from the US Census Bureau. From each neighborhood, the team drew random blocks (10 at a time).
blocks were post-carded regarding the study. When face-to-face contact was not possible, a postcard containing the contact information of the study team was left at the participants home. The potential participants then connected with the study team to obtain more information about the study and to enroll in the study. A $50 incentive was provided for participation. Data were collected from 398 participants across the six neighborhoods via in-person paper surveys between 17 October 2016 and 25 October 2017. For the survey 1700 households were post-carded and the survey response rate was 23%.

3. Developing the data-driven analysis approach to inform livability. The data-driven analysis approach aims to identify physical and social provisioning systems that are correlated with SWB, thereby yielding a typology to inform their prioritization for advancing livability. The typology is derived based on the relationship between infrastructure satisfaction and SWB, explored using ordered logistic regression models utilizing the STATA software application [46]. Based on tests for multicollinearity and considerations of the available sample size, 21 of the SEIUS attributes shown in table 2 at the home, neighborhood and city scale were included in the final analysis as well as key social and demographic variables known to influence SWB, including a key intrapersonal variable, optimism (personality) [47, 48], as well as age, gender, and presence of spouse/partner [49–54] (tables 4 and 5). The 21 SEIUS attributes included were home size, home heating and cooling, home water supply, streets in the neighborhood, parking in the neighborhood, bike trails/paths in the neighborhood, access to public transportation in the neighborhood, access to highways in the neighborhood, drainage in the neighborhood, snow removal in the neighborhood, access to quality leisure, recreation and entertainment, access to quality grocery stores and farmers’ market, access to places of worship, access to quality medical facilities, access to quality education institutions, access to quality banks and financial institutions, safety from crime in the neighborhood, government services, noise in the neighborhood, air quality in the neighborhood, and neighborhood greenery.

To develop a typology of infrastructural provision systems, we conducted a split regression (shown in table 5). An aggregate satisfaction score with the above mentioned 21 SEIUS attributes included in the study was calculated and used to divide the survey population into two groups based on low aggregate satisfaction (group A in table 5) and high aggregate satisfaction (group B in table 5). This approach is consistent with prior studies that have used aggregate scores of various neighborhood characteristics [55–57]. The aggregate satisfaction score of the 21 infrastructure and environmental attributes ranged from 43 to 104, with a Cronbach’s alpha score of 0.85, indicating that the scale is reliable. The two groups were split based on the median value of the aggregate satisfaction score, with scores of 83 and less constituting the low attribute satisfaction group and scores of 84 and above constituting the high attribute satisfaction group. This led to two approximately equal groups: a low attribute satisfaction group of 183 respondents and a high attribute satisfaction group of 171 respondents. Median splits, such as the one used for this analysis, are frequently used in many fields, including public health, medicine, statistics, psychology, consumer research, etc [58, 59]. We also performed a sensitivity analysis that excluded one or two infrastructure variables from the aggregate satisfaction scale, which showed a

| Typology | Conceptualization | Insights from regression | Key correlates of the Cantril ladder score in the Twin-Cities region |
|----------|-------------------|-------------------------|------------------------------------------------------------------|
| Foundational | Exploring a plateau effect in SWB | The attribute is significantly correlated with SWB only in the low attribute satisfaction group (i.e., a basic need) | • Home heating and cooling<br>• Access to public transportation<br>• Snow removal in the neighborhood<br>• Neighborhood greenery<br>• Health |
| Consistently important | Exploring the absence of a plateau and threshold in SWB (a consistent relationship) | The attribute is significantly correlated with SWB in both the high and low attribute satisfaction groups (i.e., important for all) | • Home size<br>• Family relationships |
| Added bonus | Exploring a threshold effect in SWB | The attribute is significantly correlated with SWB only in the high attribute satisfaction group (i.e., a luxury) | • Streets in the neighborhood<br>• Education<br>• Social relationships |

*See details results in table 5.
Table 4. Global multivariate ordered logistic regression of the overall self-reported SWB of all 354 individual survey responses in the study regressed against 26 social, ecological, and infrastructural attributes.

| Study variables                                                                 | Cantril ladder (coeff) |
|---------------------------------------------------------------------------------|------------------------|
| **Full sample (N = 354)**                                                        |                        |
| **Satisfaction with infrastructure: household scale physical attributes**       |                        |
| Home—size                                                                       | 0.2052                 |
| Home—heating and cooling                                                        | 0.3398***              |
| Home—water supply                                                               | 0.0426                 |
| **Satisfaction with infrastructure: neighborhood and city scale physical attributes** |                        |
| Streets in the neighborhood                                                     | 0.1948                 |
| Parking in the neighborhood                                                      | −0.0906                |
| Bike trails/paths in the neighborhood                                            | 0.0347                 |
| Access to public transportation in the neighborhood                             | 0.2479**               |
| Access to highways in the neighborhood                                           | 0.0468                 |
| Drainage in the neighborhood                                                     | 0.0018                 |
| Snow removal in the neighborhood                                                 | 0.1765                 |
| Access to quality leisure, recreation, and entertainment                         | 0.1591                 |
| Access to quality grocery stores and farmers market                              | −0.1059                |
| Access to places of worship                                                     | −0.0536                |
| **Satisfaction with infrastructure: neighborhood and city scale social attributes** |                        |
| Access to quality medical facilities                                             | −0.1684                |
| Access to quality education institutions                                         | −0.0615                |
| Access to quality banks and financial institutions                               | 0.0724                 |
| Safety from crime in the neighborhood                                           | −0.0325                |
| Government services                                                             | 0.1598                 |
| **Satisfaction with environment: neighborhood and city scale environmental attributes** |                        |
| Noise in the neighborhood                                                        | −0.118                 |
| Air quality in the neighborhood                                                  | 0.0047                 |
| Neighborhood greenery                                                            | 0.2879***              |
| **Satisfaction with social variables: individual level attributes**             |                        |
| Income                                                                          | 0.3048*                |
| Education                                                                       | 0.2842                 |
| Health                                                                          | 0.2506***              |
| Leisure time                                                                    | 0.1153                 |
| **Satisfaction with social variables: interpersonal attributes**                |                        |
| Family relationships                                                             | 0.3302***              |
| Social relationships                                                             | 0.1359**               |
| **Control variables (no performance recoding used)**                            |                        |
| Intrapersonal attributes and individual characteristics                          |                        |
| Optimism                                                                        | 0.1935***              |
| Age                                                                             | 0.0031                 |
| Living with spouse/partner                                                       | 0.5786***              |
| White                                                                           | 0.2233                 |
| Female                                                                          | 0.146                  |
| Pseudo $R^2$                                                                    | 0.186                  |

*Notes: * $p < 0.05; ** p < 0.01; *** p < 0.001.

very modest impact on the composition of the two groups (with less than five respondents changing from one group to the other). The two groups were found to differ across various characteristics. A higher percentage of respondents in the high-satisfaction group had higher incomes, were white, and belonged to higher income neighborhoods compared to the low-satisfaction group (tested using chi-square tests at 0.05 significance).
Table 5. Split sample multivariate ordered logistic regression of overall self-reported SWB of 354 individual survey responses divided into two groups: (A) low aggregate satisfaction with 21 infrastructure and environmental variables and (B) high aggregate satisfaction with 21 infrastructure and environmental variables regressed against 21 social, ecological, and infrastructural attributes<sup>a,b,c,d</sup>.

| Cantril ladder (coeff) | Group A (N = 183) | Group B (N = 171) |
|------------------------|-------------------|-------------------|
| **Study variables**    |                   |                   |
| Satisfaction with infrastructure: household scale physical attributes |                   |                   |
| Home—size              | 0.1503**          | 0.8132**          |
| Home—heating and cooling | 0.3021*          | 0.5191          |
| Home—water supply      | 0.3168            | −0.3833          |
| Satisfaction with infrastructure: neighborhood and city scale physical attributes |                   |                   |
| Streets in the neighborhood | 0.3807          | 0.2640*          |
| Parking in the neighborhood | −0.3013       | 0.0528          |
| Bike trails/paths in the neighborhood | 0.1235      | 0.023           |
| Access to public transportation in the neighborhood | 0.2572**        | 0.0753          |
| Access to highways in the neighborhood | 0.0443        | 0.0946          |
| Drainage in the neighborhood | −0.1462        | 0.3757          |
| Snow removal in the neighborhood | 0.3732***      | 0.0387          |
| Access to quality leisure, recreation and entertainment | 0.1833         | 0.1823          |
| Access to quality grocery stores and farmers market | −0.1388      | −0.1515         |
| Access to places of worship | 0.1782         | −0.4376         |
| Satisfaction with infrastructure: neighborhood and city scale social attributes |                   |                   |
| Access to quality medical facilities | −0.3777      | 0.3705          |
| Access to quality education institutions | 0.1223       | −0.2338         |
| Access to quality banks and financial institutions | 0.1357       | −0.1253         |
| Safety from crime in the neighborhood | 0.0072        | −0.2254         |
| Government services | 0.2019          | 0.0701          |
| Satisfaction with environment: neighborhood and city scale environmental attributes |                   |                   |
| Noise in the neighborhood | −0.0345      | −0.1332         |
| Air quality in the neighborhood | −0.0999    | 0.1419          |
| Neighborhood greenery | 0.4428**        | −0.0128         |
| Satisfaction with social variables: individual level attributes |                   |                   |
| Education | 0.1274      | 0.7628***      |
| Health | 0.4381***  | 0.21          |
| Leisure time | 0.1381   | 0.3326         |
| Satisfaction with social variables: interpersonal attributes |                   |                   |
| Family relationships | 0.4393**    | 0.3437***      |
| Social relationships | −0.0081   | 0.3224***      |
| **Control variables (no performance recoding used)** |                   |                   |
| **Intrapersonal attributes and individual characteristics** |                   |                   |
| Optimism | 0.2137*** | 0.2234**      |
| Age | 0.0011 | 0.0129          |
| Living with spouse/partner | 1.0057*** | 1.0961*** |
| Female | 0.1452 | 0.4847*      |
| Pseudo R<sup>2</sup> | 0.20 | 0.19          |

<sup>a</sup>Notes: *p < 0.05; **p < 0.01; ***p < 0.001.
<sup>b</sup>Foundational attributes: home heating and cooling, access to public transportation, snow removal in the neighborhood, neighborhood greenery, and health.
<sup>c</sup>Consistently important attributes: home size and family relationships.
<sup>d</sup>Added bonus attributes: streets in the neighborhood, education, and social relationships.
Finally, since income and race are known to significantly shape infrastructure provisioning in US cities [16, 60, 61], these two attributes were removed from the split-sample multivariate regression in Table 5 to enable focus on the importance of infrastructure itself on SWB. For example, previous studies have shown that tree cover is highly correlated with income in many US cities [60]; home floor area is highly correlated with household income [61]; while home heating and cooling efficiency is influenced both by race and by income [16]. Thus, income and race were excluded from the split sample multivariate analysis, which aimed at identifying infrastructure typology at low and high satisfaction. These attributes were subsequently used for the analysis of income and racial inequality.

3.1. Typology of infrastructure attributes based on their relationship with SWB to inform prioritization for livability

Based on the split regression we developed a three-way typology of key SEIUS correlates of the overall SWB reported by the survey respondents. Our interest in the context of livability, that is, the features of a place, is in satisfaction with infrastructure (physical and social) and environmental attributes at household, neighborhood and city scales. A three-way typology of provisioning systems can be conceptualized based on the nature of the relationships in Figure 2 and Table 3, as follows:

- Foundational attributes: these attributes are significantly correlated with SWB at low aggregate attribute satisfaction but are not correlated with SWB at high aggregate attribute satisfaction, indicating a plateau effect.
- Consistently important attributes: these attributes are significantly correlated with SWB at both low aggregate attribute satisfaction and high aggregate attribute satisfaction, indicating that they are consistently important for the entire population.
- Added bonus attributes: these attributes are not significantly correlated with SWB at low aggregate attribute satisfaction but are correlated with SWB at high aggregate attribute satisfaction, indicating a threshold effect.

From a policy perspective, Figure 2 and Table 3 suggest that to advance well-being—that is, quality of life and, hence, livability—policymakers should first prioritize the attributes that are foundational and consistently important. This enables a focus first on those residents reporting the lowest SWB and lowest satisfaction with attributes that are foundational and attributes that are important to all.

4. Informing infrastructure prioritization at the nexus of livability and equity

For the assessment of inequality, average satisfaction scores of foundational and consistently important attributes were examined based on income and race (being Black/African American). Statistically significant differences in satisfaction between groups were identified using t-tests at a 5% significance level.

3. Results

We organize key results based on our research questions. Together, the survey and analysis methods used to answer the three questions contribute to developing a data-driven approach that furthers connecting the dots between urban infrastructure, well-being, livability, and equity. Tables 3–5 summarize the results of the application of such a data-driven approach in the Twin Cities metropolitan area.

3.1. Physical and social provisioning systems correlated with SWB

Table 4 presents a global multivariate regression with all SEIUS variables, indicating that the key correlates of SWB are home heating and cooling ($\beta = 0.34; p < 0.001$), public transportation ($\beta = 0.25; p < 0.01$), neighborhood greenery ($\beta = 0.29; p < 0.001$), income ($\beta = 0.31; p < 0.05$), health ($\beta = 0.25; p < 0.001$), family relationships ($\beta = 0.33; p < 0.001$), and social relationships ($\beta = 0.14; p < 0.01$). The influences of various individual-level attributes on SWB are consistent with previous studies that have shown SWB to be correlated with subjective assessments of personal health, income, living with spouse/partner, and personality [48–54, 62]. Interestingly, our study reveals important household, neighborhood, and city infrastructure attributes that are correlated with SWB after controlling for various individual-level attributes, such as personal health, income, education, living with spouse/partner, and personality. Our results, for the first time, systematically unpack how multiple and multi-scale infrastructure shapes wellbeing to a greater extent than prior studies. For example, prior studies have studied and identified a few specific individual correlates, such as neighborhood safety [63], greenery [22, 64], transportation [21], water supply [20], social capital [19], or neighborhood wealth [65]. However, this is the first study in which these correlates have been studied together with other confounding social and demographic variables.

3.2. Physical and social provisioning systems priorities to improve livability

The results of the typology analysis in Tables 3 and 5 yield very interesting and intuitive results. Home heating and cooling (group A: $\beta = 0.3021; p < 0.05$), public transportation (group A: $\beta = 0.26; p < 0.01$), snow
removal (group A: $\beta = 0.37; p < 0.001$), and neighborhood greenery (group A: $\beta = 0.44; p < 0.01$) emerged as foundational infrastructures that were significantly correlated with SWB only at low aggregate attribute satisfaction. The emphasis on home heating and cooling, and snow removal is physically consistent with the cold climate in Minnesota. By contrast, home size (group A: $\beta = 0.15; p < 0.01$ & group B: $\beta = 0.81; p < 0.01$) emerged as a consistently important attribute for the whole sample, while satisfaction with streets in the neighborhood (group B: $\beta = 0.26; p < 0.05$) emerged as an added bonus. These results reveal local infrastructure priorities for enhancing livability by focusing on those provisioning systems noted as foundational and consistently important.

For other non-infrastructure attributes, health (group A: $\beta = 0.44; p < 0.001$) and family relationships (group A: $\beta = 0.44; p < 0.01$ & group B: $\beta = 0.34; p < 0.01$) emerged as foundational and consistently important, respectively. Interestingly, education (group B: $\beta = 0.76; p < 0.001$) and social relationships (group B: $\beta = 0.32; p < 0.001$) emerged as an added bonus, which is consistent with Maslow’s hierarchy of human needs where both attributes are high-level needs [66].

Following this classification of infrastructure into different types, we evaluated inequality by exploring the effects of income and race on satisfaction with infrastructure.

3.3. Physical and social provisioning systems priorities to improve both livability and distributional equity

The results of the inequality analysis are presented in figure 3. Statistically significant differences in satisfaction between groups was identified using t-tests at a 5% significance level. Compared with the highest income participants (earning $>75,000 or more annually), the lowest income participants (earning $<25,000 annually) reported statistically significant lower average satisfaction scores for all foundational and consistently important attributes, except public transportation and snow removal. Similarly, Black/African American respondents reported significantly lower average satisfaction scores for all foundational and consistently important attributes than white respondents, except for public transportation and family relationships. The lack of disparity in public transportation across income and race could be due to the concentration of low-income and minority residents in inner-city neighborhoods that have better public transportation infrastructure than neighborhoods farther away from the city.

Figure 3. Average satisfaction scores for foundational and consistently important attributes by income and race. * indicates a statistically significant difference between the two groups based on t-tests at a 5% significance level.

3 Average satisfaction score for public transportation was significant but higher for lowest income participants.
Although improving the income of residents may be outside the toolkit of planners, from an income equity perspective, home heating and cooling, neighborhood greenery, health, home size, and family relationships (foundational and consistently important attributes) were the top priorities in our sample. Similarly, from a racial equity perspective (Black/African American residents vs their white counterparts), home heating and cooling, snow removal, neighborhood greenery, health, and home size were the top priorities in our sample. It is interesting to note that for some attributes at the household scale, home size and heating and cooling, disparities were larger by race than by income. Given that cities often operate in limited and tight budgets, from an income and racial equity perspective, public transportation would be the last priority, even though it is a foundational attribute, as those from the lowest income group and racial minority were satisfied with it.

4. Conclusion

The results presented in this paper have several strengths that add to their significance for policy making. First, our results, for the first time, systematically unpack how multiple and multi-scale infrastructure shapes wellbeing to a greater extent than prior studies. The analysis presented incorporates a comprehensive list multi-disciplinary correlates of SWB which are typically not studied together, resulting in the misestimation of the impact of home, neighborhood and city attributes on SWB. For example, studies from urban planning often fail to control for important SWB correlates such as health and personality while studies from psychology and public health rarely focus on neighborhood and home attributes. Second, the study introduces a method for improving the well-being of residents using local primary data that enable policy makers to generate tailored context sensitive solutions. Most studies, such as the World Values Survey and the Gallup World Poll, focus on macro-level analyses. The use of the macro datasets is restrictive, as researchers cannot control for important correlates of SWB or tailor studies to local contexts. Finally, our methodology takes a significant step forward from a policy perspective by not only identifying what matters for SWB but also enabling prioritization for provision or improvement of infrastructure and services to have the maximum impact on SWB and promote equitable and livable cities.

It is equally important to highlight some limitations of the study and discuss its broader applicability. First, the survey tool was based on an extensive review of literature from public health, psychology, geography and urban planning to identify over 50 correlates of SWB. The analysis presented here, to the best of our knowledge, includes the assessment of the most extensive list of multi-disciplinary variables in relation to SWB. However, the authors acknowledge that there is the need to test the survey across multiple cities before suggesting broader applicability. To that end, the study team is in the process of testing the survey and analysis methods across cities in the USA with larger sample sizes and will be expanding the survey to international cities in the near future. Second, while using this methodology to compare correlates of SWB across geography it is important to keep in mind that place-specific conditions, such as culture, socio-economic conditions, and population characteristics may play a role in the extent that neighborhood attributes influence SWB. Therefore, the geography of the comparison must be carefully considered. For instance, a neighborhood in the USA cannot be compared to one in India. Third, our study is cross-sectional which limits the casual inferences of our findings, as our ability to detect and accommodate for changes in characteristics of the target population over time and to avoid recall bias is limited. Fourth, our exploratory study had a small sample size, which may have influenced the identification of provisioning system priorities. Finally, until confirmed by similar research in other cities, the results of this analysis (priorities identified) are applicable only to the Twin Cities, where the study was conducted.

Despite these limitations, our results indicate the feasibility of developing a data-driven methodology that can be used to unpack the relationship between key provisioning systems and SWB to simultaneously address livability and equity. Applying this method in the Twin Cities, USA, we answered three research questions that are vital to connecting the dots between urban infrastructure, well-being, livability, and equity.

First, we identified and collected data on over 50 correlates of SWB, including social and physical provisioning system variables spanning multiple scales and individual characteristics. To explore what physical and social provisioning systems are correlated with SWB we conducted a global multivariate regression with 32 SEIUS and individual control variables and found that the key correlates of SWB are home heating and cooling, public transportation, neighborhood greenery, income, health, family relationships, and social relationships. Our results, for the first time, systematically unpack both social and physical provisioning system correlates of SWB spanning multiple scales, from the household to the neighborhood to the city, after controlling for a number of interpersonal, intrapersonal, and demographic variables, providing a holistic assessment of SWB and its SEIUS correlates.

Second, using our split multivariate regression approach, we identified a typology of infrastructure to inform its prioritization for quality of life—that is, livability. In this initial exploratory study, the three-way typology was intuitive (expected) and insightful in terms of attributes. In the context of foundational
attributes, given the climate in Minnesota, home heating and cooling and snow removal emerging as foundational attributes were not surprising. Neighborhood greenery was also indicated as foundational, wherein our study quantitatively demonstrated, for the first time, the relative importance of greenery to SWB compared to other infrastructural attributes at the home, neighborhood, and city scale. Public transportation was also found to be foundational for SWB, which is expected, as it is an important public service and one that appears to be equitably provided in Minneapolis, given that lower-income and minority participants reported higher satisfaction (see figure 3). The result of home size being consistently important for SWB has important implications for environmental sustainability. The results in table 5 and figure 2 suggest that home size is important, even for those populations experiencing higher SWB and aggregate infrastructure satisfaction. This has important implications for the concept of sufficiency [67] given the continuously increasing size of newly constructed homes in the USA [68] and elsewhere in the world [69]. More research is critically needed to understand how people think about home size, their well-being, and the environmental impacts associated with increased material and energy use. Based on these results, policymakers should prioritize attributes that are foundational and consistently important to focus on those residents reporting the lowest SWB and lowest satisfaction with attributes that are basic needs and attributes that are important to all.

Third, further assessment of inequality related to those provision systems classified as foundational and consistently important identified sectors that are important from a distributional equity perspective. The inequality analysis by income and race suggested a lower priority for improving public transportation in wealthier, suburban neighborhoods as compared to improving heating and cooling, snow removal, neighborhood greenery, and health (foundational attributes), as well as consistently important attributes like home size and family relationships in poorer, minority neighborhoods. Continuing to invest in infrastructure without paying attention to these priorities to improve equity can exacerbate these disparities in the future.

Overall, this paper demonstrated a data-driven methodology that can be used simultaneously to identify provision system priorities to address both livability (quality of life) and distributional aspects of social equity. The case study demonstrated that our method is not only feasible but also able to provide tangible information that can help policymakers design infrastructure-based interventions at different scales to promote SWB and social equity. The replication of this methodology across larger populations and across cities, including the Cantril ladder and other measures of SWB (affective and eudemonic), will be the next Frontier in developing livable and equitable cities in the future. Future surveys across socio-economic strata conducted in multiple cities can help further elucidate what infrastructure attributes are considered foundational versus consistently important versus added bonus, offering critical insight on how concepts such as sufficiency and Maslow’s hierarchy of needs relate to SWB. Additionally, the classification of infrastructure types developed in this study to inform livability priorities can be combined with data on carbon intensity, such as those developed in Oswald et al (2020), to chart pathways toward low-carbon, equitable, and livable cities.

Acknowledgments

This review was funded by the Sustainable Research Network project of the National Science Foundation of USA: Integrated Urban Infrastructure Solutions for Environmentally Sustainable, Healthy and Livable Cities. (Award #: 1444745).

The authors would like to thank Kyle Flanegin (formerly at the University of Minnesota—Humphrey School of Public Affairs) for contributing initial ideas for the analysis of SWB and livability.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Author contributions

AR conceptualized the livability—wellbeing—inequality linkages in the paper. All authors contributed to the survey design. KD conducted field implementation of the survey with primary advising from YF. AR and KD, developed the data analysis method with additional feedback from JC and YF. KD and AR equally wrote the bulk of the paper and designed the graphics.
Conflict of interest

The authors have no competing interests to report.

ORCID iDs

Anu Ramaswami https://orcid.org/0000-0002-0476-2315

References

[1] O’Neill D W, Fanning A L, Lamb W F and Steinberger J K 2018 A good life for all within planetary boundaries Nat. Sustain. 1 88–95
[2] Ramaswami A, Russell A G, Culligan P J, Sharma K R and Kumar E 2016 Meta-principles for developing smart, sustainable, and healthy cities Science 352 940–3
[3] Ramaswami A 2020 Unpacking the urban infrastructure nexus with environment, health, livability, well-being, and equity One Earth 2 120–4
[4] Stanton E A 2007 The human development index: a history PERI Working Papers (Political Economy Research Institute, University of Massachusetts Amherst) p 85
[5] Hellwell J, Layard R, Sachs J and De Neve J 2020 World Happiness Report 2020 (New York:Sustainable Development Solutions Network Saatavilla) https://happiness-reports3.s3.amazonaws.com/2020/WHR20.pdf
[6] Center for Disease Control and Prevention 2018 Well-being concepts|HRQOL|CDC updated 05 November 2018 available from: https://cdc.gov/hrqol/wellbeing.htm
[7] United Nations Department of Economic and Social Affairs 2015 Sustainable Development Goals (United Nations) available from: https://sdgs.un.org/goals
[8] The United Nations Conference on Housing and Sustainable Urban Development 2016 The newurban agenda available from: https://habitat3.org/the-new-urban-agenda/
[9] Ramaswami A, Weible C, Main D, Heikila T, Siddiki S, Duvall A, Pattison A and Bernard M 2012 A social-ecological-infrastructural systems framework for interdisciplinary study of sustainable city systems: an integrative curriculum across seven major disciplines J. Ind. Ecol. 16 801–15
[10] National Center for Immunization and Respiratory Diseases (NCIRD) 2021 Health equity considerations and racial and ethnic minority groups: centers for disease control and prevention available from: https://cdc.gov/coronavirus/2019-ncov/community/health-equity/race-ethnicity.html
[11] United Nations Human Settlements Programme 2020 World Cities Report 2020: The Value of Sustainable Urbanization (United Nations)
[12] Clark L P et al 2022 A data framework for assessing social inequality and equity in multi-sector social, ecological, infrastructural urban systems: focus on fine-spatial scales J. Ind. Ecol. 26 145
[13] World Health Organization 2008 Social Determinants of Health (WHO Regional Office for South-East Asia)
[14] Kennedy C et al 2013 Greenhouse Gas Emissions from Global Cities (Washington, DC: American Chemical Society)
[15] Prüss-Ustün A, Wolf J, Corvalán C, Neville T, Bos R and Neira M 2017 Diseases due to unhealthy environments: an updated estimate of the global burden of disease attributable to environmental determinants of health J. Public Health 39 464–75
[16] Tong K, Ramaswami A, Xu C K, Feiock R, Schmitz P and Ohlsen M 2021 Measuring social equity in urban energy use and interventions using fine-scale data Proc. Natl Acad. Sci. 118 e2023554118
[17] Braveman P 2006 Health disparities and health equity: concepts and measurement Annu. Rev. Public Health 27 167–94
[18] Oguz S, Merad S and Snape D 2013 Measuring National Well-Being-What Matters Most to Personal Well-Being (London: Office for National Statistics)
[19] Farrell S J, Aubry T and Coulombe D 2004 Neighborhoods and neighbors: do they contribute to personal well-being? J. Community Psychol. 32 9–25
[20] Chindarkar N, Chen Y J and Gurung Y 2019 Subjective well-being effects of coping cost: evidence from household water supply in Kathmandu Valley, Nepal J. Happiness Stud. 20 2581–608
[21] Singleton P A 2019 Walking (and cycling) to well-being: modal and other determinants of subjective well-being during the commute Travel Behav. Soc. 16 249–61
[22] Mavoa S, Davern M, Breed M and Hahs A 2019 Higher levels of greenness and biodiversity associate with greater subjective wellbeing in adults living in Melbourne, Australia Health Place 57 321–9
[23] The City of New York 2019 OneNYC 2050 (New York City)
[24] Metropolitan Council 2021 Livable Communities Program Minnesota (Metropolitan Council) available from: https://metrocouncil.org/About-Us/Facts/Communities/FACTS-Livable-Communities.aspx
[25] City of El Paso Sustainability Program 2008 Livable City Sustainability Plan El Paso, Texas City of El Paso Sustainability Program (City of El Paso Sustainability Program) available from: https://uccrnna.org/wp-content/uploads/2017/06/45_El-Paso_2008_UrbanPolicyRes._ procurements.pdf
[26] Lowe M, Whitzman C, Badland H, Davern M, Aye L, Hes D, Butterworth I and Giles-Corti B 2015 Planning healthy, liveable and sustainable cities: how can indicators inform policy? Urban Policy Res. 33 131–44
[27] Organisation for Economic Co-operation and Development 2011 How’s Life?: Measuring Well-Being (Paris: OECD)
[28] Mercer W M 1999 Worldwide Quality of Living Survey (Mercer)
[29] McArthur J and Robin E 2019 Victims of their own (definition of) success: urban discourse and expert knowledge production in the livable city Urban Stud. 56 1711–28
[30] The Economist Intelligence Unit 2021 The Global Livability Index The Economist available from: https://eiu.com/n/campaigns/global-livability-index-2021/utm_source=google & utm_medium=cpc & utm_name=livelability21 & utm_term=livelability_definition & utm_content=general & gclid=CjwKCAjwxs8ifBbwEiwA2quaq0hPSuE_ReLfTwlXLTfEjzHOxynaazpCD699Dq8b6OpeZjBPEkwRoC8BbUQAvD_BwE

13
[31] International Organization for Standardization 2018 Sustainable Development of Communities—Indicators for City Services and Quality of Life available from: https://iso.org/standard/62436.html (International Organization for Standardization)

[32] Asian Development Bank 2014 Developing Indicators and Monitoring Systems for Environmentally Livable Cities in the People’s Republic of China (Metro Manila, Philippines: Asian Development Bank)

[33] WHOQOL Group 1998 Development of the world health organization WHOQOL-BREF quality of life assessment Psychol. Med. 28 551–8

[34] Tan K G, Woo W T, Tan K Y, Low L and Aw G E L 2012 Ranking the Liveability of the World’s Major Cities: The Global Liveable Cities Index (GLCI) (Singapore: World Scientific)

[35] VanZerEM M and Seskin S 2011 Recommendations Memo #2 Livability and Quality of Life Indicators (Portland: CH2M Hill)

[36] City of Melbourne 2020 Liveability and quality of life (City of Melbourne) available from: https://melbourne.vic.gov.au/about-melbourne/research-and-statistics/Pages/liveability.aspx

[37] Litman T 2010 Sustainability and Livability: Summary of Definitions, Goals, Objectives and Performance Indicators (Victoria Transport Policy Institute)

[38] Oswald Y, Owen A and Steinberger J K 2020 Large inequality in international and intranational energy footprints between income groups and across consumption categories Nat. Energy 5 231–9

[39] KANO N 1984 Attractive quality and must-be quality J. Japan. Soc. Quality Control

[40] Helliwell J F and Barrington-Leigh C P 2010 Viewpoint: measuring and understanding subjective well-being J. The Quality of Life: Perceptions, Evaluations, and Satisfactions

[41] Mikulic J (ed) 2007 The Kano model–a review of its application in marketing research from 1984 to 2006 Doctoral Dissertation University of Minnesota

[42] Das K V, Jones-Harrell C, Fan Y, Ramaswami A, Orlowe B and Botchwey N 2020 Understanding subjective well-being: perspectives from psychology and public health Public Health Rev. 41 1–32

[43] Das K V 2020 Assessing the influence of the neighborhood environment on evaluative and emotional subjective well-being Dissertation University of Minnesota

[44] Cantril H 1965 Pattern of Human Concerns (New Brunswick, NJ.: Rutgers University Press)

[45] Glassmer H, Rief W, Martin A, Mewes R, Brähler E, Zenger M and Hinz A 2012 Psychometric properties and population-based norms of the life orientation test revised (LOT-R) Br. J. Health Psychol. 17 452–45

[46] Long J S and Freese J 2006 Regression Models for Categorical Dependent Variables Using Stata (College Station, Texas: Stata Press)

[47] Cha K-H 2003 Subjective well-being among college students Soc. Indicators Res. 62 455–77

[48] Daukantaitė D and Zukauskiene R 2012 Optimism and subjective well-being: affectivity plays a secondary role in the relationship between optimism and global life satisfaction in the middle-aged women, Longitudinal and cross-cultural findings J. Happiness Stud. 13 1–16

[49] Andrews F 1986 Research on the Quality of Life (Ann Arbor: Survey Research Center, Institute for Social Research, University of Michigan Press)

[50] Campbell A, Converse P E and Rodgers W L 1976 The Quality of American Life: Perceptions, Evaluations, and Satisfactions (New York: Russell Sage Foundation)

[51] Lamu A N and Olsen J A 2016 The relative importance of health, income and social relations for subjective well-being: an integrative analysis Soc. Sci. Med. 152 176–85

[52] Kutek S M, Turnbull D and Fairweather-Schmidt A K 2011 Rural men’s subjective well-being and the role of social support and sense of community: evidence for the potential benefit of enhancing informal networks Aust. J. Rural Health 19 20–6

[53] Lee A and Browne M O 2008 Subjective well-being, sociodemographic factors, mental and physical health of rural residents Aust. J. Rural Health 16 290–6

[54] Hellwell J F and Putnam R D 2004 The social context of well-being Phil. Trans. R. Soc. B 359 1435–46

[55] Zhang Z and Zhang J 2017 Perceived residential environment of neighborhood and subjective well-being among the elderly in China: a mediating role of sense of community Environ. Psychol. 54 82–94

[56] Patterson P K and Chapman N J 2004 Urban form and older residents’ service use, walking, driving, quality of life, and neighborhood satisfaction Am. J. Health Promot. 19 43–52

[57] Menec V H and Nowicki S 2014 Examining the relationship between communities’ ‘age-friendliness’ and life satisfaction and self-perceived health in rural Manitoba, Canada Rural Remote Health 14 159–72

[58] Iacobucci D, Posavac S S, Kardes F R, Schneider M J and Popovich D L 2015 The median split: robust, refined, and revised J. Consum. Psychol. 25 690–704

[59] Iacobucci D, Posavac S S, Kardes F R, Schneider M J and Popovich D L 2015 Toward a more nuanced understanding of the statistical properties of a median split J. Consum. Psychol. 25 652–65

[60] Schwarz K et al 2015 Trees grow on money: urban tree canopy cover and environmental justice PLoS One 10 e0122051

[61] Goldstein B, Gounaridis D and Newell J P 2020 The carbon footprint of household energy use in the United States Proc. Natl Acad. Sci. USA 117 19122–30

[62] Grant S, Langan-Fox J and Anglim J 2009 The big five traits as predictors of subjective and psychological well-being Psychol. Rep. 105 205–31

[63] Ben-Arieh A and Shimon E 2014 Subjective well-being and perceptions of safety among Jewish and Arab children in Israel Child. Youth Serv. Rev. 44 100–7

[64] Blessi G T, Grossi E, Pieretti G and Landi A 2015 Cities, the urban green environment, and individual subjective well-being: the case of Milan, Italy Urban Stud. Res. 2015 137027

[65] Dittmann J and Goebel J 2010 Your house, your car, your education: the socioeconomic situation of the neighborhood and its impact on life satisfaction in Germany Soc. Indicators Res. 96 497–513

[66] Maslow A and Lewis K J 1987

[67] Steinberger J K and Roberts J T 2010 From constraint to sufficiency: the decoupling of energy and carbon from human needs, 1975–2005 Ecol. Econ. 70 425–33

[68] Moura M C P, Smith S J and Belzer D B 2015 120 Years of U.S. Residential housing stock and floor space PLoS One 10 e0134135

[69] Lamb W F et al 2021 A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018 Environ. Res. Lett. 16 073005