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Social-ecological research in urban natural areas: an emergent process for integration

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Abstract

Understanding the structure and function of urban landscapes requires integrating social and ecological research. Here, we integrate parallel social and ecological assessments of natural areas within New York City. We examined social data (from a rapid assessment of park use and meaning, collected at a park zone level) alongside ecological data (from a plot-based assessment of forest structure and diversity). In-depth interviews with researchers and managers ($n = 11$) involved with the social and ecological assessments revealed commonly-held values considered critical for integration, including clear communication, openness, trust, and shared goals and also identified barriers to the integration process, including the scales at which each dataset was collected. We applied an informed, shared problem framing to investigate the relationships between visitor use and ecological condition in urban natural areas. We began with fuzzy cognitive modeling, where researchers developed models of defining a "healthy urban forest." We then developed two social-ecological typologies to examine the integrated dataset in relation to how visitors may affect or perceive ecological health and threat. Typologies identify NYC natural areas where social indicators (number of visitors, diversity of park use motivations) are either high or low and ecological condition is either high or low. Examination of these typologies led to exploring correlations between social and ecological variables, to team discussions, and to developing new research questions. We conclude this paper with a discussion of tradeoffs of this type of emergent, integrative approach to social-ecological synthesis research.

Keywords Social-ecological · Urban forest · Typology · Integration · Synthesis

Introduction

Understanding the structure and function of urban landscapes is a key step towards sustainable natural resources management and requires integrating social and ecological factors. Conducting research to integrate these factors is often challenging. Social science and ecological theory, methods, and data differ, which can impede synthetic approaches, analyses, and a holistic understanding of the system. Palmer et al. (2016) discuss some of the difficulties of conducting socio-environmental synthesis research, where researchers must creatively use existing data. They also illuminate the promise of "actionable science," or fundamental research that informs policy and decision making.

Urban parks offer an ideal opportunity to integrate social and ecological research approaches. Social-ecological research can provide direct benefits to managers balancing urban ecosystem management and people's access and use of natural spaces. Parks provide valuable ecosystem services and habitat in a landscape with limited green space (Gómez-Baggethun et al. 2013),

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and they are intended to provide much needed cultural services to city residents (Bolund and Hunhammar 1999; Andersson et al. 2015). Many urban parks contain natural areas, including upland and maritime forests, as well as grasslands, freshwater wetlands, and salt marshes. Ecologists have studied the vegetation structure and composition of urban forests for decades (e.g., Hobbs 1988; McDonnell and Pickett 1990; Zipperer 2002). At the same time, social scientists have examined urban park use and meaning (e.g., Chiesura 2004; Irvine et al. 2013). Research on cities as social-ecological systems has also emerged (e.g., Pickett et al. 2001; Grove et al. 2006; Alberti 2010), which has led to interest in understanding the structure and function of urban natural areas as social-ecological systems.

In New York City (NYC), social and ecological scientists from the Natural Areas Conservancy, NYC Department of Parks & Recreation (NYC Parks), and the US Forest Service recently conducted the first citywide ecological and social assessments of NYC urban parklands and their natural areas. These assessments provide rich datasets and an opportunity to explore urban natural areas as social-ecological systems. The goal of the ecological assessment (EA) was to "provide quantitative baseline data to enable categorization of the extent and condition of NYC's natural areas" (Forgione et al. 2016). The social assessment (SA) of NYC's parklands was conducted to provide a social context for the ecological study of urban natural areas and parklands and capture a snapshot of who uses urban green spaces, how they use them, and why (Auyeung et al. 2016; Campbell et al. 2016).

The SA serves as a complement to the EA; together, these studies were developed to inform adaptive management actions to improve ecological health and benefit the public through an enhanced way of understanding, valuing, managing, and programming parks in the future. The EA provides a baseline dataset for NYC's natural areas, and can be applied towards setting site-specific and system-wide management targets. The SA applies a mixed-method field protocol to measure how park visitors use, value, and assign meaning to urban green space, including the less programmed natural areas in city parkland. Understanding the social dynamics of city parks and their natural areas may help urban park managers cultivate and support an active and engaged constituency, thereby ensuring the continued viability of these critical natural resources.

SA and EA researchers exchanged ideas and information through a series of meetings and a fuzzy cognitive modeling exercise, leading to the data exploration and research questions we focus on in this paper. Here, we combine data from these assessments and interviews to ask the following research questions:

1) How is ecological condition related to number of visitors in urban forested natural areas?
2) How is ecological condition related to motivations for park use by visitors to urban forested natural areas?
3) What new holistic research questions or approaches emerge from the iterative process of comparing and integrating social and ecological data?

In this paper, we present an example of empirical data exploration that combines data from different methods, disciplines, and scales and reflect on our iterative, transdisciplinary research process and the development of new research questions.

Urban forest integrity and health

Ecological integrity is the ability of an ecosystem to support and maintain a community of organisms with composition, diversity, and function comparable to natural habitats within the same region (Karr and Dudley 1981). Research on the ecological integrity of urban forests has primarily focused along a gradient of urbanization. For example, in the Lake Tahoe region, remnant native forests along a development gradient retained much of their compositional and structural character, except for the density and decay of both snags and logs and the density of understory trees (Heckmann et al. 2008). Most studies examining the effects of urbanization apply such aggregated measures, but the effects of different urban forms remains unknown (Alberti 2010). Ordóñez and Duinker (2012) point out that the holistic concept of ecological integrity has not been applied to urban forests in a robust manner.

Forest health differs somewhat from forest integrity in its focus on a flourishing system, rather than level of intactness (Karr 1996). No scientific consensus currently exists on the exact meaning of forest or ecosystem health, though these are widely-used terms (Ross et al. 1997; Lackey 2001). As in other multi-use landscapes, urban land managers and park users may have a variety of perspectives on the most important cultural or biophysical ecosystem services provided by the natural resource. Definitions of forest health and associated forest management goals for a particular site may be most effectively formed through engagement with local stakeholders (Arnott et al. 2015; Sulak and Huntsinger 2012). A study from Ontario, Canada found convergence between scientific and public views of forests and forest health, including the importance of indicators such as 'variety of tree sizes' and 'size and integrity of forest area' (Patel et al. 1999). However, all participants in this study were judged to be relatively well-informed about the environment, which may have impacted their views of forest health. Prior knowledge can also impact forest health values; declining trees damaged by invasive pests were perceived more negatively by informed park users than by those who were not aware of the problem (Buhyoff et al. 1979, 1982).

In urban natural areas, the relationship between visitor presence and ecosystem health is not well understood. Depending on one's value orientation and definition of forest health, the greatest threats to forest health may be human impacts on naturally-occurring processes (Abrams et al. 2005). A study from Ontario showed that human recreational impact did not affect plant species diversity or density, median sapling height, proportion of native species, or leaves with foliar damage. However, an increase in plant species cover was related to human use, possibly because the presence of visitors prevented heavy deer browsing (Patel et al. 1999), an example of an unexpected or unintended consequence in a complex social-ecological system. Additionally, modifications to a site from informal and formal trails can affect forest structure, resulting in small amounts of forest loss, reductions in tree density, and an increase in saplings in Australian forests (Ballantyne and Pickering 2015).

Park values, meanings, and motivations

Visitors experience and understand the benefits of urban parks in multiple ways. Urban parks are perceived to be most important for providing recreational ecosystem services (a type of cultural ecosystem service), followed by regulating ecosystem services, other cultural ecosystem services such as tourism and aesthetic appreciation, supporting ecosystem services, and provisioning ecosystem services (Bertram and Rehdanz 2015). NYC parklands provide psycho-social-spiritual benefits for both passive visitors and those who actively shape parklands and natural areas through stewardship and other activities related to spirituality and well-being (Svendsen et al. 2016). Additionally, Bertram and Rehdanz (2015) found urban park characteristics important to visitors may be summarized by four factors: neatness, naturalness, spaciousness, and sociability, which are consistently ranked in that order of importance across four European cities.

Outside of cities, cultural ecosystem service provision is related to landscape features and land cover type (Plieninger et al. 2013; van Berkel and Verburg 2014). A similar relationship may exist between provision of cultural ecosystem services and the varied landscapes of forests, fields, meadows, playgrounds, beaches, and marshes that can comprise urban parks. Demographics may also play a role in service provision. When Loukaitou-Sideris (1995) examined patterns of meaning in neighborhood urban parks, she found the use and perception of space varies dramatically, with aesthetics, social, relaxation, educational, and other meanings mentioned at different frequencies, or not at all for different user groups. Additional research is needed to understand why park users prefer different site types within urban parks.

One theme of social science research focuses on the values and meaning that people hold about the environment. Abstract layers of meaning arise from specific relationships between the observer and the environment and are linked to deeply-held personal beliefs and specific social contexts (Gee and Burkhard 2010). As meanings rely on these specific relationships between the observer and the environment, ecological condition may affect visitors' experiences and meanings. However, studies on the relationships among actual and perceived biodiversity and self-reported human well-being have found conflicting results which reveal the complexity of human-biodiversity interactions (Pett et al. 2017). In a review of urban biodiversity perception studies, Botzat et al. (2016) found most studies examining biodiversity at finer scales than an ecosystem find positive biodiversity effects, but universal patterns are lacking due to differing methodologies and the relative scarcity of studies. It is not well known whether people differentiate between species richness and vegetation cover; there is a need for more research on this distinction in the perception of vegetation in urban green spaces (Gunnarsson et al. 2017) and the meanings it holds for diverse groups.

Much research has been conducted on people's landscape preferences, including in urban parks (e.g., Nassauer 1995; Elmendorf et al. 2005). Relating preferences to ecological integrity can be difficult, as aesthetic quality and ecological quality sometimes overlap, but also can strongly diverge (de Groot and Ramakrishnan 2005). Fry et al. (2009) developed a framework identifying overlaps between visual quality and ecological quality, including the concept of naturalness. In a study of urban parks in Sweden, higher perceived naturalness of a site was correlated with more activities, higher aesthetic values, and self-reported well-being for residents that live close to urban green spaces (Sang et al. 2016). In this context, perceived naturalness may be more a measure of visual quality rather than ecological quality. More research is needed to understand the strengths and absences of these overlaps. Previous ecological knowledge appears to increase these overlaps; interventions may alter visual preferences to align with ecological quality (Gobster et al. 2007).

Values and meanings held about parks often are related to visitation motivations (Iso-Ahola 1982). Motivations for urban park use in Sheffield, England were related to physical activities, space qualities (nature, park features), children, cognitive, social, and unstructured time (Irvine et al. 2013). A study of Brisbane, Australia parks found park visitation rates reflected the availability of parks, while people with a greater orientation towards nature were willing to travel farther for parks with greater amounts of vegetation (Shanahan et al. 2015). Brown (2008) found a strong relationship between park size and the diversity of park values, while also finding a weak inverse relationship between diversity of park values and distance between a park and a person's residence. These studies suggest that park values depend upon an individual's attitudes and preferences, the qualities of the park itself, and distance needed to travel to the park.

Drawing upon current literature on forest health and park values, meanings, and motivations, we apply social-ecological typologies to examine natural areas in NYC parkland using social and ecological datasets.

Approach and methods

Study area

NYC has one of the most diverse park systems in the United States, totaling 11,736 ha of parkland (City of New York 2011). In 2001, the NYC Parks Natural Resources Group created the Forever Wild Program to protect roughly 3642 ha of forests, wetlands, and meadows. The SA study area includes 3611 ha of publicly-accessible parkland managed by NYC Parks across the five boroughs of New York City, including 1979 ha of lands designated as Forever Wild (Fig. 1). The EA study area includes 4047 ha of natural areas managed by NYC Parks, including 2914 ha of forestlands. For the purposes of this paper, we focus on areas where data from the ecological and social assessments overlap, totaling 82 zones from the SA and 752 EA plots within these zones, for a total of 3319 ha.

Datasets

This paper integrates data from three studies: the EA, the SA, and reflexive research on our process for integrating the

Fig. 1 Overlapping social assessment zones and ecological assessment plots in NYC parklands and natural areas

assessment datasets (Table 1). Data from the ecological and social assessments are applied to explore questions of the intersection of ecological and social conditions in natural areas. These make use of EA and SA field collection methods, described in Supplementary Materials (ESM 1). More detailed methods for the SA are described in Campbell et al. (2016) and Auyeung et al. (2016); methods for the EA are described in Forgione et al. (2016). Our reflexive research makes use of assessment researcher interviews, fuzzy cognitive modeling results, meeting notes, and participant observation, described at the end of this section, with the interview protocol provided in Supplementary Materials (ESM 1).

Social and ecological data

To address our two research questions relating ecological condition to visitor density and park use motivations, we applied a combination of ecological and social indices to develop two typologies of park zones: Typology 1, based on ecological condition and visitor density (visitor count normalized by zone size) and Typology 2, based on ecological condition and diversity of park use motivations. EA data were collected on 10-m fixed radius plots, while SA data were collected in larger park zones with uniform land use/land cover (e.g., natural area, landscaped lawn, playground). Zones were delineated manually by SA researchers using aerial imagery, to identify areas of similar use and land cover (see Auyeung et al. 2016 for further details). To combine these datasets, we aggregated the plot-level EA data to the SA zone level, by calculating the mean, median, standard deviation, and standard error of an ecological condition index, along with the index's input variables, for EA plots within each SA zone. We also calculated diversity of park use motivations using the Shannon-Weiner index, which adjusts for the number of interviews per SA zone. All typology variables used are aggregated variables. Visitor count can be subdivided by activity type, ecological condition can be subdivided into individual ecological metrics, and diversity of park use motivations is comprised of individual park use motivations.

To examine the two typologies, we began with 82 SA zones where our social and ecological data overlapped. We excluded zones with fewer than six ecological plots, to address variation in ecological data within zones. We excluded zones with no interviews for the typology including diversity of park use motivations. This resulted in a total of 37 zones, or natural areas, for Typology 1, and 23 zones for Typology 2. We then created scatterplots for each typology to visualize relationships between these variables and to identify a subset of natural areas to explore further as case studies. Each zone on the scatterplot was assigned to a quadrant based on whether it had high or low ecological condition and either a) high or low visitor density (Typology 1) or b) high or low park use motivation diversity (Typology 2). For both typologies, high or low categories were determined as being above or below the mean value for a variable.

We also examined Pearson's correlations between input data for the ecological index, visitor count, and park use motivation diversity variables. For this analysis, we examined ecological data correlated with social data, but excluded ecological-ecological and social-social correlations.

Reflexive data on the integration process

In addition to the social and ecological field data collected in NYC Parks' natural areas, this paper draws on qualitative datasets resulting from an examination of this social-ecological integration process, including participant observation, meeting notes, a set of fuzzy cognitive modeling (FCM) workshops in 2015, and confidential interviews with researchers.

FCM is a method of concept mapping that offers a way to understand our internal representations of the world. Mental models are personal, cognitive representations of external realities that vary based on worldviews and life experiences. They influence the way people process and store information, make decisions, and behave. FCM works by developing qualitative static models and translating them into semi-quantitative dynamic models (Gray et al. 2014). It can be used as tool for transdisciplinary learning, to standardize and represent abstract knowledge and perceptions, and to facilitate collaborative planning given anticipated changes to a system (Jones et al. 2011).

In an effort to identify and align the different perceptions of forest health and goals among managers, research ecologists and research social scientists, HM (a researcher not previously

Table 1 Datasets applied in this paper

Data source	Types of data	Initial research questions
Ecological assessment	Plot-based vegetation metrics on structure and composition	What is the ecological condition of natural areas in NYC parklands?
Social assessment	Visitor counts and interviews at a sub-park, or zone, level	What are the uses, functions, and meanings of urban parkland as conveyed through people's behaviors, descriptions, and narratives?
Reflexive research	Researcher interviews and participation observation	What are the opportunities and challenges to social-ecological integration research?

involved in the EA or SA) convened twelve researchers and practitioners (some of whom are co-authors) who had been part of the EA and/or the SA. They participated in a FCM exercise to define a "healthy NYC upland forest." As a step toward informing the management of natural areas as integrated social-ecological systems the goals of the exercise were to: 1) identify potential problems and clarify communication among stakeholders; 2) create a collective representation of a system to improve decision making processes; and 3) support social learning (Gray et al. 2013; Jones et al. 2011). Each participant was asked to draw a model of a "healthy NYC upland forest" by identifying the components of the system, whether each had positive or negative influences on the system, and the relationships among components. HM also condensed individual participants' FCM models into a shared model of "NYC upland forest health."

After data collection was complete for each assessment and researchers began to discuss and plan integrating the datasets, two co-authors conducted confidential, semi-structured interviews ($n = 11$), with all researchers associated with each assessment, along with land managers involved in assessment development and interested in the outcomes of both assessments (see interview protocol in ESM 1). Individuals were invited to be interviewed based upon their involvement with the assessment or their familiarity and interest in applying assessment results; no potential interviewees refused participation. These interviews focused on two topics: the integration process in general and the development of an FCM of forest health. Dual coders established initial codes and definitions, coded a subsample of text, compared coding results, and revised initial codes to facilitate agreement (Neuman 2003). Initial codes and definitions were developed through an emergent coding process (Lofland et al. 2005; Ryan and Bernard 2003). Coded text was then summarized and analyzed for trends, repeating patterns, and illustrative quotes. Participant observation and detailed meeting notes were used to triangulate emergent themes and provide additional support and detail about the full timeline of the integration process (Table 2).

Results

We present our results chronologically, with illustrative quotes from researcher interviews included and designated as [RI#].

Assessment research design

Initial efforts for a SA of parks and an EA of natural areas within parks occurred as separate efforts. One researcher interviewee [RI6#] identified challenges to integration as a

Table 2 Emergent themes around social-ecological integration research from researcher interviews, with associated definitions ($n = 11$)

Emergent theme	# Mentions in researcher interviews
Supportive Elements (things that support integration/collaboration)	
Communication: Participants communicate with each other often and openly with mutually understandable language.	19
Resources: Participants don't have enough time for the project/process; funding; and personnel; Political support	11
Respect / Openness: Participants are open to new ideas, projects, theories, disciplines, and what counts as 'research,' 'data,' and 'methods.' Participants respect each other as individuals and in terms of their expertise.	11
Personalities: Personalities work together well.	10
Tangible problem to be solved: Not doing it just for the sake of research or in a general way	8
Specialists and spanners: Representation of people who both have deep knowledge in one area as well as people/person with knowledge across areas/disciplines	7
Trust: Participants trust each other.	7
Incentive structure: Within job responsibilities/ expectations	6
Leadership: central, dispersed, quality	3
Willingness to reveal lack of knowledge: Participants are willing to listen to or are comfortable asking naïve questions.	3
Challenging elements (things that challenge integration/ collaboration)	
Disciplinary boundaries: Academic disciplines conceptualize the issue or use methods or vocabulary in different ways, creating boundaries.	13
Theoretical vs practical: Some participants approach the issue at an abstract theoretical level, while other participants think about the issue in a practical way.	7
Framing (holistic/parallel): Project framing can be holistic (EA and SA are one assessment) or in parallel (EA and SA are separate).	6
Scale: Data are collected at varying spatial and/or temporal scales.	6
Integration Process	
Transformation / evolution: A change over time in an individual's thinking, the process, or products of the EA-SA integration.	4

result of the lack of time spent on shared goals in the development of both studies. People went back to their own incentive structures and communicated intermittently, which made it difficult to arrive at shared outcomes. A number of researcher interviewees framed the EA and SA as unified in concept, while others pointed to them as distinct—conceived of and implemented separately, with some communication to facilitate later integration at the analysis stage. One researcher interviewee [RI4#] noted:

> "[These projects were] conceived separately, not together, which is a key problem. It would have been better to have both field crews integrated and go out together. We need to conceive of these on an equal plane. The success of the project should not rest on having all the data meet up. It may be apples and oranges, but it doesn't mean we can't learn from a fruit basket!"

Assessment data collection

When the social and ecological assessments were at the data collection stage, researchers involved in each assessment held integrated team meetings to coordinate efforts for sampling and gain a general understanding of the other group's work, including discussions to understand the research questions, objectives, and methods of each project. These meetings focused on logistics, with some research ideas discussed. At the end of the second field season, researchers convened field assistants from both assessments to elicit reflections on their work and identify synergies across social and ecological aspects of natural areas. The theme of communication emerged as contributing to successful integration of social and ecological data: "This is why we should be collecting social and ecological data. To be talking to each other." [RI#8].

FCM modeling (2015)

The FCM process revealed that participants had a range of understandings of a "healthy NYC upland forest." Some models included humans in the system; some did not. Some understood human influence on the system to be positive and negative, others only negative. Participants described how drawing their models helped clarify their own ideas about the system (e.g., the pathways between stewardship, use, and forest health) and that seeing others' models and hearing how the variables were chosen and how the relationships were depicted promoted a deeper understanding of the distinctions and common ground across participants.

Subsequently, two co-authors (HM and MJ) condensed ten individual models into a shared, group model which was discussed with participants in follow up meetings. This shared model consolidated 43 unique factors into 20 factors. This was done by combining similar factors such as vandalism of property, vandalism of vegetation, anthropogenic fire, and negative visitor impacts into the factor negative visitor impacts; locally informed managers, scientifically informed managers, goal setting for management, and effective management were consolidated into effective management. See Fig. 2 for a simplified version of the group model. This group model shows direct influences on the urban forest only for clarity, as discussion of all 43 factors is beyond the scope of this paper. The model illustrates the perception of the negative relationship between visitors and forest health. At the same time, it shows that frequent park use and forest health are perceived to have a positive feedback relationship. This perception of park users both positively and negatively influencing ecological condition led to the research questions asked in this paper. The model also illustrates the perception that native species are a strong positive influence and invasive plants are a strong negative influence on forest health. Interestingly, these are perceived to be stronger influences than effective management. This may be due to NYC Parks' existing management practices, which largely focus on invasive plant removal and native planting, already being indirectly represented by these specific factors. All of these perceived relationships can be seen as hypotheses themselves worthy of critical research and reflection. Participants confirmed the group FCM model represented their ideas, and then used it to identify hypotheses and research questions for future directions. Questions included: Do stewardship activities, like mulching or weeding, improve long-term survival rates of planted trees? What is the relationship between frequency of park use and negative visitor impacts? What are the relationships among historical disturbances, soil quality, and invasive plants? Participants also used the FCM model to identify gaps in our collective understanding and data sets, which suggested future research directions. For example: How do fragmentation and patch size relate to urban forest management? Can forest patches that are being managed ever be self-sustaining? Given that we will never remove all invasive species, what are reasonable and accurate indicators of successful or effective management? How are social aspects and human health related to our understanding of the forest and what we should be managing for? Salient themes that emerged in the researcher interviews about the effects of the process centered on: the clarification and transformation of one's own ideas, increased understanding of others' perspectives, shared learning, and how the process helped to facilitate agreement among participants.

Researcher interviews

Themes of success and challenges emerged from researcher interviews held after the FCM modeling stage of our integration process. Here, we focused on two interview questions: 1) In general, what supports or enables integration in our

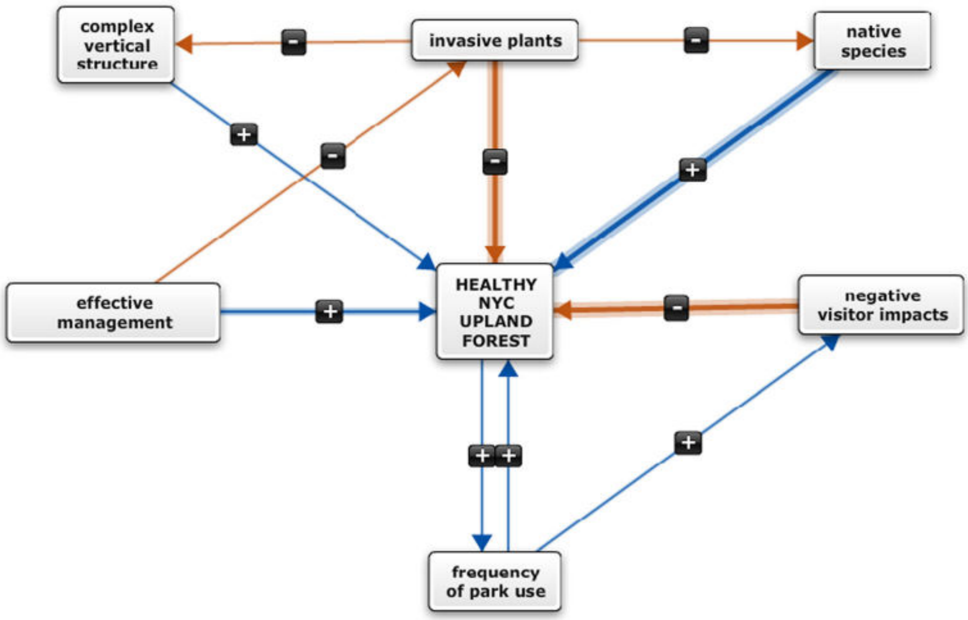

Fig. 2 Healthy New York City Upland Forest Model, created with Mental Modeler (Gray 2015). This simplified version of the model is based a condensed model that combined all models created during the FCM Workshop. For clarity this version shows only the components that were described as having direct influence on the forest. Other secondary influences are not shown here. In this model, the 'frequency of park use' and the 'negative visitor impacts' relate to the visitor count analyzed in this paper. Blue lines show positive influences. Orange lines show negative influences. The width of the line corresponds to the intensity of influence. Thicker lines show a stronger influence than thinner ones

research? and 2) What are challenges to integrating this research or research generally? Supportive elements generally drew on attributes of individuals (e.g., communication, respect / openness) and their support system (e.g., resources), while challenging elements involved aspects of integration such as problem framing and scale of the data. Additionally, some team members noted a transformation or evolution in their own thinking about the social-ecological nature of urban forests through participation in this EA-SA integration effort. These transformations included changes in the perceptions of natural areas over time, reflections on how the FCM expanded social-ecological thinking, and the recognition that thinking about both social and ecological analytical frames affect one's approach to the issue. One researcher [RI#2] noted:

> "...when we look at the human impacts to places... from a social perspective and not putting a value judgment on it has been an interesting way to think about things, while from a biophysical perspective, I still can't separate it from a negative impact… from a social viewpoint I can still see that as evidence of human use, or human passing by…so it's interesting to think about both things at the same time."

Data integration

After the FCM workshop and individual interviews, meetings with members of the ecological and social assessment teams continued, focusing on data integration methods. One issue that emerged in these discussions was the limitations of combining the existing data types. RI#9 noted:

> "that makes one of the components [of successful integration] being easily linked data sets. They should be at a similar scale, easily linked. It was like trying to fit a round peg in a square hole. We were scaling some things up and some things down in order to be able to compare them…"

The teams discussed analyses involving forest typologies and cluster analyses, looking at both qualitative and quantitative ways to categorize natural areas with respect to observed park use, park use motivations and ecological condition. During these discussions, research questions emerged, and we began to notice these discussions generated new questions and research designs.

To integrate the two datasets and address spanning research questions, we focused on a typology approach, to address the disparate scales and methods of data collection. We distilled ecological data into an ecological condition index, including aspects of both forest health and threats. After iterations of examining the data, the SA team focused on two simplified metrics for examining the SA datasets: visitor density and diversity of park use motivations. We then held a series of group meetings to examine the data, viewing the raw data and applying data exploration tools (maps of zones assigned to each typology, scatterplots for identifying the zone types, and correlation tables of aggregated and input EA and SA variables).

To explore our first two research questions, we plotted aggregated EA data against aggregated SA data (Fig. 3a, b) to determine if ecological condition was related to the number of visitors or the motivations for park use by visitors to urban forested natural areas. Zone-level patterns for these indices did not identify clear linkages between the ecological and social datasets – in other words, the ecological condition of a zone appeared to be independent of the simplified SA metrics, number of visitors, and diversity of park use motivations. We identified some zones containing high ecological condition and high visitor density, while other zones contained high ecological condition and low visitor density. We found the same pattern with regard to park use motivation diversity. Regardless of the ecological condition of the zone, visitors cited many of the same reasons for visiting the park. The main pattern we found was that larger zones tended to have higher park use motivation diversity, likely because these zones had more visitors and therefore more interviews. In Typology 1, we observed fewer parks with high visitor density and high ecological condition, while zones were more evenly distributed across all four quadrants for Typology 2, park use motivations and ecological condition.

We then selected case study zones in the extremes of each quadrant for both typologies. Examining case study zones grounded our typologies, and enabled us to discuss factors beyond our own datasets. For example, zones in Staten Island, like Wolfe's Pond Park Zone A, were often in the high ecological condition and low visitor density quadrant. Zones from parks in other boroughs were more dispersed across the four quadrants. This led to discussions about other factors that affect ecological and social conditions such as geographic features, surrounding neighborhood characteristics, land use, and population density. We then brought these contextual concepts back to the larger datasets. For example, we examined the distribution of visitor density relative to ecological condition and speculate that Staten Island parks were influencing the distribution of zones across the four quadrants for Typology 1, as they typically have higher ecological condition and lower visitor numbers. Notably, the few zones in the high visitor use and high ecological condition were in easily accessible "flagship parks" known for their forests, including Inwood Hill Park in Manhattan and Forest Park in Queens, as well as a zone in Clove Lakes Park, near the more densely urbanized part of Staten Island.

a

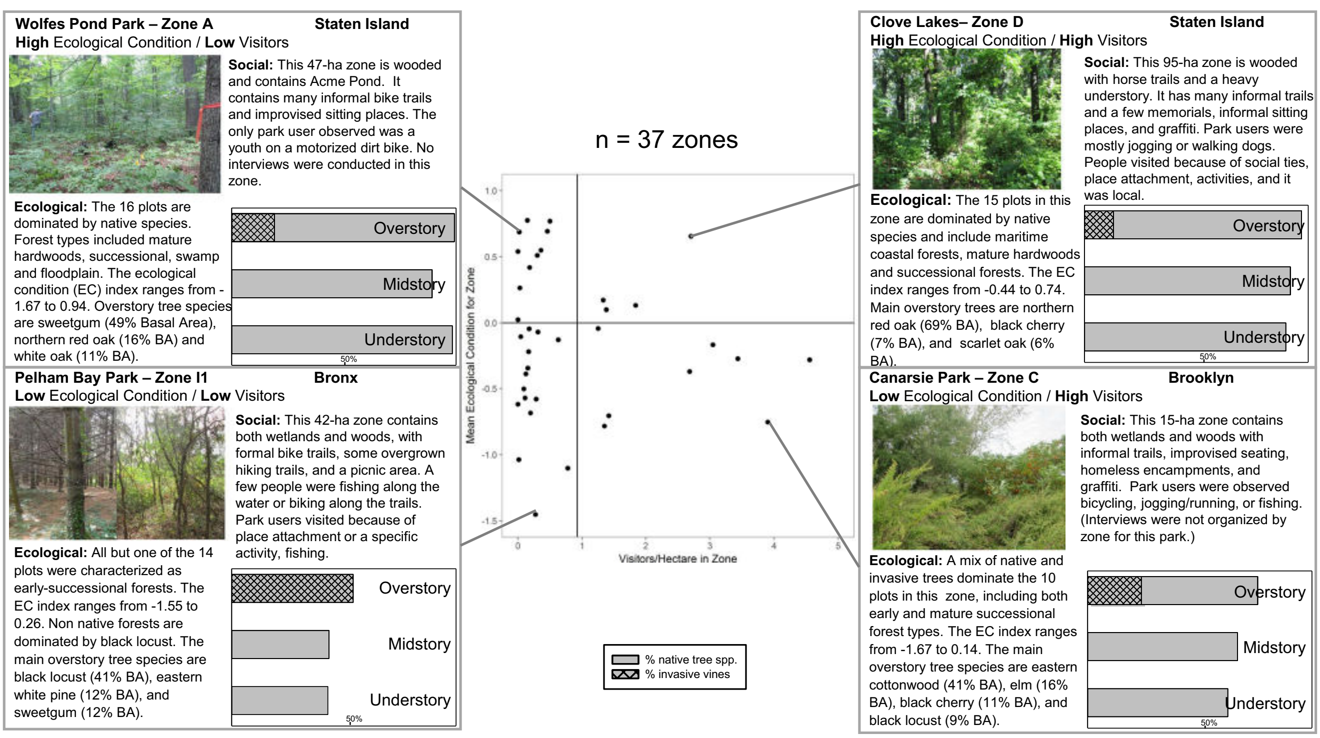

Fig. 3 **a** Typology 1: Variation in Ecological Condition and Visitors in Zone/Hectare in forested natural areas in New York City ($n = 37$). High or low ecological condition is determined as being greater or less than the mean ecological index across all EA plots in the full EA dataset ($n = 1124$). High or low visitor density is based on whether their visitor density was greater or less than the mean visitor density across all SA natural area zones with at least six ecological plots. **b** Typology 2: Variation in Ecological Condition and Diversity of Park Use Motivations in forested natural areas in New York City ($n = 23$). High or low ecological condition is determined as being greater or less than the mean ecological index across all EA plots in the full EA dataset ($n = 1124$). High or low park use motivation diversity is based on whether a zone's park use motivation diversity is greater or less than the mean park use motivation diversity across all SA natural areas zones with at least one interview ($n = 23$)

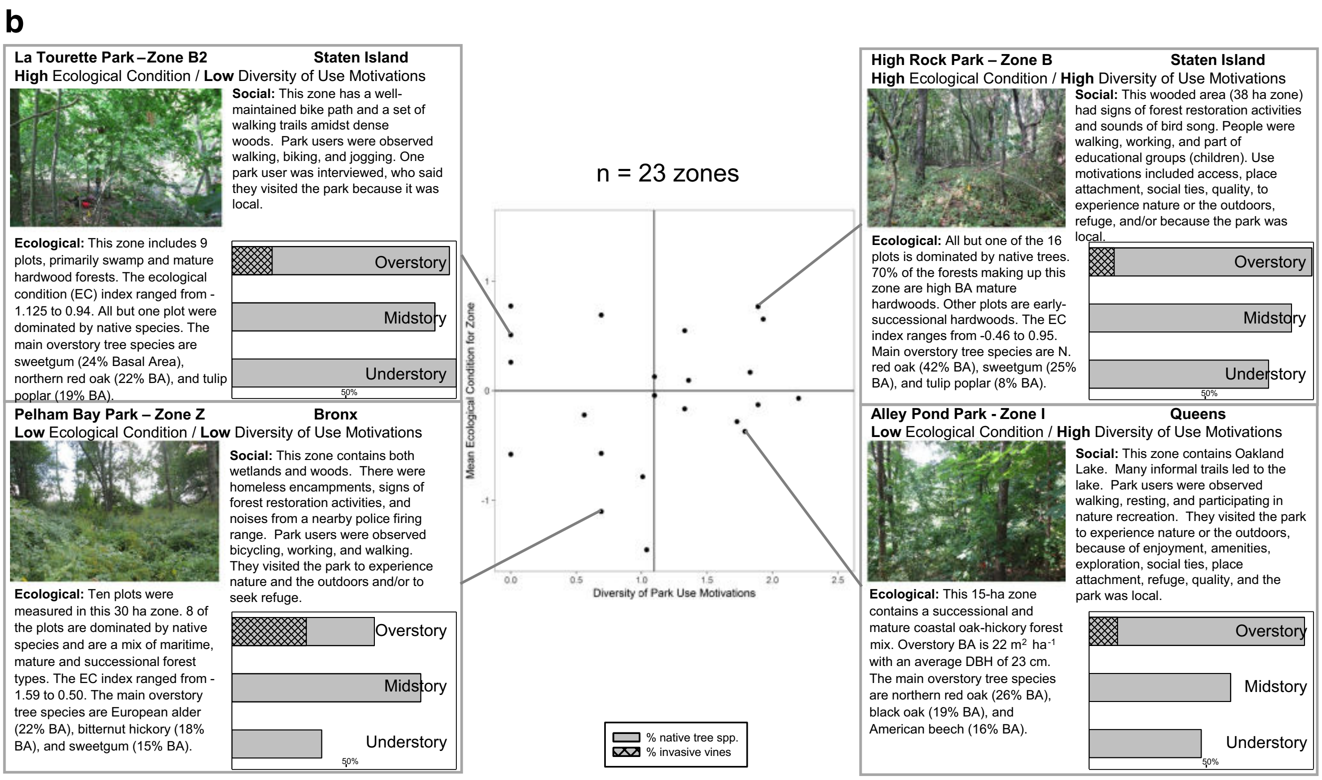

Fig. 3 (continued)

Further investigation of our first two research questions involves examining correlations among the individual social and ecological variables. Pairwise Pearson's correlations among input variables of the aggregated ecological and social measures identified a number of significant positive and negative correlations (Table 3). Overall, the relationship strength of significant correlations was moderate, ranging from 0.34 to 0.56. Percent of visitors walking in a zone was negatively correlated with four ecological threat variables and positively correlated with two ecological health variables and the aggregated ecological condition variable. The opposite was true for percent of visitors bicycling. Park use motivations (derived from the coded thematic responses to SA interview question "why do you come to this park?") positively associated with aspects of ecological health included percent sociability and percent enjoyment; park use motivations associated with aspects of ecological threat included percent activity and percent enjoyment. Most inputs to the ecological condition index were significantly correlated with some aspect of the SA visitor counts and/or park use motivations; native canopy basal area was the only EA input variable with no significant correlations.

Discussion and conclusions

In this paper, we examine ways of combining social and ecological datasets through FCM, typologies, and correlations, and we reflect on these approaches. Beginning with our two initial research questions, we find evidence that ecological condition is related to both number of visitors and motivations for park use. We find that there is a positive correlation between an aggregated ecological condition index and certain types of visitor use (e.g., walking and jogging). These results align with Sang et al. (2016), who identified relationships between perceived naturalness and walking, although the spectrum of parks in their analysis extended beyond natural areas to include modified park areas. Our result of bicycling being negatively correlated with measures of ecological condition also aligns with the inverse relationship between cycling and perceived naturalness. We also find significant correlations between individual aspects of the ecological condition and individual park use motivations. Motivations were correlated with both health and threat aspects of ecological condition. Most of these relationships were expected (e.g., visitor activity was positively linked with aspects of ecological threat; sociability and enjoyment were positively linked with aspects of ecological health), but the positive correlation between enjoyment and amount of invasive canopy vines was unexpected and warrants further investigation. The results from this integrated look at the relationships between social and ecological datasets illuminates areas for future research that could address the causality of these relationships.

Examining our data through many lenses proved necessary, as both the social and ecological datasets were very

Table 3 Significant ($p < 0.05$) pairwise Pearson's correlations between ecological condition input variables with percent of visitors engaged in an activity and/or identifying a particular motivation for park use, at the zone level (out of correlations with 25 social variables for each ecological variable). For more details on how ecological condition variables, visitor counts, and motivation for park use were collected, please see ESM 1

Variable	# positive	# negative
Ecological Threat	• % activity (motivation) • % bicycling (visitor count)	• % walking (visitor count)
Invasive vine midstory (square root)	• % activity (motivation) • % bicycling (visitor count)	• % walking (visitor count)
Invasive midstory stem (log +1)	• % sitting (visitor count)	
Invasive canopy basal area (square root)	• % bicycling (visitor count) • % working (visitor count)	• %walking (visitor count) • % jogging (visitor count)
Invasive herb cover (log +1)	• % activity (motivation) • % bicycling (visitor count)	• % walking (visitor count)
Invasive canopy vines (square root)	• % enjoyment (motivation)	
Ecological Health	• % walking (visitor count)	• % bicycling (visitor count)
Native richness (square root)	• % walking (visitor count)	
Native shrub (log +1)	• % sociability (motivation)	• % education group (visitor count)
Native midstory (log +1)	• % sociability (motivation) • % stewardship	
Native canopy basal area (square root)	No significant correlations found	
Native herb cover (square root)	• % enjoyment (motivation)	• % education group (visitor count)
Native seedling (square root)	• % sitting (visitor count) • % stewardship (visitor count)	
Ecological Condition (Ecological Health + inverse of Ecological Threat)	• % walking (visitor count)	• % bicycling (visitor count)

heterogeneous. Visitor count data showed visitors walking on formal and informal trails, stewarding natural areas, appreciating natural areas, and advocating for nature conservation. At the same time, we know that informal trail use can affect vegetation structure and other visitor activities can negatively impact the ecological condition of natural areas (e.g., dumping). Untangling these relationships is complex, particularly when the ecological condition data are intertwined with a site-specific history of disturbance and management. Our focus on case studies allows us to identify other aspects of a particular site that could influence our results, beyond the datasets we included in our quantitative analysis.

Our typology approach was productive, in part because of the distribution of our integrated dataset. Each quadrant of the two typologies contained zones of natural areas, indicating the presence of zones with all four types (high social/high ecological condition, high social/low ecological condition, low social/high ecological condition, and low social/low ecological condition). Categorizing urban parks in this way enables managers to consider a large number of diverse urban parks at once and visualize their similarities and differences. Social-ecological typologies consider the social and ecological functions of park natural areas – where people are using parks, what motivates people to use certain natural areas, and where natural areas are more or less healthy. Interdisciplinary discussions about how to integrate the datasets led to the creation of aggregated indices of ecological condition and diversity of park use motivations. Each dataset contained a large number of variables, so we created indices to focus our data exploration. Future work could expand on these typologies to include additional datasets on the surrounding neighborhoods, land use, and management interventions (Hunter and Luck 2015).

Given the emergent nature of our interdisciplinary work, we also found exploratory data analysis to be beneficial to informing new holistic research questions. While our social and ecological indices were perceived by researchers and land managers as useful indicators of ecological quality and park use motivations, causal relationships were unclear between these aggregated variables. We did not find strong statistical relationships between these indices. However, data mining of the input variables allowed us to explore and discuss relationships between ecological and social datasets more fully. Individual variable correlations identify aspects of ecology and visitor use and benefits that should be investigated further, such as the relationships between stewardship and forest health and between bicycling and forest threat. Additionally, our discussions raised questions about relationships between these data and other aspects of our assessment datasets, such as forest structure and visitors' perceived safety.

Understanding how we can preserve healthy urban ecosystems while ensuring that people in urban areas have access to natural spaces is critical to managing cities for sustainability. At the onset of the two assessments, we had limited knowledge and available data on connections between ecological and social conditions of forested urban natural areas. After evaluating integration efforts mid-process with our reflexive interviews, we found continuing the conversation and making time for exploration to be critical factors that allowed us to refine our research questions. Also, we had a tangible problem to solve, which helped focus our analysis and better integrate our datasets. Many of the themes we identified in these reflexive interviews align with Turner II et al. (2016) lessons from case studies of social-ecological systems research, including co-learning, being flexible, and accounting for knowledge diversity.

Through our continued engagement around this issue of integration, we identified ways to overcome challenging factors like different scales, units of analyses, assumptions and methodologies. We developed creative methods to address and explore issues of data scale by exploring multiple types of data aggregation (spatial, indices). We note that the EA and SA datasets successfully answered the questions they were designed to address. After a considerable amount of effort spent on field data collection, the ecological condition of NYC's natural areas was measured, as well as a snapshot of park use and meaning across 15 NYC parks containing natural areas. However, our interdisciplinary team faced challenges integrating these datasets, due to a mismatch between the spatial and temporal scales of both the assessments and the social and ecological patterns and processes the assessment datasets represent. Through data aggregation, we were able to match spatial scales of the datasets, but future research efforts could better align the intensity and scale of data collection methods from the onset to enable more robust analyses.

Also, the transformation we experienced ourselves through this process, noted as a theme in the interviews, strongly influenced our identification of research questions of common interest. These questions evolved over time in discussions with each other and with land managers. Our process relied upon a series of methods and analyses to effectively synthesize the ecological and social datasets. The initial challenge of combining the datasets, collected at different scales and to answer independent research questions, may have taken the most time and creativity to address. We had many conversations that enabled us to learn about the data, research questions, and disciplinary approaches associated with the "other" research (i.e., ecologists learned about the SA and social scientists learned about the EA). Engaging in the FCM process provided another opportunity for researchers and practitioners from different disciplines to share and learn about each other's ways of thinking by centering on a concrete issue. The FCM process also allowed us to step back and frame the larger social-ecological system.

Synthesis research enables scientists to tackle critical socio-environmental research questions using existing datasets; however, beginning with an integrated research question first would result in a completely different study design. Going forward with this line of research, our social learning process enabled us to develop a series of research questions and identify appropriate methodologies to pursue them. Research questions that emerged from discussions and data exploration generally related to the following categories: 1) the role of neighborhood (social) and landscape (ecological) context, 2) where and when people act as agents of positive ecological change versus degrading site integrity, 3) assessments of the quality of cultural ecosystem services provided by a site, and 4) ecological and aesthetic overlaps of landscape preference, given the diversity of NYC demographics and the novel ecosystems present in NYC's natural areas. Unlike our exploratory "fruit basket" where we were limited to correlational analysis of a heterogeneous dataset, controlled experiments may allow us to determine the impact of ecological condition on cultural ecosystem service quality and the impact of park use and stewardship on ecological condition. In both cases, different social or ecological treatments may be compared to reveal causal relationships. However, we also note that controlled experiments can be difficult to implement in a densely-populated city with many competing uses for natural areas, causing us to also look to natural experiments, survey experiments, and landscape visualizations as additional ways to identify causal relationships.

Understanding the structure and function of urban landscapes requires integrating social and ecological assessment methodologies. This is easier said than done. We used data from parallel social and ecological assessments in forested natural areas to examine relationships between park use and ecological condition. Along the way we reflected on and examined the dynamics involved in working across disciplines. Through this process we were able to identify important characteristics necessary for collaboration, new research questions, and ways to create fully integrated social-ecological research projects. Such aspects of this synthesis project are readily transferable to other research teams willing to engage in such a process.

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