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RESEARCH ARTICLE

Perceived services and disservices of natural treatment systems for urban stormwater: Insight from the next generation of designers

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Abstract

1. Natural treatment systems (NTS) for stormwater have the potential to provide a myriad of ecosystem services to society. Realizing this potential requires active collaboration among engineers, ecologists and landscape planners and begins with a paradigm shift in communication whereby these groups are made aware of each other's perceptions about NTS and the presence of knowledge gaps that their respective disciplines can bridge.
2. Here we participate in the first part of what we hope will be a reciprocal exchange: presenting results from a landscape perceptions survey to urban planners, ecologists and landscape architects that illustrates how the next generation of engineers perceives NTS relative to other landscape features, and the implications of those perceptions for future infrastructure development.
3. Our results suggest that although lawns, gardens and native ecosystems were perceived as multifunctional, providing characteristic bundles of services/disservices, perceptions of NTS were more variable (i.e. there was no social norm for their perception).
4. Environmental worldviews, knowledge, attitudes about ecosystem services and demographics were all significant drivers of perceived services. However, students had difficulty identifying NTS correctly, and factual knowledge about NTS did not help students associate NTS with typical design services like flood reduction more than features not designed for those purposes, such as lawns. This

suggests that engineering students lack familiarity with the outward appearance of NTS and have difficulty placing NTS services into a broader landscape context.
5. Expertise from urban planning and ecology could help bridge these knowledge gaps, improving the capacity of tomorrow's engineers to co-design NTS to meet diverse community needs.

KEYWORDS
ecosystem services, green infrastructure, green stormwater infrastructure, landscape perception

1 | INTRODUCTION

Urban communities face many challenges globally, including altered hydrology, which has cascading impacts on water quality and public/ecosystem health (Askarizadeh et al., 2015; Walsh et al., 2016). The management of urban stormwater runoff requires simultaneous consideration of all such impacts but has conventionally emphasized flood control. Although multi-objective stormwater management has become more prevalent, the range of services designed for remains narrow, including water volume and quality, erosion control, groundwater recharge, stream channel protection and to a lesser extent biodiversity (NRC, 2009). Perceptual services important for quality of life such as aesthetics, sense of place and recreation, longtime foci of landscape architects, are infrequently designed for by engineers (NRC, 2009; Schifman et al., 2017). Re-envisioning urban infrastructure to collectively support sustainability, environmental and quality of life objectives will require a collaborative effort bridging these disciplines (and many others). Accomplishing this task is considered one of 14 grand challenges facing society in the 21st century by the National Academy of Engineering (NAE, 2019).

Distributed green infrastructure approaches are anticipated to play an important role in addressing this challenge. They aim to foster human wellbeing through ecosystem services provisioning (Fletcher et al., 2015), including services associated with urban stormwater such as infiltration and groundwater recharge, flood control and protection of downstream ecosystems from pollutants and unnatural flow regimes, as well as services related to human health and wellbeing more broadly such as recreation and aesthetics, urban cooling and carbon storage, and biodiversity and pollination (Colla et al., 2009; Coutts et al., 2012; Duke et al., 2016; Getter et al., 2009; Parker et al., 2017; Rippy et al., 2021; Schubert et al., 2017; Walsh et al., 2016; Winfrey et al., 2018). Designing green infrastructure for a broad range of services is important, given the projected costs of such infrastructure (estimated at 10.5 US dollars per m^3 stormwater capture in the United States and 7.2 US dollars per m^3 stormwater capture in Europe; Chen et al., 2019; Quaranta et al., 2021), which can exceed projected benefits if the range of ecosystem services considered is narrow (Alves et al., 2019; Quaranta et al., 2021; Vandermeulen et al., 2011). This makes co-provisioning of services (i.e. multifunctionality) important for cost-effectiveness.

The emphasis green infrastructure places on ecosystem services (and increasingly, multifunctionality; Rippy et al., 2021; Winslow, 2021) is aligned with the concept of Nature-based solutions (NbS), a popular sustainable urban greening concept in the E.U. and a growing part of the global climate solution toolkit (Portner et al., 2021). It also sets green infrastructure apart from 'grey' infrastructure (pipes, combined sewers, detention basins, open channels), which lie at the opposite end of the so-called green–grey stormwater infrastructure continuum, and tend to be single function (Bell et al., 2019; Dorst et al., 2019; Moosavi et al., 2021). Green infrastructure encompasses both a philosophy of greening/urban design and a collection of technologies in line with that philosophy, the latter being analogous to sustainable urban drainage systems (SUDS), structural best management practices (BMPs) and stormwater control measures (SCMs) (Fletcher et al., 2015; Moosavi et al., 2021). Vegetated technologies that mimic nature and use natural processes to deliver desired services are emphasized (Fletcher et al., 2015; Levin & Mehring, 2015). In Southern California these technologies are sometimes referred to as natural treatment systems (NTS), a popular term with local water districts (see, for instance IRWD, 2021). NTS include both blue (constructed wetlands, restored streams) and green (green roofs, bioswales, rain gardens/biofilters) systems, with this study focusing primarily on green NTS. Although the stated goal of NTS is ecosystem services provisioning, they also have the potential to generate environmental outcomes that cause harm known as ecosystem disservices or sinks of ecosystem services (Villa et al., 2014). Vector control problems, allergen production and greenhouse gas emissions are all examples of disservices (Grover et al., 2013; Metzger et al., 2008; Pataki et al., 2011).

While grey stormwater infrastructure is often a hidden component of urban landscapes, NTS are more visible (Finewood et al., 2019). This visibility, combined with public influence over installation and upkeep (Everett et al., 2018; Gobster et al., 2007; Nemes et al., 2016), makes perception key to the success of NTS in urban areas. Extensive NTS programs in the United States where perceptions have been evaluated include the Tabor to the River program in Portland, Oregon (Church, 2015; Everett et al., 2018;

Shandas, 2015), the Save the Rain Initiative in Syracuse, New York (Barnhill & Smardon, 2012; Foley, 2012), New York City's Green Infrastructure Plan (Miller & Montalto, 2019), Philadelphia Pennsylvania's Green City, Clean Waters Program (McGarity et al., 2015) and the City of Chicago's Green Infrastructure Strategy (Ando et al., 2020). Surveys, interviews, choice experiments and community-based participatory research conducted in these cities point to water quality (and to a lesser extent flood control) as among the most recognized and valued NTS services in the United States. Aesthetics, socio-economic factors (e.g. community amenities, reduced inequality) and improved aquatic habitat were also perceived as important (McGarity et al., 2015; Miller & Montalto, 2019). Safety and public health risks emerged as commonly perceived disservices (Barnhill & Smardon, 2012; Everett et al., 2018; Foley, 2012; Miller & Montalto, 2019). Most studies reported the average perceived value of each service or disservice across all individuals, making the extent to which the public perceives NTS as multifunctional unclear.

A handful of studies have explored possible drivers of how NTS are perceived, with attitudes, beliefs, individual knowledge, the surrounding physical environment and demographic variables like age, education, race and gender variously reported as significant (Fernandez-Canero et al., 2013; Foley, 2012; Shandas, 2015). Work in this area is limited relative to parks and gardens, however (Bertram & Rehdanz, 2015; Kendal et al., 2012; Kurz & Baudains, 2012; Ozguner & Kendle, 2006), and to our knowledge neither perceptions of NTS nor their drivers have been explored in the context of other landscape features. This omission is important, because implementing NTS in a neighbourhood does not necessarily mean replacing pavement with NTS; it could also involve replacing other landscape features such as lawns (i.e. in some instances it may be the character of urban greenspace that changes, not the total amount).

Because NTS (like all design elements) reflect the cognitive biases and values of their designers, it is important to pay attention to who is involved in NTS design, which may differ substantially in different countries (Adem Esmail & Suleiman, 2020; Finewood et al., 2019; Suleiman et al., 2020; Zischg et al., 2019; Zuniga-Teran & Gerlak, 2019). In the United States, green infrastructure is often associated with prevention of Clean Water Act violations and framed more narrowly as green stormwater infrastructure (Bell et al., 2019; Finewood et al., 2019; Holloway et al., 2014), which brings engineers into the design process early and prioritizes stormwater-associated services. NTS, however, are also part of the urban fabric, and this greater whole (often the focus of landscape architects, urban planners and increasingly urban ecologists) regulates the delivery of entire suites of services (sometimes framed as co-benefits; Bell et al., 2019; Walsh et al., 2016) from NTS to the public. This makes the combined efforts of engineers and the social and ecological sciences critical for NTS to provide services successfully, a collaboration that can be challenging to navigate in practice (Albert et al., 2021; Shanstrom, 2017). Bridging such divides and facilitating co-production of credible shared knowledge across disciplines is difficult because it requires moving beyond disciplinary jargon to develop shared concepts and metrics, fostering an open, inclusive, and participatory culture, and building consensus around ultimate goals (key tenants of both boundary work and convergence research; Adem Esmail et al., 2017; Clark et al., 2016; NRC, 2014). We contend that bridging such divides with respect to green infrastructure and NTS begins with a paradigm shift in communication that emphasizes the next generation of designers: engineering students must be exposed to the breadth of urban ecologists' and planners' knowledge (and vice versa), and the perceptions held by each group about NTS should be actively shared.

Multidisciplinary efforts to bring these groups together in what one might call ‘boundary programs’ for sustainability education are already underway at multiple universities; examples from the U.S. include Drexel (SWRE, 2020), Northwestern (CEE-346), the University of Michigan (SEAS-Sustainable Systems), Carleton College (InTeGrate), Syracuse University (Flynn, 2017; Flynn et al., 2015), the Universities of California, Irvine, San Diego, and Los Angeles (UCI Water PIRE), University of Massachusetts Amherst (Ryan, 2014), Virginia Tech (McWhirter & Shealy, 2018) and Villanova University (SIBE-VUSP), among others. These efforts aim to integrate engineering with other disciplines in ways that promote sustainable decision making and foster the development of the so-called post-conventional engineer (i.e. engineers that recognize engineering as requiring complex decision making in a multidisciplinary sphere and embody an ethic of social responsibility; Flynn et al., 2015).

This article builds upon this foundation. We evaluate engineering students' perceptions about NTS and other common greenspace forms (lawns, gardens and native ecosystems) at four major public universities in California, some of whom have adopted the kinds of integrated curricula noted above, with the goal of conveying those perceptions (and misperceptions) to a broad community of researchers, practitioners and educators addressing green infrastructure and their services. We have elected to focus the initial stages of what we hope will be an ongoing dialogue on engineering students, due to the tendency of engineers in the United States to be involved early-on in NTS design when stormwater is a concern. This means they play a role in constraining the possibility space in which subsequent decisions about ecosystem services are made, making understanding engineering perspectives about a broad spectrum of ecosystem services important. This choice also reflects the lead author's role in an engineering program with a vested interest in the education of the next generation of engineers.

The specific questions we pose and answer are tailored to knowledge gaps identified previously, including; (a) to what extent does the next generation of engineers perceive NTS as multifunctional (i.e. capable of providing a broad spectrum of ecosystem services, including water quality, flood regulation, urban cooling, recreation, aesthetics, biodiversity, carbon sequestration and pollination)?, (b) are their perceptions of ecosystem services provisioning similar or different across urban landscape features (NTS, lawns, gardens and native ecosystems), and how? and (c) what role do environmental worldviews, attitudes about ecosystem services, individual knowledge and demographics play in shaping those perceptions? In addressing these questions, we illuminate challenges that the stormwater management community is likely to face regarding how NTS are perceived relative to other greenspace elements (even among those trained to know them well), as well as opportunities for engineers, urban planners and urban ecologists to work together and overcome them through broadening the knowledge base of tomorrow's engineers.

2 | METHODS

2.1 | Study area

Engineering student perceptions of NTS and other landscape features (lawns, gardens and native landscape remnants) were surveyed at four university campuses each serving between 24,000 and 45,000 students (see Figure 1a). The land cover of each surveyed campus was 44%–66% impervious surfaces, with the remainder divided between irrigated landscaping and un-irrigated open space such as sage scrub (C4) and chaparral (C1–C3). Two campuses (C2 and C4) are coastal, with blue water views. The remainder are farther inland (5–9 miles from the coast). The landscape immediately surrounding C1, C2, and C4 is primarily suburban residential or commercial, with C3 being more urban (i.e. within the greater metropolitan area of a megacity).

Across all campuses, structural practices for managing runoff include grey (concrete culverts, separate storm sewers) and green infrastructure approaches (permeable pavers, sand filters and NTS such as bioswales, planter-box biofilters, green roofs, constructed wetlands and restored streams, among others). Most green infrastructure is located in new campus development (at C1 this concentrates green infrastructure in student housing facilities to the north/northeast of campus; Figure 1b). No campus save C2 had interpretive signage for green infrastructure when our surveys were administered.

The amount/type of green infrastructure surrounding each campus varies. More than 2,400 green infrastructure elements (~0.2/km^2) have been inventoried in the counties where C1 and C3 are located. Most of this infrastructure is situated near C1, and includes rain gardens, bioswales, biofiltration and bioretention, with constructed wetlands also being prevalent (Huang et al., 2018; Silvertooth et al., 2019). The counties in which C2 and C4 are located also have ongoing green infrastructure programs, with the former emphasizing regional elements such as infiltration basins and constructed wetlands, and the latter focusing on green streets featuring bioswales, rain gardens and permeable pavement (GSCW, 2021; ISRP, 2021).

2.2 | Survey methods

Two survey instruments were administered with Institutional Review Board (IRB) approval: HS #2017–3998 and HS #18–1143. Each instrument had a different principal objective, with the first (full survey) focusing on depth (i.e. a comprehensive evaluation of student perceptions at a single university campus; C1, Figure 1a), and the second (short survey) focusing on breadth (i.e. evaluating student perceptions at multiple university campuses; C2–C4, Figure 1a, using a reduced number of survey questions). A roadmap detailing

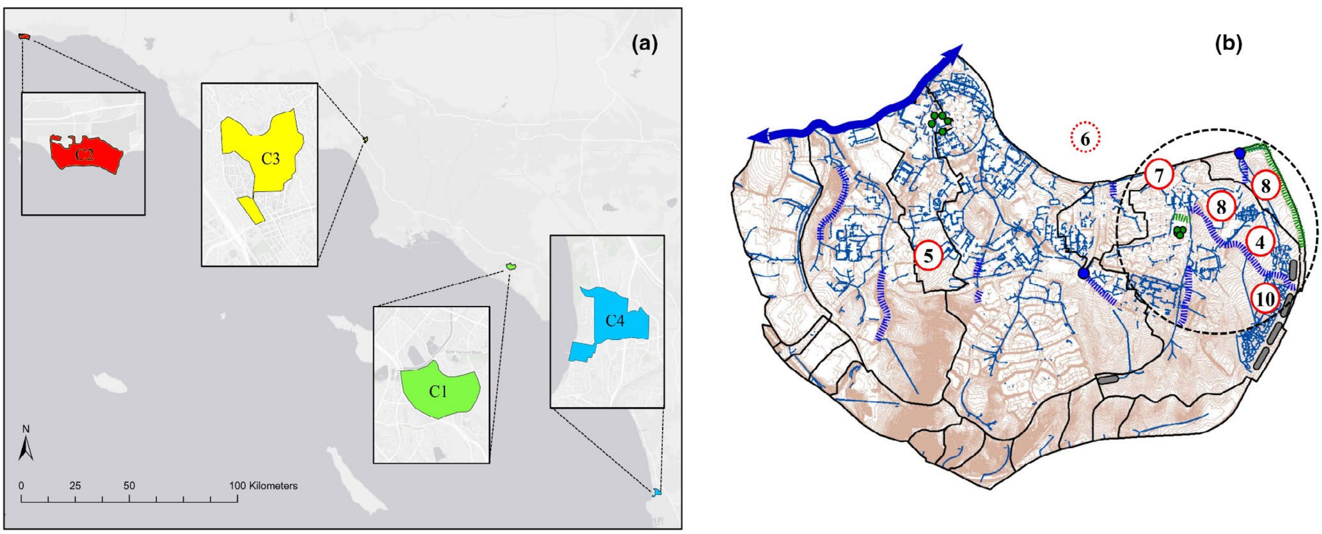

FIGURE 1 (a) Map of surveyed universities (C1–C4). (b) Detail map of C1 illustrating topography (brown lines), the storm sewer system (dark blue lines), major stormwater catchments (solid black lines), and green stormwater infrastructure (bioswales—dashed green lines, restored streams—dashed blue lines, wetlands—blue dots, rain gardens, sand filters, and/or green roofs—green dots, and subsurface stormwater detention systems—grey boxes). The number of survey participants reporting to reside in specific campus housing developments are shown using solid red circles. Participants that claimed to live on campus but were slightly beyond its northern border are shown using a dashed red circle. Housing developments within 300 m of a rain garden, swale or wetland are encircled by a black dashed line. The northwest border of the campus is a large creek, indicated by a blue arrow the similarities and differences between each survey instrument, deployment details by campus and how responses were analysed, is presented in Figure 2, and is intended to serve as a methods guide for this paper. A copy of the full survey (including the consent form) is provided in Appendix A. Written informed consent was obtained electronically from all participants using a form field checkbox (see Appendix A).

2.2.1 | Survey deployment and response curation

The full survey instrument was distributed to 139 undergraduate engineering students enrolled in a required civil and environmental engineering (CEE) course at university C1 using the Canvas learning platform (Canvas from infrastructure, LMS). The surveyed population constitutes 27% of CEE undergraduates at C1, including freshman, sophomores, juniors and seniors (Figure 2). Neither stormwater-related nor NTS-related topics were addressed in the class. Individual responses were anonymous and participation was incentivized using extra course credit. Ninety-six per cent of recruited students consented to complete the survey.

The short format survey was administered (primarily by email) at universities C2–C4 using SurveyMonkey (SurveyMonkey, Inc). Details of survey deployment at each campus can be found in Pierce et al. (2021) and Appendix B.1. The number of engineering student respondents to the short survey was low relative to the total number of registered engineers at C2–C4 (0.4%–2.1%, campus depending; Figure 2), suggesting the surveyed population should not be viewed as broadly representative of the engineering student body. Given this, we have elected to use the short format survey as part of a weight of evidence approach, giving the full survey (representative of students at C1), broader context.

To ensure quality responses to both survey instruments, completed surveys were curated prior to analysis based on (a) time to survey completion (students taking <25 min, one standard deviation below the median completion time, were excluded); (b) runs of incomplete responses (students skipping >5 consecutive questions were excluded); (c) ambiguous responses to open ended questions (students with >1 response that did not appear to address the question posed were excluded); and (d) question sets with built in consistency checks (i.e. *if your prior response was 'X', please answer the following question, if not select 'Not Applicable'*). Students failing to logically answer at least 70% of these questions were excluded). One hundred twenty-four of 134 full surveys and 103 of 123 short surveys met these data curation constraints (Figure 2).

2.2.2 | Survey format

Both surveys were designed to evaluate the ecosystem services/disservices that engineering students perceive terrestrial NTS (biofilters and swales) provide, and compare them to perceptions of other landscape features (lawns, gardens, native ecosystems). Students were shown colour photographs of urban landscape features, in

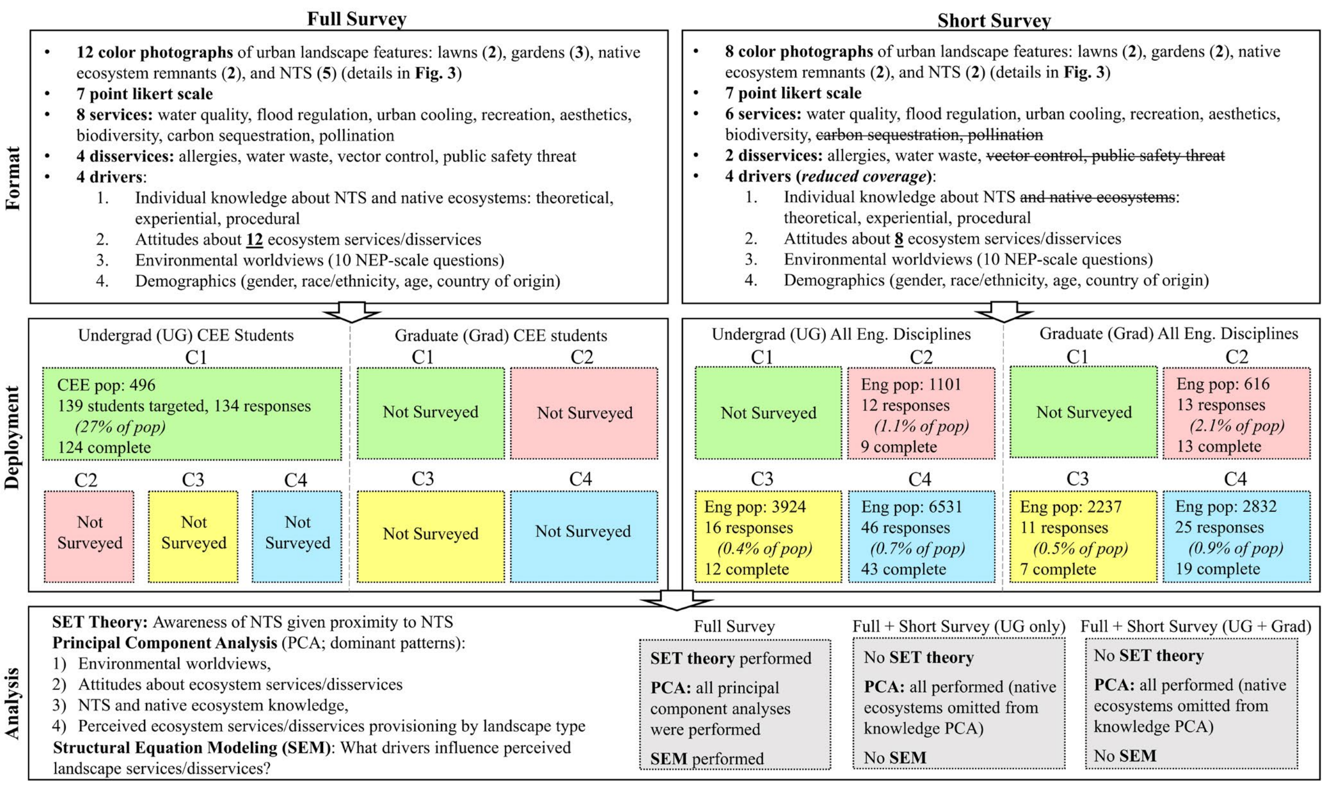

FIGURE 2 Overview of methods, highlighting similarities/differences between full and short survey instruments, deployment details by survey instrument and campus, and the analytical approaches used to evaluate survey results

random order (example in Figure 3), with a reduced number of photographs used in the short survey relative to the full survey (details in Figure 2). Each landscape photograph was large format (9.9 cm by 19.8 cm) and shown on its own page (i.e. perceptions of each photograph were elicited separately). To reduce bias associated with background content and lighting, all photographs contained both urban (roads, parking lots, buildings) and landscaped elements, were standardized to have the same sky colour and brightness, and selectively blurred as in Kendal et al. (2012) using graphics editing software (GIMP 2.8) to focus attention on the landscape feature of interest. Participants were asked to determine the extent of services/disservices provisioning each landscape feature could provide on a 7-point Likert scale (prompt in Figure 3m). A total of eight services (water quality, flood regulation, urban cooling, recreation, aesthetics, biodiversity, carbon sequestration and pollination) and four disservices (allergies, water waste, vector control and public safety threat) were assessed in the full survey. A reduced number (six services and two disservices) were assessed in the short survey (details in Figure 2).

Both surveys also addressed possible drivers of variability in perceived services/disservices provisioning by landscape. Four major categories of drivers were assessed: (a) individual knowledge (reduced coverage in short survey; Figure 2), (b) participant attitudes about ecosystem services/disservices (reduced coverage in short survey; Figure 2), (c) environmental worldviews and (d) demographics. Each driver is described further below.

Individual knowledge

Survey questions assessing individual knowledge targeted engineering (urban runoff, NTS) and the environment (native ecosystems, biodiversity), focusing on three knowledge categories: theoretical (factual), experiential (acquired through observation/experience) and procedural (knowing *how* something works) (Niedderer, 2007). Knowledge-related questions were reduced in the short survey relative to the full survey (see Figure 2 for details).

Theoretical knowledge of urban runoff, NTS and biodiversity was assessed using multiple response questions (Appendix C: Table

(m) **Prompt: I believe this system will...** *Scale: 1 (not at all) to 7 (very likely)*
Improve water quality
Remove carbon dioxide from the air
Soak water into the ground, reducing flooding
Attract mosquitos, rodents, and other pests
Waste water (especially in summer)
Cool down the urban environment
Attract bees, butterflies, and other pollinators
Make urban landscape more beautiful
Increase diversity of animals
Provide landscape for relaxation and recreation *(walking, picnicking, biking, jogging, cycling, or team-sports)*
Reduce the visibility of surrounding areas making people feel less safe
Cause allergies

FIGURE 3 Photographs (a–l) and the prompt (m) from the main body of the survey (shown smaller than they appeared to survey participants). Photographs depict different landscape forms, including: lawns (a and i), gardens (b: palms, j: succulents, k: roses), native ecosystem remnants (c: chaparral, l: coastal sage scrub), and natural treatment systems (g: biofilter, d, e, f, and h: swales)

S1). Upon completing these questions, participants were prompted to read an informative paragraph that defined urban runoff and NTS, establishing a consistent terminology for the remainder of the survey (Appendix D). Experiential knowledge questions focused on whether participants had ever talked about or seen NTS or native ecosystems, respectively, during organized campus activities (class, research, outreach and tours). Follow-up questions addressed details of those experiences (i.e. type of features seen, the presence/absence of interpretive signage), and determined which participants lived on campus and where. This latter information was used to assess the effects of NTS proximity on student awareness of NTS (Appendix C: Table S1). Procedural knowledge was assessed by determining if participants could translate theoretical/experiential knowledge about NTS or native ecosystem remnants into procedures for identifying them (Appendix C: Table S1). Participants were shown photographs from the main body of the survey (Figure 3), asked to determine which were of NTS and which were of native ecosystem remnants, and then scored based on their capacity to correctly identify NTS and native ecosystems more often than they misidentified other landscape features (for instance lawns) as NTS or native. Participants were also asked to report their confidence in classifying landscape features on a 7-point Likert scale.

Attitudes about services/disservices

Attitudes indicate whether individuals view specific concepts, intentions or behaviours favourably or unfavourably (Meddin, 1975). Full and short survey instruments addressed attitudes about 12 and 8 services/disservices, respectively (Figure 2). Participants were asked to quantify the importance of each service/disservice on a 7-point Likert scale, responding to the prompt: 'how much does each benefit or negative outcome of urban landscapes matter to you?': 1—*not at all* to 7—*very important*; Appendix E: Table S2).

Environmental worldviews

Environmental worldviews are core environmental belief systems that influence attitudes/opinions about specific environmental issues (recycling, water conservation, etc.). The New Ecological Paradigm (NEP) scale is a 15-item measure of environmental worldviews that targets five environmental facets: the balance of nature, limits to growth, anti-anthropocentrism, human exemptionalism (the idea that humans are exempt from the constraints of nature) and ecocrises (concern about potentially catastrophic environmental shifts such as climate change) (Dunlap et al., 2000). In both surveys, environmental worldviews were assessed using an abbreviated set of 10 NEP questions, excluding 5 that have been shown to have low item-total correlations in other studies (Saphores et al., 2012).

Demographics and education

In both surveys, participants were asked about demographic attributes previously shown to be associated with landscape preferences (gender, race/ethnicity, age and country of origin) (Foley, 2012; Kurz & Baudains, 2012; Shandas, 2015). Gender, race and ethnicity were assessed using multiple choice questions including options for 'Other' and 'prefer not to state', whereas age, country of origin and educational trajectory (i.e. academic major) were assessed using open response questions.

2.3 | Statistical analyses

2.3.1 | SET theory—Awareness of NTS

SET theory was used to frame a series of questions regarding participant awareness of NTS on campus at C1, the only campus where students were asked follow-up questions about their on-campus NTS experiences (see Appendix C: Table S1, Figure 2). The set of questions posed includes: (a) the probability (P) of seeing NTS on campus—$P(Saw)$; (b) the probability of seeing signed versus unsigned NTS—is $P(Saw \cap Signed)$ significantly different than $P(Saw \cap Unsigned)$?; (c) the probability that participants know what kind of NTS they have seen—$P(Know|Saw)$; and (d) the probability that participants know what they have seen if they saw signed versus unsigned NTS—is $P(Know|Saw \cap Signed)$ significantly different than $P(Know|Saw \cap Unsigned)$? Ninety-five per cent confidence bounds were calculated for each probability as described in Appendix B.2. A z-test for proportions was used to determine if paired probabilities in questions 2 and 4 were significantly (or marginally significantly) different at a $p < 0.05$ (or $p < 0.1$) level (Ang & Tang, 2007).

2.3.2 | Principal component analysis—Patterns in knowledge, attitudes, worldviews and landscape perceptions

Principal component analysis (PCA) was used to identify dominant patterns (PC modes) in (a) perceived services/disservices provisioning across urban landscape types (*responses to landscape photographs, section 2.2.2*), (b) NTS and native ecosystem knowledge *(responses to questions in Individual knowledge'*), (c) attitudes about ecosystem services/disservices *(responses to questions in 'Attitudes about services/disservices'*) and (d) environmental worldviews *(NEP scale questions, Environmental worldviews' section*). Analyses were performed on full survey responses (undergraduate engineers, C1), full and short survey responses (undergraduate engineers, C1–C4), and full and short format survey responses (undergraduate and graduate engineers, C1–C4) (Figure 2). This nested approach allows us to determine the extent to which results from the full survey at C1 are consistent with engineering student perspectives at other Southern California campuses across different levels of educational atainment.

A resampling-based stopping rule (Rippy et al., 2017) was employed to identify PC modes that were significantly different than random, and nonparametric bootstrap techniques (Babamoradi et al., 2013) facilitated identification of variables that contributed significantly (or marginally significantly) to each mode ($p < 0.05$ and $p < 0.1$ level respectively). For our landscape perceptions PCA, groups of services or disservices that contributed significantly to the same mode were defined as services/disservices bundles.

For improved visualization, all patterns in knowledge, attitudes, worldviews and landscape perceptions were assessed probabilistically using the empirical joint probability distribution of individual participant responses (PC scores) (Appendix B.3). This results in unique probability heatmaps that are easier to interpret than raw PC scores (Rippy et al., 2021).

2.3.3 | Drivers of landscape perceptions

The relative importance of knowledge, environmental worldviews, attitudes and demographics for explaining variability in perceived services/disservices provisioning across landscapes was assessed using path analysis conducted in R software (package LAVAAN; Rosseel, 2012). Only full survey responses, which reflect a complete set of driver variables, were evaluated (Figure 2). Our proposed path model was hierarchical: (a) demographics, education and individual knowledge impact landscape perception both directly and indirectly through environmental worldviews or attitudes about ecosystem services/disservices, (b) worldviews impact landscape perception both directly and indirectly through attitudes and (c) attitudes impact landscape perception directly (Figure 4). This path model reflects prevailing cognitive outlook constructs, where attitudes are a level of abstraction below worldviews, and perceptions/opinions about more narrowly defined topics are a level of abstraction below attitudes (Meddin, 1975). Individual knowledge impacts the entire network (including worldviews) because recent studies suggest that worldviews of young adults are malleable and can be influenced by knowledge acquisition (Stevenson et al., 2014).

Two types of variables were included in our path analysis: manifest variables reflecting responses to individual survey questions (i.e. demographics, academic major and domain-specific knowledge about urban runoff and biodiversity), and composite variables constructed using PCA (see Section 2.3.2) for concepts evaluated using six or more questions (i.e. NTS and native ecosystem knowledge, attitudes about ecosystem services, environmental worldviews and landscape perception). Final path analysis models were evaluated for significance as described in Appendix B.4 (Beaujean, 2014). Post-hoc power analysis (package SIMSEM, R Software) was used to determine the statistical power of each model, given the size of our study population. Regressions found to be significant at a $p < 0.05$ level but with moderate to low statistical power (i.e. <0.7) should be interpreted with caution. These relationships may be real, but their effect magnitude is relatively small—a larger study is required to confirm or refute them.

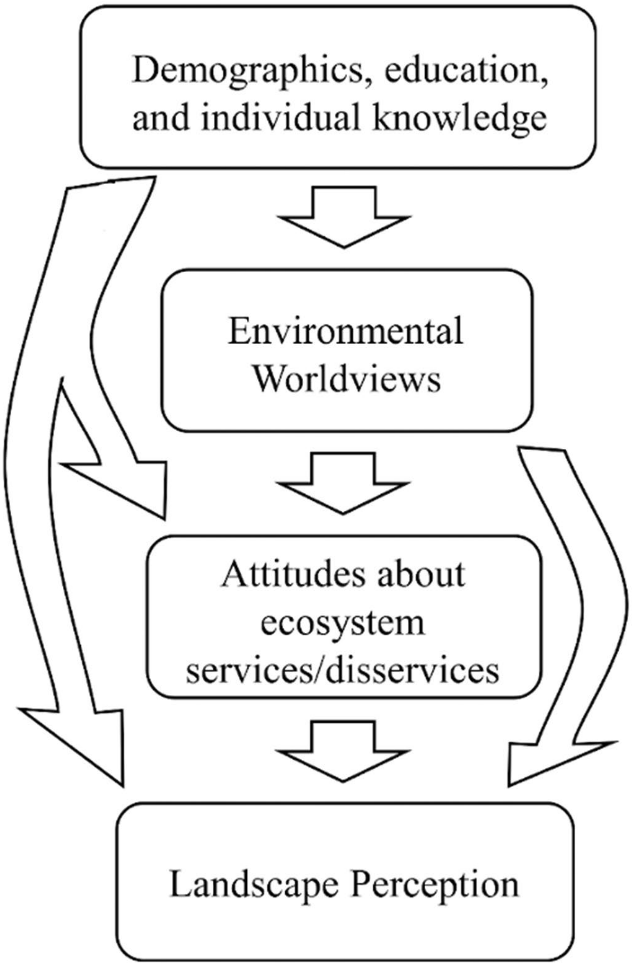

FIGURE 4 Schematic of the relationships evaluated between demographics, education, individual knowledge, environmental worldviews, attitudes, and landscape perception in Models 1 and 2

3 | RESULTS

3.1 | Demographics/education

Participant demographics were comparable across both surveys (Table 1). Most participants grew up in the United States (77%–78%), with the remainder having spent their childhood in East Asia (12%–13%), West Asia (2%–3%), South East Asia (2%–3%), South Asia (0%–2%) or South/Central America (2%–3%). Participants primarily identified with three racial categories (Asian/Asian American (42%–45%), Caucasian (18%–23%) or Other (24%–34%), with individuals that selected 'Other' being primarily of Hispanic or Latino ethnicity. Participant gender was 41%–43% female and median participant age was 20–21 years old.

The distribution of academic majors differed across surveys. In the full survey at C1 (column a, Table 1), civil engineering was the primary major, followed by environmental engineering, and other engineering disciplines (mechanical, general). When responses from the short format and full survey were pooled, the fraction of civil engineering majors dropped significantly (from 79% to 48%), the fraction of students in other engineering disciplines (particularly mechanical and electrical) rose significantly (from 5% to 39%), and the fraction of environmental engineers remained essentially unchanged at around 15% ($p < 0.05$; column c, Table 1).

Pooled survey results were consistent with the general campus demographic at C1–C4 with respect to race, ethnicity and country of origin (column c vs. d, Table 1). However, our study recruited significantly more female students and civil and environmental engineers

TABLE 1 Study demographics

	a Survey: full Campus: C1 Students: UG (95% CIs)	b Survey: full & short Campus: C1–C4 Students: UG (95% CIs)	c Survey: full & short Campus: C1–C4 Students: UG & G (95% CIs)	d Actual campus demog. (C1–C4, UG & G, inclusive of all majors)[1]	e Practicing engineers (National)[2]
Race					
American Indian/Alaska Native	1% (0-3)	1% (0–2)	0% (−1–2)	0%	0%
Asian/Asian American	42% (33–51)	45% (38–53)	45% (38–52)	41%	14%[e(a,b,c)]
Black or African American	0% (NA)	1% (0–2)	0% (−1–2)	2%[d(a)]	4%[e(a,b,c)]
Native Hawaiian/Pacific Islander	2% (0–4)	2% (0–4)	2% (0–4)	0%	—
Caucasian	18% (11–25)	19% (13–25)	23% (18–29)	28%[d(a,b)]	74%[e(a,b,c)]
Other Race	34% (26–42)	27% (21–34)	24% (18–29)	—	—
Prefer not to State	3% (0–6)	4% (1–7)	5% (2–8)	—	—
Ethnicity					
Hispanic/Latino	35% (27–43)	28% (22–35)	25% (19–31)	20%[d(a,b)]	7%[e(a,b,c)]
Country of origin					
USA	77% (70–84)	78% (72–85)	77% (71–82)	73%	78%
East Asia	13% (7–19)	12% (7–17)	13% (8–18)	—	—
West Asia	3% (0–6)	2% (0–4)	2% (0–4)	—	—
South East Asia	3% (0–6)	2% (0–4)	2% (0–4)	—	—
South/Central America	3% (0–6)	3% (0–5)	2% (0–4)	—	—
South Asia	0% (NA)	1% (0–2)	2% (0–4)	—	—
Other	0% (NA)	1% (0–4)	2% (0–4)	—	—
Age (years)					
Median	20 (18–33)	20 (18–33)	21 (18–33)	—	—
Percent ≤ 24	97% (93–100)	96% (93–99)	91% (87–95)	*83%*[d(a,b,c);3]	—
Gender					
Male	58% (49–67)	55% (47–64)	56% (49–62)	75%[d(a,b,c)]	84%[e(a,b,c)]
Female	41% (32–50)	43% (35–50)	42% (35–48)	25%[d(a,b,c)]	16%[e(a,b,c)]
Other	0% (NA)	1% (0–2)	0% (−1–2)	—	—
Prefer not to State	1% (0-3)	1% (0–2)	1% (0–2)	—	—
Engineering discipline					
Civil Engineering	79% (72–86)[a(b,c)]	57% (50–65)[b(a)]	48% (42–55)[c(a)]	10%[d(a,b,c)]	14%[d(a,b,c)]
Environmental Engineering	16% (10–22)	16% (10–21)	14% (9–19)	1.6%[d(a,b,c)]	—
Other	5% (1–9)[a(b,c)]	28% (21–35)[b(a)]	39% (32–45)[c(a)]	88.1%[d(a,b,c)]	—

Notes. Significant differences between surveyed populations are noted in columns a,b, & c, where a(b,c) would indicate that a is significantly different from b & c. Significant differences between surveyed populations and actual campus or practicing engineer populations are noted in columns d and e.

Abbreviation: G, graduate; UG, undergraduate.

[1]Data sourced from IPEDS: https://nces.ed.gov/ipeds

[2]Data sourced from the Scientists and Engineers Statistical Data System, 2013; https://ncsesdata.nsf.gov/us-workforce/2013

(CEE) than expected due to chance. The latter suggests our survey is more representative of CEE student perspectives than engineering perspectives in general. We may also have surveyed a younger demographic than expected due to chance; we only know for certain that the fraction of surveyed engineering students 24 years old or younger was higher than what has been reported more broadly for students at C1–C4 across all university majors (Table 1).

Our survey demographic exhibits some notable differences from that of practicing US engineers (column c vs. e, Table 1). Consistent with the above, women and CEE students were overrepresented relative to the national demographic. Asian/Asian American and Hispanic/Latino students were likewise overrepresented whereas Caucasian and Black/African American students were underrepresented. The latter is not unexpected given that all surveyed campuses are Hispanic Serving Institutions (HSIs) or emerging HSIs and two (C1 and C2) are Asian American and Native American/Pacific Islander Serving Institutions.

3.2 | Environmental worldviews

Participants exhibited two types of environmental worldviews consistently across both surveys (see PCs 1 and 2 in Figure 5a, Appendix F). The first concerned the presence (negative $PC1_{WV}$) or absence (positive $PC1_{WV}$) of pro-environmental perspectives (27%–29% variance explained [VE]; Figure 5a, Appendix F). Three NEP-scale environmental facets loaded significantly on this worldview. These include (a) anti-anthropocentrism—median agreement of 5–6 in response to 'plants and animals have as much right as humans to exist' and 3 in response to 'humans were meant to rule over the rest of

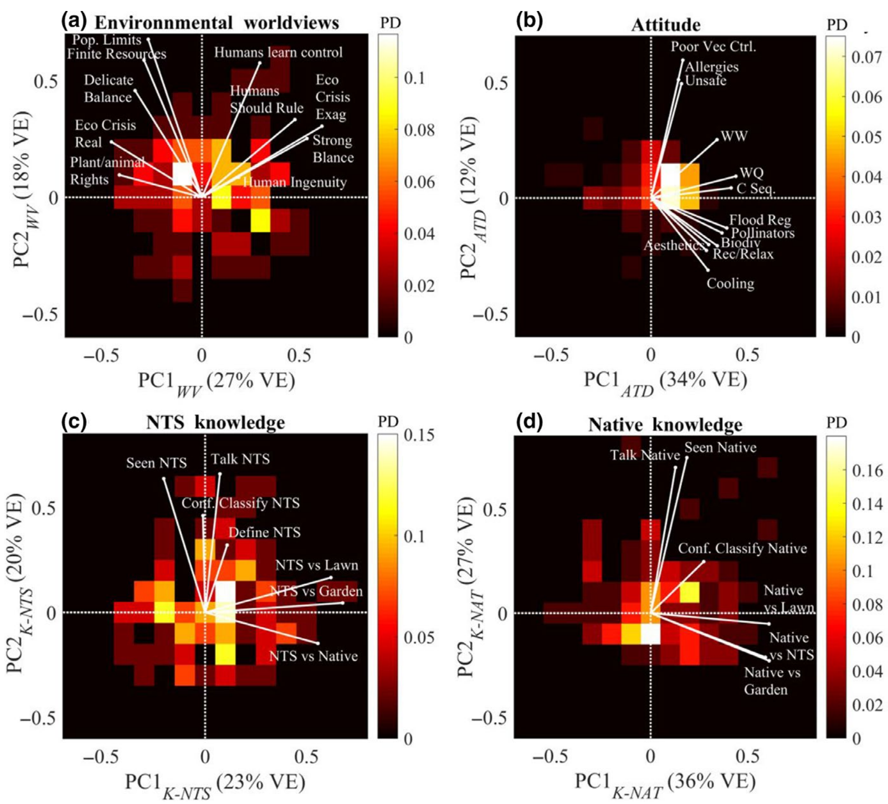

FIGURE 5 Biplots illustrating patterns in (a) worldviews, (b) attitudes about services, (c) knowledge about NTS, and (d) knowledge about native ecosystem remnants *(full survey)*. See Appendix C, E, and F for a comparison of full survey results, full + short format survey results (undergraduate students only) and full + short format survey results (undergraduate and graduate students). Dominant patterns (PC1) are on the *x*-axis and secondary patterns (PC2) are on the *y*-axis. Plot color reflects probability density (PD), with probability hotspots (white) indicating those knowledge types, worldviews or attitudes that participants most consistently exhibit. Abbreviations used in (a)—Nature strong: nature is strong enough to withstand humans, Nature delicate: nature's balance is delicate, Growth Limited: earth's population is near its limits, Finite Resources: earth's resources are finite, Plant/Animal Rights: plants and animals have as much right to exist as humans, Humans Should Rule: humans are meant to rule over nature, Human ingenuity: human ingenuity will keep earth livable, Humans Learn Control: humans will learn enough about nature to control it, Eco Crisis Exag: the ecological crisis facing mankind is exaggerated, & Eco Crisis Real: the ecological crisis facing mankind is real. Abbreviations used in (b)—Poor Vec Ctrl: vector control disservices, Allergies: allergy disservices, Unsafe: safety disservices, WW: water waste disservices, WQ: water quality services, C. seq: carbon sequestration services, Flood Reg: flood regulation services, Biodiv: biodiversity services, Pollinators: pollination services, Rec/Relax: recreation/relaxation services, Aesthetics: aesthetic services, & Cooling: urban cooling services. Abbreviations used in (c)—Seen NTS: have seen NTS, Talk NTS: have talked about NTS during an organized campus activity, Define NTS: can define NTS, Conf Classify NTS: confident classifying landscapes as NTS, & NTS vs Lawn, Garden, or Native: identify NTS correctly more often than not. Abbreviations in (d) are similar to (c) with native replacing NTS

nature'; (b) feeling earth's ecological future is not secure—median agreement of 6 in response to 'if things continue on their present course, we will soon experience a major ecological catastrophe' and 2–3 in response to 'the so-called ecological crisis facing humankind has been greatly exaggerated'; and (c) perceiving nature as delicate and requiring protection—median agreement of 5 in response to 'the balance of nature is delicate and easily upset' and 2.5–3 in response to 'the balance of nature is strong enough to cope with the impacts of modern industrial nations' (Table 2). High (low) couplets for each of the above-noted question pairs were associated with pro-environmental worldviews, with 7 being the highest score possible (strongly agree) and 1 being the lowest score possible (strongly disagree).

The second worldview revealed by PCA (15%–18% VE) separated out individuals who identified with ecological modernism, which sees human innovation and technology as solutions to earth's ecological problems (Nordhaus et al., 2015; positive $PC2_{WV}$), from individuals who felt earth's capacity to sustain humans is vast and beyond human control (negative $PC2_{WV}$). Two NEP-scale environmental facets loaded significantly on this worldview, including (a) human-exemptionalism—median agreement of 4 in response to 'humans will eventually learn enough about how nature works to be able to control it'; and (b) limits to growth—median agreement of 5–6 in response to 'we are approaching the limit of the number of people the earth can support' and 'the earth is like a spaceship with very limited room and resources' (Table 2). High scores for each of these questions were associated with ecological modernism.

Participant worldviews were roughly evenly distributed in PC space (see central hotspot, Figure 5a, Appendix F), although a slight bias towards ecological modernism (positive PC quadrants) was evident, suggesting this worldview was more commonly held than not.

3.3 | Attitudes

One significant pattern was identified for attitudes about ecosystem services. The pattern was consistent across both surveys ($PC1_{ATD}$: 34%–37% VE; Figure 5b, Appendix E: Figure S2) and separated out individuals who felt ecosystem services were important (positive $PC1_{ATD}$) from those who did not (negative $PC1_{ATD}$). The strongest contributing services were carbon sequestration (*only evaluated in the full survey*), water quality regulation and flood regulation. These services were among the most important to engineering students (median scores of 7, 7 and 6 respectively). Two disservices, perceived lack of safety (*only evaluated in the full survey*) and allergies, were least important to engineering students (median scores of 5) (Appendix E: Table S2).

3.4 | Individual knowledge

Participants possessed theoretical, experiential and procedural knowledge about NTS and native landscapes to varying degrees. Across both surveys, 40%–70% of participants could at least partially define and had talked about NTS before (theoretical knowledge), 34%–40% had seen NTS before (experiential knowledge), and 38%–42% correctly identified NTS more often than they misidentified them (procedural knowledge) (Appendix C: Table S1). Significantly more students reported having previously talked about NTS in the full survey (56%) than across both surveys combined (40%) ($p < 0.05$, Appendix C: Table S1). Knowledge about native ecosystem remnants was only queried in the full survey, with procedural knowledge (63%) exceeding experiential knowledge (52%), which exceeded theoretical knowledge (32%) (Appendix C: Table S1). For both landscape features procedural knowledge ($PC1_{K\text{-}NTS}$: 23%–28% VE and $PC1_{K\text{-}NAT}$: 36% VE) was orthogonal to theoretical and experiential knowledge ($PC2_{K\text{-}NTS}$: 20%–21% VE; $PC2_{K\text{-}NAT}$: 27% VE), illustrating that possessing one knowledge type did not increase the likelihood of possessing the other (Figure 5c,d, Appendix C: Figure S1).

Biodiversity and urban runoff knowledge were largely comparable across surveys (Appendix C: Table S1). Most participants could accurately define biodiversity at its base level (i.e. as the variety of life: 78%–83%), with some defining it more broadly (i.e. as the variety of life, communities, genotypes and biological processes: 19%–23%). The capacity of participants to correctly define urban runoff was more limited with 31% defining it correctly, 34%–39% providing partially correct (but incomplete) answers, and 30%–35% providing incorrect answers. This said, most participants recognized that urban runoff is a leading water quality problem in developed countries (81%–87%), and that runoff is typically not treated before it is discharged to downstream waterbodies (68%–76%).

3.5 | Participant awareness of NTS

Across both surveys, 34%–40% of survey participants reported having seen NTS on campus (Appendix C: Table S1). The largest percentage of participants (24%–26%) reported seeing NTS on their own. Significantly fewer saw them during a class (6%), tour (3%–6%), 'other' campus activity (3%–6%), outreach (2%–3%) or research (1%) ($p < 0.05$). Roughly half (41%–57%) of students that reported seeing NTS could recall what type they had seen. 31%–35% of sightings were biofilters or rain gardens, 28%–30% were downspout disconnections to some form of greenspace, 18%–25% were wetlands, 10%–14% were detention basins or 'other' NTS, and 8%–19% were bioswales.

In the full survey where NTS signage was addressed, unsigned NTS were reported by participants significantly more often than signed NTS (29% vs. 11% of the time; $p < 0.05$), and more participants were able to recall the specific type of NTS they had seen when they reported having seen signed NTS (79% vs. 50%; marginally significant, $p = 0.07$). Only 40% of participants reported that they live on campus at C1, with the majority residing in housing developments co-located with NTS (Figure 1, Appendix C: Table S1). Living near NTS (i.e. within 300 m of treatment wetlands, rain gardens or swales)

TABLE 2 Student worldviews—Median scores on the new ecological paradigm scale

NEP-Scale Environmental Facets (1–7 Likert scale; 4 is neutral)	Pro-environmental worldview	Environmental modernist worldview	a Survey: full Campus: C1 Students: UG (95% CIs)	b Survey: full & short Campus: C1–C4 Students: UG (95% CIs)	c Survey: full & short Campus: C1––C4 Students: UG & G (95% CIs)
Balance of nature					
The balance of nature is strong enough to cope with the impacts of modern industrial nations	<4 is pro-environmental	ns[1]	3 (2–4)	3 (2–3)	2.5 (2–3)
The balance of nature is delicate and easily upset	>4 is pro-environmental	ns	5 (5–5.5)	5 (5–5)	5 (5–5)
Limits to growth					
We are approaching the limit of the number of people the earth can support	ns	>4 is env. modernist	5 (5–5)	6 (5–6)	6 (5–6)
The earth is like a spaceship with very limited room and resources	ns	>4 is env. modernist	6 (5–6)	5 (5–6)	5 (5–6)
Anti-anthropocentrism					
Plants and animals have as much right as humans to exist	>4 is pro-environmental	ns	6 (6–6)	5 (5–5)	5 (5–5)
Humans were meant to rule over the rest of nature	<4 is pro-environmental	ns	3 (3–4)	3 (2.5–3)	3 (2–3)
Human exemptionalism					
Human ingenuity will ensure that we do not make the earth unlivable	ns	ns	5 (5–5)	5 (5–5)	5 (5–5)
Humans will eventually learn enough about how nature works to be able to control it	ns	>4 is env. modernist	4 (3–4)	4 (3–4)	4 (3–4)
Ecocrises					
The so-called "ecological crisis" facing humankind has been greatly exaggerated	<4 is pro-environmental	ns	3 (2–3)	2 (2–3)	2 (2–2)
If things continue on their present course, we will soon experience a major ecological catastrophe	>4 is pro-environmental	ns	6 (5.5–6)	6 (6–6)	6 (6–6)

Abbreviation: G, graduate; UG: undergraduate.

[1]ns indicates concepts that do not significantly contribute to a particular worldview.

did not significantly increase NTS awareness; students living on campus, but far from campus NTS (>1 km away) were equally likely to report seeing NTS as students living on campus and near campus NTS (39% and 41% respectively; $p = 0.67$). Given the respective densities of NTS on and off campus (roughly 3.2 NTS per km on campus and 0.2 NTS per km off campus; Silvertooth et al., 2019), it seems unlikely that this result is due to students who are far from campus NTS still being proximal to off-campus NTS, although we cannot rule out this possibility.

3.6 | Perceived services/disservices

PCA revealed two significant patterns in perceived ecosystem services/disservices across landscape features (45%–49% VE; Figure 6, Appendix G). These patterns were consistent across both surveys for all services/disservices they had in common (i.e. all excepting pollination, carbon sequestration, lack of safety and vector control problems, which were only evaluated in the full survey of undergraduate students at C1; Appendix G). A description of our full survey results is provided below. Absent patterns pertaining to the above-mentioned services/disservices, this description is commensurate with short format survey results. Supplemental figures illustrating perceived services provisioning for each survey demographic are provided in Appendix G and H.

The first pattern in perceived services/disservices separated individuals who thought urban landscape features provide many services from those who thought they provide few ($PC1_{ES}$: 32%–33% VE; Figure 6, Appendix G). Biodiversity, climate regulation, aesthetics, water quality, flood regulation and pollination were the strongest contributors to $PC1_{ES}$, whereas most disservices (lack of safety, poor vector control, allergies) contributed only weakly. The second pattern ($PC2_{ES}$: 13%–17% VE), revealed two coherent groups of services/disservices (hereafter referred to as services/disservices bundles) that individuals perceived landscapes provide. Bundle 1 (positive $PC2_{ES}$) included organism-associated services/disservices (biodiversity, allergies, pollination and poor vector control) and perceived lack of safety. Bundle 2 (negative $PC2_{ES}$) included cultural services (recreation/relaxation and aesthetics), as well as the disservice water waste. Regulating services (flood and water quality regulation, urban cooling and carbon sequestration) did not contribute significantly to either bundle ($p < 0.05$).

Different types of landscape features clustered in different quadrants of PC space (see probability hotspots in Figure 6, Appendix G), suggesting that survey participants felt lawns, gardens, native ecosystem remnants and NTS provide different ecosystem services/disservices. Median perceptions (across all photographs and participants) varied by landscape feature for all services/disservices except flood regulation, water quality services and carbon sequestration (Figure 7, Appendix H).

Lawns clustered in quadrant 4 (+, −) of PC space, indicating they were perceived to provide many services/disservices, particularly those from bundle 2 (Figure 6a, Appendix G). Lawns were perceived to provide the best opportunity for recreation/relaxation, have the lowest safety risk, and waste the most water of any landscape feature (red symbols, Figure 7, Appendix H). Native ecosystem remnants were perceived differently, clustering primarily in quadrant 1 (+, +), and quadrant 2 (-, +), the opposite end of the services/disservices spectrum from lawns (Figure 6b, Appendix G). This indicates that participants generally felt native ecosystem remnants provide more bundle 1 than bundle 2 services/disservices, with participants in quadrant 2 scoring native ecosystem remnants lowest for bundle 2 services/disservices provisioning. Native ecosystem remnants were perceived as having more vector control problems, less urban cooling and fewer aesthetic services than lawns or gardens, but also less water waste (green symbols, Figure 7, Appendix H). They were also perceived as less safe than lawns or NTS, but were not considered unsafe (median of 4, on a scale from 1 = safe to 7 = unsafe, Figure 7). Gardens were positioned between native ecosystem remnants and lawns (splitting quadrants 1 and 4; Figure 6c, Appendix G). They were perceived as more aesthetically pleasing and likely to attract pollinators than any other landscape feature (pink symbols, Figure 7, Appendix H).

In contrast to other landscapes, NTS exhibited no strong clustering in any PC quadrant (Figure 6d, Appendix G). NTS were perceived to be less safe than lawns but safer than native ecosystem remnants or gardens, cause fewer allergies than native ecosystem remnants or gardens, waste less water than gardens or lawns, and cause more vector control problems than gardens or lawns (blue symbols—Figure 7, Appendix H). They were never perceived as the most likely landscape to provide a service.

3.7 | Drivers of landscape perceptions *(full survey)*

The capacity of our conceptual diagram (Figure 4) to explain the above-noted variability in student landscape perceptions was evaluated using results from the full survey only, which better characterized both knowledge variables and perceptions. Each services/disservices mode described above was modelled separately. Model 1 (for $PC1_{ES}$) addressed the question: what determines if a landscape feature is perceived to provide many services or few? Model 2 (for $PC2_{ES}$), addressed the question: what determines if a landscape feature is perceived to provide bundle 1 or bundle 2 services/disservices? Global fit metrics were strong for both models, suggesting our conceptual framework for modelling student perceptions is reasonable (χ^2 *p*-value > 0.05; CFI > 0.95; SRMR > 0.06; details in Appendix I). This said, not all hypothesized relationships were significant (details of those that were, are provided below). Model 1 explained 10%–32% of the variance in landscape perceptions (gardens [32%] > native ecosystem remnants [24%] > NTS [19%] > lawns [10%], Figure 8a). Model 2 explained less variance than Model 1 (lawns [17%] > gardens [13%] > NTS [8%] > native ecosystem remnants [5%]; Figure 8b), suggesting that knowledge, worldviews, attitudes and demographics are less important for shaping which services/disservices students feel landscapes provide than if they feel they provide services at all.

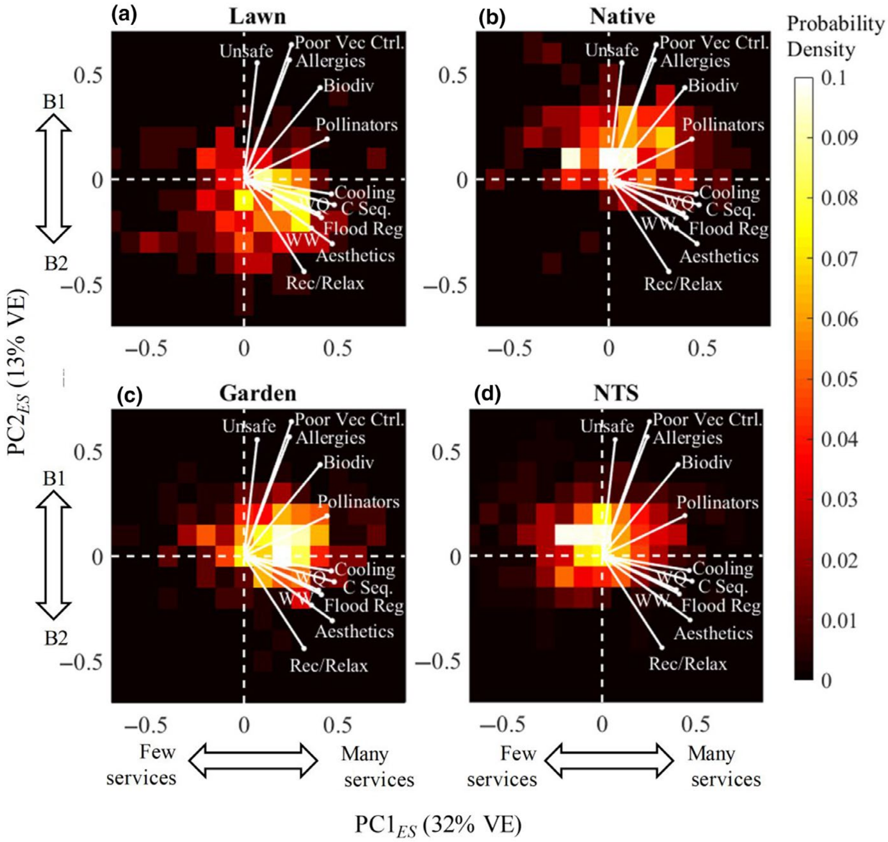

FIGURE 6 Biplots of perceived ecosystem services/disservices provisioning by lawns (a), native landscape (b), gardens (c), and natural treatment systems (NTS; d) (*full survey responses*). See Appendix G for a comparison of full survey results, full + short format survey results (undergraduate students only) and full + short format survey results (undergraduate and graduate students).The dominant significant pattern in perceived services/disservices provisioning ($PC1_{ES}$; positive—many services and negative—few services) is on the *x*-axis. A secondary significant pattern ($PC2_{ES}$) is on the y-axis and identifies two bundles of co-associated services/disservices: Bundle 1 (B1) includes organism-associated services/disservices and safety concerns and bundle 2 (B2) includes cultural services and the disservice water waste. Individual white vectors denote specific services or disservices (abbreviations provided below), with vectors that strike primarily in the horizontal (vertical) contributing mostly to $PC1_{ES}$ ($PC2_{ES}$). Color indicates the probability that participants feel landscape features provide specific services/disservices (increasing from black to white). Abbreviations—Poor Vec Ctrl: vector control disservices, Allergies: allergy disservices, Unsafe: safety disservices, WW: water waste disservices, WQ: water quality services, C. seq: carbon sequestration services, Flood Reg: flood regulation services, Biodiv: biodiversity services, Pollinators: pollination services, Rec/Relax: recreation/relaxation services, Aesthetics: aesthetic services, & Cooling: urban cooling services

The following relationships among driver variables were significant for both Models 1 and 2. Significant relationships with high statistical power are shown using solid coloured lines in Figure 8. Relationships that are significant but have moderate to low statistical power (e.g. small effect magnitudes given the study size of our population) are shown using dashed coloured lines.

Environmental worldviews (pro-environmental: $PC1_{WV}$ and environmental modernism: $PC2_{WV}$) were influenced by demographics (race or country of origin) and knowledge variables (urban runoff or biodiversity) (Figure 8). Environmental modernism was more common in participants who identified as Asian/Asian American, and marginally more common (significant effect, but low effect magnitude) in participants from the United States and those who did not know urban runoff is a leading water quality problem in developed countries. Pro-environmentalism was also more common among participants from the United States, but was positively associated with urban runoff knowledge and (more weakly) the capacity to define biodiversity at a base level (i.e. as the variety of life). Attitudes about ecosystem services ($PC1_{ATD}$) were directly and positively influenced by pro-environmentalism, and therefore indirectly by country of origin and knowledge variables (significant effect, low effect magnitude). Biodiversity and urban runoff knowledge also impacted attitudes directly, with participants who had a broad understanding of biodiversity and could define urban runoff being more likely to find ecosystem services important (strong and marginal effect magnitudes respectively).

3.7.1 | Model 1 specific relationships

Across all landscape types, the single largest determinant of perceived services provisioning was respondents' attitudes about

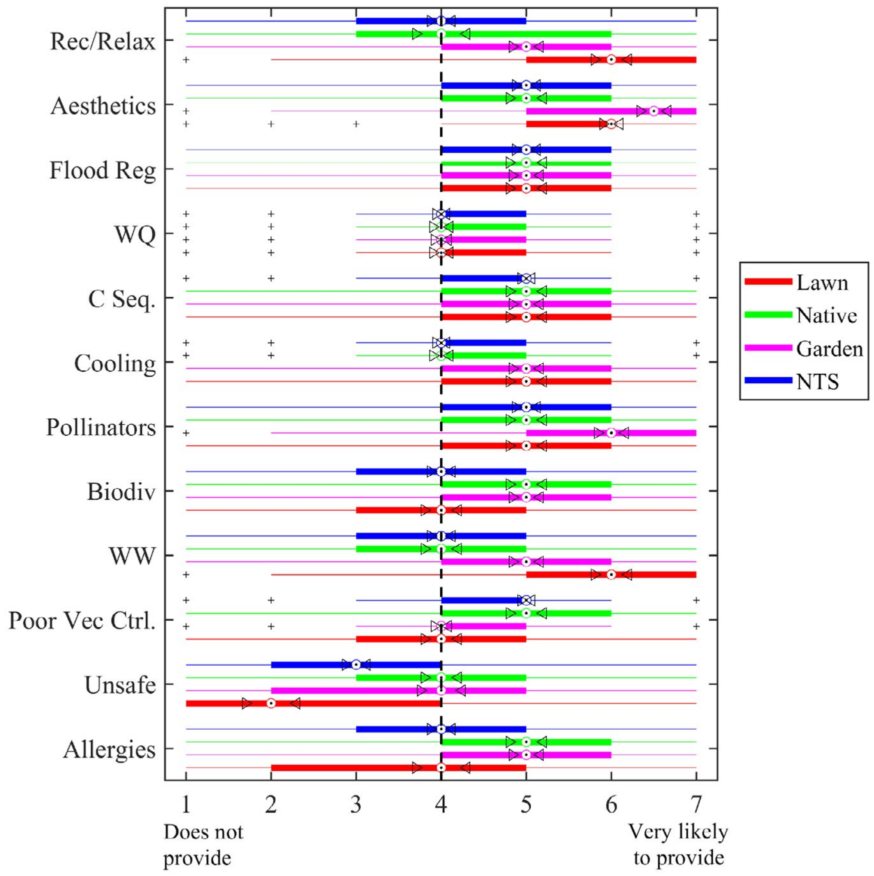

FIGURE 7 Box and whisker plot illustrating perceived provisioning of each service and disservice by landscape type (lawns: red, native ecosystem remnants: green, gardens: magenta, and NTS: blue) *(full survey responses)*. See Appendix H for a comparison of full survey results, full + short format survey results (undergraduate students only) and full + short format survey results (undergraduate and graduate students). The *x*-axis indicates the degree of expected provisioning on a scale from 1 (does not provide) to 7 (very likely to provide), with 4 being neutral (black dashed line). The *y*-axis denotes the 12 services and disservices evaluated. Abbreviations are the same as in Figure 5. Medians are indicated using white circles. Medians are significantly different when the triangles that bound them (95% confidence bounds) do not overlap. Colored boxes indicate the 25% and 75% bounds of the data and whiskers indicate the 5% and 95% bounds of the data. Outliers are shown using plus signs

ecosystem services, with participants who felt services were important being more likely to think urban landscapes provided them than those who did not (Figure 8a). Pro-environmental worldviews were fully mediated by attitudes, suggesting that pro-environmentalism primarily impacts student perceptions of service provisioning through engendering positive attitudes about services (significant effect, moderate effect magnitude). In contrast, environmental modernist worldviews increased perceived services provisioning directly. This relationship typically had a strong effect magnitude and was observed for all landscapes except lawns. The net result is that worldviews appear to have both indirect and direct effects on landscape perceptions (as postulated in our conceptual diagram; Figure 4), with the type of effect and effect magnitude varying by worldview. Similar to environmental modernism, theoretical/experiential knowledge of NTS ($PC2_{K\text{-}NTS}$) increased perceived services provisioning directly for all landscapes except lawns.

Other effects on perceived services provisioning were specific to individual landscape types (Figure 8a). Participants who knew that runoff is a water quality problem perceived higher services provisioning by lawns, and participants who knew urban runoff is not typically treated prior to discharge perceived higher services provisioning by NTS. Significant, but marginal landscape-specific effects were also detected for gardens, with participants who had the capacity to distinguish native from non-native landscapes (procedural knowledge; $PC1_{K\text{-}NAT}$) perceiving higher services provisioning, and participants identifying racially as Caucasian perceiving lower services provisioning. Two demographic variables (age and gender) as well as two knowledge variables (theoretical/experiential knowledge about native landscapes; $PC2_{K\text{-}NAT}$, and procedural knowledge about NTS; $PC1_{K\text{-}NTS}$) were not significant determinants of any other variable.

3.7.2 | Model 2 specific relationships

In Model 2, only urban runoff knowledge influenced perceptions across all landscape features, with participants who knew urban runoff is typically not treated prior to discharge being more likely to perceive higher bundle 1 (or lower bundle 2) services/disservices provisioning (Figure 8b). All other relationships were landscape specific. Participants who identified as male and had a positive attitude about ecosystem services were less likely to feel lawns provided bundle 1 services/disservices. Participants possessing theoretical/experiential knowledge of native ecosystem remnants were also less likely to feel lawns provided bundle 1 services/disservices, but this effect was more marginal. Participants who had a positive attitude about ecosystem services, who identified as Asian/Asian American and who had limited procedural knowledge of native landscapes (strong, marginal and marginal effect magnitudes respectively), were less likely to feel gardens provided bundle 1 services/disservices. The remaining two drivers were stronger demographic effects, with participants born in the United States being less likely to feel NTS

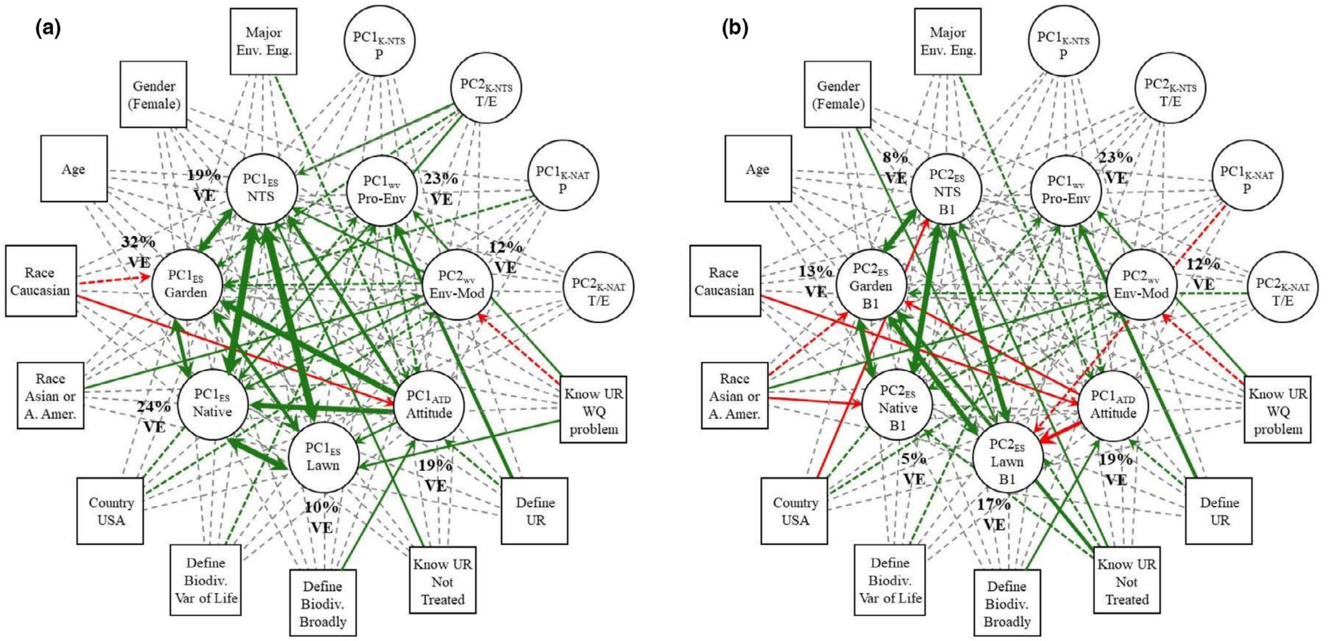

FIGURE 8 Path diagrams illustrating the relationships between dominant patterns in perceived services/disservices for each type of landscape feature (a: $PC1_{ES}$—lawns, gardens, native ecosystem remnants, and NTS provide many services and b: $PC2_{ES}$—lawns, gardens, native ecosystem remnants, and NTS provide bundle 1 services/disservices) and hypothesized driver variables. Path models were developed using full survey responses only. Manifest (measured) variables are shown as squares and composite variables as circles. Arrows illustrate hypothesized relationships among variables: single sided arrows are regressions and double-sided arrows are covariances. Arrow color indicates whether relationships are positive (green) negative (red), or non-significant (grey dashed). Arrow width indicates relationship strength (thicker being stronger). Dashed red or green arrows denote relationships that are significant but have statistical power <0.7. Abbreviations—$PC1_{K\text{-}NTS}$ P and $PC1_{K\text{-}NAT}$ P: procedural knowledge about NTS and native ecosystem remnants, respectively, $PC2_{K\text{-}NTS}$ T/E and $PC2_{K\text{-}NAT}$ T/E: theoretical/empirical knowledge about NTS and native ecosystem remnants, respectively, $PC1_{WV}$ Pro-Env and $PC2_{WV}$ Env-Mod: pro-environmental and environmental modernist worldviews, respectively, $PC1_{ATD}$: positive attitude about ecosystem services, Major Env. Eng.: academic major is environmental engineering, Race Asian or A. Amer.: Race is Asian or Asian American, Country USA: born in the US and resided there as a child, Define Biodiv. Var of Life: define biodiversity as the variety of life, Define Biodiv. Broadly: define biodiversity broadly as the variety of life, species, communities, and genotypes, Know UR Not Treated: know that urban runoff is typically not treated prior to being discharged to natural waterbodies, Define UR: correctly define urban runoff, and Know UR WQ problem: know that urban runoff is a leading water quality problem in developed countries

provided bundle 1 services/disservices, and participants identifying as Asian or Asian American being less likely to feel native landscapes provided bundle 1 services/disservices. Overall, the influence of demographic characteristics was stronger in Model 2 than Model 1. The opposite was true for attitudes and worldviews; environmental worldviews had no direct effects on how landscapes were perceived in Model 2 and the effect of attitudes was diminished by half. Age and NTS knowledge were not significant determinants of any other variable.

4 | DISCUSSION

4.1 | Representativeness and context-specific limitations

The overarching goal of this study was to evaluate how engineering students perceive NTS relative to other landscape features, and establish the initial conditions for a dialogue between engineers and landscape architects, urban ecologists and urban planners about the implications of those perceptions for future NTS development. This goal necessitates identifying consistent patterns in engineering student perceptions such that useful inferences regarding them can be made. Such consistency is evident in this study, with stable patterns in perceived services and disservices present from the full survey at C1 through the combined survey at C1–C4. The per cent variance explained by these patterns was likewise stable (32%–33% for PC1 and 13%–17% for PC2) illustrating that their relative importance did not significantly change upon consideration of a more extensive respondent pool, including more universities, graduate as well as undergraduate students, and a broader range of engineering disciplines (Table 1). This suggests our study has identified views about landscape services/disservices that are commonly held by engineering students, and may be generalizable, at least within the state of California where this work was conducted.

We might also expect our findings to be transferrable to other semi-arid or Mediterranean areas of the United States with comparable vegetation communities and landscaping practices. The corollary is that perceptions are expected to differ in regions with different climates (e.g. higher rainfall, facilitating NTS communities that are less drought tolerant; NC DEQ, 2020; PA BMP, 2006), different native ecosystems (shifting the contextual relationship between NTS and native landscape features), different landscape norms (for instance, strong community preferences for manicured lawns (Persaud et al., 2016), which can impact perceived appropriateness of NTS) or with different actors involved in NTS design (often the case in other countries; Zuniga-Teran & Gerlak, 2019; Adem Esmail & Suleiman, 2020), which can fundamentally alter NTS appearance and function, impacting how they are perceived. Such context-specific limitations mean that care must be taken when translating the results of this study to other US states, regions or countries, particularly given the status of NTS as emerging technologies with differing levels of adoption (and public exposure) in different parts of the world (Adem Esmail & Suleiman, 2020; Ando et al., 2020; Church, 2015; Douglas, 2018; McGarity et al., 2015; Nickel et al., 2014).

We also must acknowledge that our study's demographics (generally representative of the campuses evaluated; Table 1) are not representative of practicing engineers in the United States today; we represent women, Hispanics and Asians significantly more (and Caucasian men less) than they are represented in practice (Table 1). This bias may be forward looking, however, as US population growth over the next 5 decades is projected to be associated principally with Hispanic and Asian immigration (Cohn & Caumont, 2016) and the engineering demographic is expected to track this change, with the proportion of Asian and Hispanic (White) engineering students increasing 2%–6% (decreasing 6%) by 2030 (Roy, 2018; Wang, 2018). The proportion of women in engineering has also been increasing in the United States, particularly in environmental engineering, the sub-discipline most likely to work with NTS, where a higher percentage of women were awarded bachelor degrees in 2018 than any other engineering discipline (Roy, 2018). This may make the student demographic evaluated in this study a kind of microcosm of what is to come.

4.2 | Student awareness and NTS knowledge

We hypothesized that engineering students would have higher awareness of NTS than the general public because of their exposure to engineering infrastructure in course curricula. In general, our study supports this premise as the proportion of student participants who were aware of NTS was at the high end of literature values reported for the general public, both the United States and in other countries (i.e. up to 70% in this study; Appendix C: Table S1, compared with 26%–33% in Dundee, Scotland (Bastien et al., 2011; Jose et al., 2015), 27%–69% across England (Williams et al., 2019), 34% in Seoul, Korea (Kim & An, 2017) and 40% in Fort Worth, Texas, U.S. (Abrahams, 2010); Venkataramanan et al., 2020). However, our study suggests that student awareness of NTS does not translate to deeper levels of understanding (i.e. experiential or procedural knowledge). Although most students could define NTS or had talked about them in class, fewer reported having seen them on campus, and only a fraction of those who did, knew which type of NTS they had seen (Appendix C: Table S1). This may, in part, reflect the lack of interpretive signage on campus. Signs have been linked to increased understanding of NTS in other studies (Church, 2015) and our work suggests that the same is true on college campuses, with signs increasing student understanding of NTS by ~30% (Appendix C: Table S1). This result suggests that unsigned NTS in student housing developments are a missed opportunity for learning. However, because engineers may respond to signs differently than other students, the 30% gain we report should be interpreted as a hypothesis only.

Student understanding of NTS might also have been limited by infrequent exposure to built NTS in course curricula: only 6% of student participants reported visiting NTS as part of a class and 1% for research (Appendix C: Table S1). This suggests that current student experiences with NTS at C1–C4 may be somewhat superficial (features observed in passing, but not critically evaluated). The orthogonal relationship between theoretical/experiential and procedural knowledge about NTS (Figure 5a, Appendix C: Figure S1) also points to superficial NTS experiences, highlighting the difficulty engineering students have translating what they have heard and seen into procedures for differentiating NTS from other landscape features. This is an instance where exposure to urban planning knowledge (e.g. through integrated engineering and landscape architecture courses and curriculum; Ryan, 2014; SEAS; SIBE-VUSP) could greatly improve student outcomes, helping them understand NTS as part of a broader integrated whole. It would also provide an opportunity to foster appreciation for the role landscape architects and urban planners play in green infrastructure projects, setting the stage for the kinds of cross-disciplinary collaborations necessary to redesign public spaces in ways that meet diverse community needs (i.e. encouraging engineering students to interpret green infrastructure and its services broadly, rather than adopting the more engineering-centric term green stormwater infrastructure, increasingly popular in the United States; Finewood et al., 2019).

4.3 | Landscape perceptions and multifunctionality

Our study suggests that engineering students at C1–C4 perceive all urban landscape features as multifunctional (Figure 6, Appendix G). For common landscape features (lawns, gardens, native ecosystems) student perceptions were cohesive (i.e. different photographs belonging to the same landscape category were perceived to provide similar services/disservices [see quadrant-specific skew of hotspots in Figure 6a–c]). This points to clear social norms for how these landscapes are perceived. NTS were an exception: there was no obvious social norm for their perception (see central hotspot in Figure 6d, Appendix G). This may reflect the limited ability of students to distinguish NTS from other landscape features (Appendix C: Table S1), with NTS being variously ascribed characteristics of landscapes they were deemed 'most similar to' by each individual perceiver. It likely also reflects the stage of NTS implementation in Southern California (for instance, with respect to social–technological transitions; Adem Esmail & Suleiman, 2020; Brown et al., 2016); although NTS have become increasingly prevalent in recent years due to industry and utility led field projects (particularly in new development), they are not yet fully mainstream, making social norms for their perception less likely (Kim & Tran, 2018; Zuniga-Teran et al., 2020).

4.4 | Attitudes as a principal driver of landscape perceptions

Some variability in individual perceptions was detected for all types of landscape features (indicated by the breadth of the probability hotspots in Figure 6, Appendix G). Our capacity to explain this variability, however, was relatively low (5%–32% VE), suggesting that factors beyond the four components included in our original conceptual diagram (knowledge, worldviews, attitudes and demographics; Figure 4) impact landscape perception. Of the drivers evaluated, attitudes about ecosystem services exerted the strongest influence over landscape perceptions (particularly, assessments of many services vs. few; Figure 8a). This finding is consistent with existing literature linking attitudes to perception and preferences for different landscape characteristics in Europe and Australia (Bertram & Rehdanz, 2015; Caula et al., 2009; Kurz & Baudains, 2012), but to our knowledge has not been previously shown for NTS. Because free-choice learning activities like nature experiences and participatory environmental programs can strongly influence attitudes about environmental topics (Ballantyne & Packer, 2006), many universities may already be well positioned as agents of change in this area through student led environmental groups, 'Cool School' challenges for raising awareness of campus sustainability issues, and innovative collaboratories, where students, faculty and university facilities management work together to design, site, construct and monitor green infrastructure on college campuses (see CU-Boulder, 'One Million Acts of Green'; Duke, Smart Home Program and Eco-Olympics; University of California, Cool Campus Challenge; Villanova, the Commons for successful programs in the context of the US education system).

4.5 | Environmental worldviews and perceptions—Inspiring students to be agents of change

Environmental worldviews also influenced perceptions, but to a lesser degree than attitudes. Pro-environmental worldviews only influenced perception indirectly through attitudes, never directly, indicating that the two are intrinsically connected and represent a single path by which perceptions are moderated (Figure 8a). However, we also detected a secondary environmental worldview in our study population (environmental modernism; Figure 8a), that acted on landscape perceptions directly, suggesting that students who believe human intervention can solve environmental problems are more likely to view urban landscapes positively, independently of their attitudes about ecosystem services. This implies that empowering students to instigate change (sometimes referred to as fostering an internal locus of control; Cleveland et al., 2005) is a second, distinct way to influence landscape perceptions that might be integrated into education/outreach programs to good effect (see, e.g. Bamberg & Moser, 2007; Yang et al., 2017).

4.6 | Knowledge and perceptions—Ecological theory, ecological aesthetics and cues to care

Surprisingly, knowledge about specific landscape features (NTS, native ecosystem remnants) had minimal impact on landscape perceptions relative to other knowledge types (Figure 8, Appendix J). Low levels of theoretical knowledge were reported for native ecosystems (32%, Appendix C: Table S1), which in combination with the high capacity of participants to distinguish native from non-native (63%, Appendix C: Table S1), suggests that native ecosystem knowledge was intuitive (i.e. students knew 'nativeness' when they saw it, but had limited factual knowledge to draw on when assessing services provisioning). NTS knowledge also had limited impact on landscape perceptions. Only theoretical knowledge of NTS was significant and only in respect to whether landscapes provide many services or few (i.e. for Model 1; Figure 8a). This suggests that current approaches to learning about NTS at C1–C4 make students more aware that urban landscapes perform services (Model 1) but do not help them link specific services to different landscapes (Model 2). This includes services that NTS are typically designed for like water quality and flood regulation, which students felt all landscapes features provided equally well (Figure 7, Appendix H). Ensuring CEE students (the students most likely to play a role in NTS design) are exposed to the basic theories of ecosystem function that pertain to NTS (outlined in Levin & Mehring, 2015) would be a good first step towards improving their capacity to link services to landscapes using ecological design principles. Furthering this connection is especially important now given the recognized need to co-design NTS to combat future global climate and biodiversity challenges (Feagin et al., 2021; Portner et al., 2021; Steffen et al., 2015). A recent joint IPBES_IPCC workshop (Portner et al., 2021), points to growing agreement in the scientific community and in practice that we require multiservice greenspace to mitigate challenges and risks associated with climate change, provide adaptation options for biodiversity, enhance provisioning of services to people and improve quality of life. Achieving this goal will require a next generation of NTS designers that are versed in ecological theory and trained to design with nature to achieve multifunctional outcomes.

Urban planning knowledge also has a role to play in this effort, particularly in the realm of landscape accessibility and aesthetics, the latter having important implications for function through normative perceptions such as 'ecological aesthetics', whereby perceptions of ecological quality underlie perceptions of aesthetic quality (Gobster et al., 2007; Gobster & Westphal, 2004). Indeed, one could cast the limited ability of engineering students in this study to discriminate between NTS and other landscape features as symptomatic of an underdeveloped ecological aesthetic, manifest as difficulty linking the visual aesthetic of engineered landscapes with their intended function. If true, then simply introducing students to the basic theories of ecosystem function that pertain to NTS only solves part of the problem. Students must also be made aware of (a) concepts from landscape architecture such as cues to care (i.e. design elements that give the perception that a landscape feature is cared for and has purpose) that can be leveraged to bring ecologically beneficial NTS designs more in line with the public's aesthetic values, which may differ dramatically by state, region and country (Dobbie, 2016; Hoyle et al., 2017; Jungels et al., 2013; Rippy et al., 2021), and (b) be encouraged to think about an analogous set of design 'cues to function' for NTS that could be highlighted in education/outreach efforts (including informational signage; Church, 2015) to bring NTS aesthetics more in line with the ecological functions designed for by practitioners (Gobster et al., 2007; Gobster & Westphal, 2004; Nassauer et al., 2001). We expect that understanding how (and which) design cues influence perceptions of NTS will both make engineering students more self-aware when perceiving NTS and better able to design new NTS that use those cues effectively to communicate care and function to the public.

4.7 | Demographics and perceptions—The importance of situational context

Importantly, communicating care and function is not simply a matter of identifying a suite of NTS design features to target or a choice education/outreach strategy to implement. Situational context must also be considered because 'the public' really represents a heterogeneous collective with various social, cultural and personal characteristics that influence perceptions in ways that are not always well captured in studies of NTS (Basnou et al., 2020; Gobster et al., 2007; Spahr et al., 2021; Venkataramanan et al., 2020). In this study several demographic variables (race, country of origin and gender) were found to influence landscape perceptions, particularly perceptions about which services/disservices each landscape could provide (Model 2, Figure 8b), demonstrating the importance of human situational context even within our relatively narrow engineering demographic. The consistent influence of race and country of origin (significant for both models, Figure 8) may point to cultural differences in how landscape features are perceived by engineering students that need be considered when developing cues to care or function for this demographic (van Heijden, 2013). Additional considerations (e.g. religious or historical traditions, local customs, level of education, income or occupation) may matter for other groups, shaping both the way NTS are perceived and the hydro-social contract they must fulfil to be viewed as valuable infrastructure in a particular setting (Albert et al., 2021; Basnou et al., 2020; Wong & Brown, 2009). Incorporating situational and landscape context in NTS design increases its capacity to provide services to a range of individuals (Albert et al., 2021; Gobster et al., 2007). This practice, referred to as culturally sensitive design (and more recently, inclusive design) is already a prominent tenet of landscape architecture and urban planning, but has been slow to pervade the engineering arena in the United States (Austin, 2014; Basnou et al., 2020; Meenar, 2019). Facilitating this transition is important for future engineers to play a pivotal role in addressing today's greenspace equity and environmental justice challenges, where understanding situational context and listening, adapting and responding to diverse community voices is paramount (Basnou et al., 2020; Schifman et al., 2017).

5 | CONCLUSIONS

This study reveals that perceptions of common urban landscapes (lawns, gardens and native ecosystems) among engineering students in southern California follow characteristic patterns, whereby each landscape is thought to provide specific bundles of ecosystem services and disservices. Landscapes were perceived as multifunctional, with lawns providing primarily cultural services, native landscapes promoting biodiversity and other organism-associated services/disservices, and gardens providing both. In contrast to traditional landscapes, NTS were not consistently associated with specific services/disservices bundles, suggesting that a social norm for NTS perception does not yet exist. Given that civil and environmental engineering students (who constituted the majority of the survey pool) are among the most likely to have been formally educated in NTS theory, and perhaps practice, we anticipate that the absence of an NTS social norm will be even more evident in the broader population.

Although engineering students were generally knowledgeable about NTS, they had difficulty identifying them, few had the opportunity to see them during a class or research experience, and the majority had trouble understanding their services in context with other landscape features, pointing to a limited understanding of the role NTS play in stormwater management relative to other urban greenspace. This could be a barrier to effective NTS design, as it has been found that students with the capacity to frame projects broadly and leverage more knowledge types when approaching problems tend to be the most effective designers (Adams et al., 2003). Engineering education about NTS might be improved by (a) incorporating and fostering appreciation for different perspectives and disciplines. This might include drawing on principles from landscape architecture that help students contextualize NTS, such as landscape and situational context assessment, cues to care and ecological aesthetics, among others (Gobster et al., 2007; Gobster & Westphal, 2004; Nassauer et al., 2001), and introducing ecological theories to engineers so that NTS ecology is not a black box and students can link elements of ecological design to the provisioning of specific services/disservices, (b) making use of existing NTS capital on campus as a teaching tool so that NTS experiences are coupled with the reflection necessary to learn (see SIBE-VUSP) and (c) fostering practical understanding of NTS design elements (overflow structures, vegetation, curb cutouts/inflow structures, etc.) improving student capacity to identify NTS in the wild. In time, some of these design elements might eventually become cues to function (at least for the engineering student community) if appropriately highlighted through coursework, fieldwork and/or interpretive signage. Indeed, we expect that, irrespective of curricular change, increased use of interpretive signage for NTS at Southern California campuses could increase student awareness of these features by up to 30%.

This study takes a holistic view of how knowledge, worldviews, attitudes and demographics interact to shape how urban greenspace is perceived, but is (of necessity) place and context specific. In other US states and countries the relationships between these factors may differ. Landscapes themselves may be different, reflecting local climate and landscaping practices as well as disciplines involved with NTS design (Adem Esmail & Suleiman, 2020; Suleiman et al., 2020; Zuniga-Teran & Gerlak, 2019). How landscapes are perceived by engineering students may be different, reflecting alternative approaches to engineering education or variation in demographics (e.g. situational context) (Gobster et al., 2007). The degree to which each of these context-specific elements can be expected to influence how engineering students (or indeed students from other disciplines involved in greenspace design) perceive and value landscape features is not well understood, but likely to be important given the influence that values and biases have on the design process (Finewood et al., 2019). Future work addressing these context-specific elements for the full range of disciplines involved in planning, implementation, design and maintenance of urban greenspace, is necessary to determine conditions under which 'lessons learned' are transferable and those where they are not. For our particular context, we argue that 'boundary' educational programs co-developed with other disciplines would greatly benefit engineering students, improving their ability to recognize NTS services/disservices and collaborate in multidisciplinary design teams. We hope this study will inform the development of such programs improving the ability of tomorrow's engineers to co-design NTS with other invested practitioners.

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CONFLICT OF INTEREST

The authors have no competing interests to declare.

AUTHORS' CONTRIBUTIONS

M.A.R. was involved in conceptualization, methodology, data curation, formal analysis, writing—original draft preparation and visualization; G.P. and D.F. were involved in conceptualization, methodology and writing—review and editing; B.W. and A.S.M. were involved in methodology and writing—review and editing; P.A.H., R.A. and L.L. were involved in funding acquisition and writing—review and editing.

DATA AVAILABILITY STATEMENT

Our IRB-approved protocol and corresponding consent form do not allow human subjects data to be shared in non-aggregated forms. As such, aggregate responses to all survey questions (means or medians with 95% confidence bounds) have been provided in lieu of discrete responses in manuscript tables (see Table 1, Table 2, Appendix C: Table S1, and Appendix E: Table S2).

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