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Review

The Socio-Ecological Factors that Influence the Adoption of Green Infrastructure

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Abstract: Green infrastructure is defined as any type of infrastructure that has the purpose of lessening the burden of development on the environment and/or has the aim of providing ecosystem services, such as runoff management, air temperature reduction, carbon sequestration, and habitat provisioning. Despite these potential benefits and a recent increase in popularity, the widespread use of green infrastructure has been limited. To ascertain why this may be the case, we asked: What are the socio-ecological factors that influence the adoption of green infrastructure? To answer this question, we carried out a review of the literature. We found 32 papers addressing our research topic, three quarters of which were published since 2009. Based on the results and conclusions of the articles we reviewed, we identify six factors that influence the adoption of green infrastructure: Education, the Provision of Ecosystem Services, Financial Incentives, Coordination Among Actors, Laws and Policies, and Planning Recommendations. We present a model of the direct and indirect effects of each factor on the adoption of green infrastructure and investigate the geographic variability of factors. Our results indicate that Education, the Provision of Ecosystem Services, and Financial Incentives are the most influential factors affecting the adoption of green infrastructure because they are supported by the greatest number of articles regardless of location of study and have the greatest number of linkages with other factors and adoption in our model. We conclude with evidence-based strategies to promote the use of green infrastructure in order to create more sustainable environments.

Keywords: green infrastructure; green building; social ecology

1. Introduction

The use of green infrastructure is considered vital to sustainability [1–3]. Large magnitudes of human-transformed energy and material are funneled through human-dominated areas. For example, the built environment consumes more than 30% of all energy in the United States [4]. The use of green infrastructure is a means by which natural patterns and processes can be restored and energy and material fluxes reduced in these areas. Many types of buildings and landscape designs that lessen the impact of human development on the environment and improve resource use efficiency qualify as green infrastructure [5]. Examples include green roofs, green alleys, greenways, bioretention ponds, and porous pavement.

Green infrastructure provides a broad variety of ecosystem services [6,7]. These include water management and quality improvement, air temperature reduction, improved energy use efficiency, air pollution and carbon sequestration, noise reduction, habitat provisioning, the provision of recreational and educational opportunities, food production, and aesthetic improvement of the built environment. For example, green roofs retain between 5% and 100% of rainfall, depending on rain event size and duration and green roof design and age [8]. Also, bioretention basins, small vegetated depressions engineered to capture and filter stormwater, host a greater diversity of ground-dwelling invertebrates than do lawns and garden beds in Melbourne, Australia [9].

Despite these potential benefits and a recent increase in popularity, the widespread use of green infrastructure has been limited. For instance, although the number of green buildings that actively sought third party certification in the United States increased from a handful in 2000 to over 5000 in 2006 [10], the number of traditional buildings that have been constructed in the U.S. during that time period is exponentially larger (approximately 9.2 million single-family homes between 1999 and 2007 [11,12] and 800,000 commercial buildings between 1999 and 2008 [13]). Considering this and the large projected increase in development over the coming decades—e.g., by 2030, half of the American built environment will have been constructed since the turn of the century [14]—research on the factors and strategies that promote the use of green infrastructure is critically needed to increase the representation of green infrastructure in existing and future development.

At the present time, our understanding of such factors and strategies is wanting [15]. Case studies have identified barriers to the implementation of green infrastructure, such as budgetary constraints, the absence of coordination between non-profit organizations and government agencies, lack of social acceptance, and lack of knowledge of the ecological processes underlying ecosystem service provisioning by green infrastructure [15,16]. This work has largely focused upon specific green infrastructure applications, such as green building [17], in specific locations. Although contextual understanding of the use of green infrastructure is necessary, a review of factors that generally influence the adoption of green infrastructure is needed to advance systemic understanding and to identify strategies that are broadly applicable. In addition, few studies examine the linkages between social and ecological factors affecting adoption [18], despite the recognition that strong ties between ecological and social factors are critical to successful implementation of green infrastructure [19].

The objective of the present work was to review the primary literature in order to identify the social and ecological factors that influence the adoption of green infrastructure. Based on the results of 32 studies, we identified six major factors. We present a model of the direct and indirect effects of each factor on the adoption of green infrastructure and investigate the geographic variability of factors among continents and economic regions of study. We conclude with suggested strategies, derived from what we found to be the most influential factors, which are intended to promote the widespread use of green infrastructure in order to create more sustainable environments.

2. Materials and Methods

We searched for articles that described the socio-ecological factors that influence the adoption of green infrastructure in the University of North Carolina at Charlotte's J. Murrey Atkins Library database and the Science Direct database between September 2012 and March 2013. We used the search terms *green infrastructure*, *sustainability*, *factors influencing the adoption of green infrastructure*, *socioeconomic factors*, *green roofs*, *vegetated swales*, *porous pavement*, *green policy*, *sustainable policies*, *environmental policy*, *factors influencing green infrastructure*, *green innovation*, *urbanization environmental aspects*, and *benefits of green infrastructure* to find articles. Each keyword or clause was bracketed with quotation marks to increase the accuracy of search results.

We used several criteria to select articles from the list that resulted from our search. First, we considered only scholarly, peer-reviewed articles published in academic journals. Second, we selected only articles that used the term *green infrastructure* in concordance with the following broad definition: any type of infrastructure that has the purpose of lessening the burden of development on the environment [5] and/or has the aim of providing environmental benefits or ecosystem services. We chose this broad definition, rather than a more specific one (e.g., [20]), to encompass the multiple meanings of the term as used in the literature [18,21]. There is currently no consensus on a single, precise definition of green infrastructure and the use of term continues to evolve, resulting in unavoidable ambiguity [22,23]. Our use of a broad definition of green infrastructure is thus in keeping with praxis and avoids the possibility of omitting otherwise pertinent articles from our review.

Finally, we limited our selection of articles to those that included information on commercial and public buildings. A different suite of factors likely motivates the adoption of green infrastructure by private homeowners than by commercial or public entities.

Of the articles that conformed to these criteria, we selected those that addressed our research topic, either directly or indirectly. The final selection of articles included articles that described research that explicitly investigated the factors underlying the adoption of green infrastructure or the political and economic reasons limiting the use of green infrastructure, articles in which the primary research focus was the investigation of the environmental impacts of green infrastructure, and articles that included recommendations for the use of green infrastructure in future projects in their conclusions.

We collected the following information from each article: the year the article was published, the location of the study, the type(s) of green infrastructure studied, the objective(s) of the study, and a summary of the study's results and conclusions as they pertained to our research topic. We synthesized the results and conclusions of all of the articles into a discrete set of factors that influence the adoption of green infrastructure and assigned one or more factors to each article based on the article's findings. We also made note of relationships among factors described by authors. We used this information to devise a model of hypothesized interactions among factors and the adoption of green infrastructure.

3. Results

We found 32 articles published between 1995 and 2013 that described the social and ecological factors that affect the adoption of green infrastructure (Figure 1, Table 1). Approximately three-quarters of articles were published in 2010 or later (Figure 1). The objectives of the majority of articles can be grouped into: (1) the development of conceptual or operational frameworks for systemic understanding of green infrastructure use and innovation [23–28]; (2) the investigation of factors, such as policy or planning instruments and the action of stewardship groups, that influence the use and performance of green infrastructure and innovation in the field [16,17,19,29–36]; and (3) the assessment of the performance of green infrastructure in providing ecosystem services [25,37–49] (Table 1). Exceptions to this grouping include two articles that described the spatial diffusion of green infrastructure technology [4] or defined sustainability and examined its underlying principles [50]. With the exception of articles that did not examine specific types of green infrastructure (31% of articles), the most common type of green infrastructure focused upon in articles was the green roof (36% of types in articles), followed by greenspace (e.g., greenways) (24% of types) and green building technologies (16% of types) (Table 1).

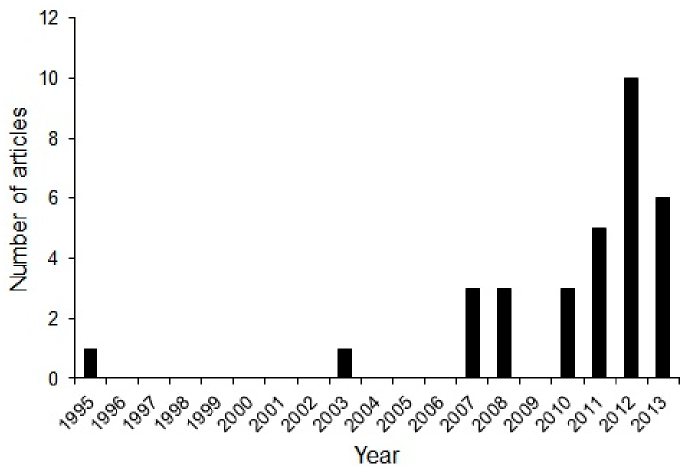

Figure 1. The number of articles that describe socio-ecological factors that influence the adoption of green infrastructure published per year.

Table 1. Articles that describe the socio-ecological factors that influence the adoption of green infrastructure. LEED: Leadership in Energy and Environmental Design.

Number	Citation	Study Objectives	Location(s)	Type(s) of Green Infrastructure	Summary of Results and Conclusions	Socio-Ecological Factor(s)
1	Connolly et al., 2013	Investigate the role of stewardship groups as bridges between public agencies and other civic organizations working to manage urban ecosystems	New York, NY, USA	Sites that provide ecosystem services	The best way to reach the common goal of providing more ecosystem services to the city is to encourage different organizations to work together	Provision of Ecosystem Services, Coordination Among Actors
2	Ellis, 2013	Develop alternative approaches to sustainable surface water management	United Kingdom	Riparian corridors, green roofs, street greening	The inclusion of green infrastructure in planning is needed	Planning Recommendations
3	Newell et al., 2013	Analyze alley greening programs to determine their environmental benefits	USA: Chicago, IL, Baltimore, MD, Los Angeles, CA, Dubuque, IA, Richmond, VA, Seattle, WA, Washington, D.C.	Green alleys	Most programs are not administered by the government, which could be an explanation for the lack of funding; stormwater management is a common project focus because funding is available to address this issue	Provision of Ecosystem Services, Laws and Policies, Financial Incentives
4	Solecki et al., 2013	Examine the components of urbanization that place stress on the environment and their interrelationships in order to identify solutions to environmental issues	Unspecified	All	Policy-makers at multiple levels of governance must have similar goals in order to reduce the negative effects of urbanization on the environment	Laws and Policies, Coordination Among Actors
5	Talberth et al., 2013	Develop a methodology for green-gray analysis	USA: Oregon, Maine, Pennsylvania	All	Higher initial cost of green infrastructure precludes its use, particularly when funding is limited; project portfolios that highlight the benefits of green infrastructure are needed because the benefits of green infrastructure are not as widely known as those of gray infrastructure	Financial Incentives, Provision of Ecosystem Services, Education
6	Young & McPherson, 2013	Explore whether stakeholders believe efforts to expand urban ecosystem services through tree planting initiatives are planned and executed as a component of municipal governance or represent new transdisciplinary strategies in metropolitan regions	USA: New York, NY, Sacramento, CA, Denver, CO, Houston, TX, Salt Lake Country, NV, Los Angeles, CA	Urban forests	Tree planting initiatives are largely driven by the public, not the private, sector	Laws and Policies
7	Allen, 2012	Construct a multi-scale operational framework for green infrastructure	United States	All	A seamless quilt of planning and implementation is needed across scales; the involvement of a variety of actors in planning is also needed	Coordination Among Actors, Planning Recommendations

Table 1. *Cont.*

Number	Citation	Study Objectives	Location(s)	Type(s) of Green Infrastructure	Summary of Results and Conclusions	Socio-Ecological Factor(s)
8	Bianchini & Hewage, 2012	Determine the economic and environmental benefits of green roofs using a lifecycle net cost-benefit analysis	Canada	Green roofs	Green technology research and development is needed to improve performance, as well as to demonstrate the benefits that green roofs can provide and familiarize people with these benefits	Provision of Ecosystem Services, Education
9	Kim et al., 2012	Determine the effectiveness of roadside bioretention facilities at reducing runoff and pollution	Texas, USA	Bioretention facilities	Bioretention facilities are a cost-effective method to mitigate pollution and runoff; knowledge of the benefits provided by bioretention facilities will help encourage their use	Provision of Ecosystem Services, Financial Incentives, Education
10	Ezeah & Roberts, 2012	Identify the failures and successes of a newly-implemented solid waste program	Abuja, Nigeria	Sustainable waste management	A sustained public education program on waste prevention and reuse is needed; four main categories of barriers were found: natural/physical (physical site characteristics), socio-economic (availability of funding), operational (lack of properly functioning equipment), and institutional/regulatory (public or private requirements)	Education, Provision of Ecosystem Services, Financial Incentives, Laws and Policies
11	Gauthier & Wooldridge, 2012	Compare alternative hypotheses of the reasons why firms choose sustainable building design	United States	Green building techniques	Green building is positively influenced by a political leadership that is committed to environmental protection; uncertain financial benefits may limit adoption	Laws and Policies, Financial Incentives
12	Ksiazek et al., 2012	Determine whether pollination services on green roofs are sufficient to support green roof plant populations	Chicago, IL, USA	Green roofs	Awareness of the pollination services on green roofs is important because it will foster the identification and commercialization of plant species that are low-maintenance because they are supported by the pollinator community that is present	Education
13	Markard et al., 2012	Review conceptual frameworks for sustainability transitions and assess the emergence of the field	International	All	Educating a variety of different groups about the benefits of green infrastructure will positively influence adoption	Education

Table 1. *Cont.*

Number	Citation	Study Objectives	Location(s)	Type(s) of Green Infrastructure	Summary of Results and Conclusions	Socio-Ecological Factor(s)
14	Schäffler & Swilling, 2013	Determine the importance of planning to the use of green infrastructure	Johannesburg, South Africa	Urban forests	Knowledge of the ecosystem services provided by green infrastructure is critical to designing sustainable cities; city officials, environmental groups, and citizens need to work together to successfully implement green infrastructure; it is imperative that municipal budgeting, accounting, and asset management processes be redesigned to better accommodate green infrastructure projects	Education, Coordination Among Actors, Financial Incentives
15	Veugelers, 2012	Determine how private clean innovation can be stimulated by green mission-oriented government policy	Japan, Germany, Korea, France, United States, United Kingdom	All	Government intervention is needed to provide private actors with incentives and funding; lack of a single definition of clean technology hinders innovation	Laws and Policies, Financial Incentives
16	Zhang et al., 2012	Evaluate the economic benefits of runoff reduction by urban greenspaces	Beijing, China	Greenspace	The lack of information on the magnitude and economic value of ecosystem services has hindered recognition of the environmental benefits that greenspaces provide; policies could be used to encourage optimal design	Provision of Ecosystem Services, Education, Financial Incentives, Laws and Policies
17	Chapple et al., 2011	Assess the application of traditional economic development models to innovation in the green economy	California, USA	All	Firms that are not environmentally conscious are the most likely to innovate (because of the need to change); research and development results in innovation and eventually widespread implementation	Provision of Ecosystem Services
18	Johansson, 2011	Assess the spatial diffusion of green building techniques	United States	Practices that contribute LEED points	The Pacific Coast and New England are the epicenters of green building; techniques can be expected to spread inland; awareness and familiarity due to proximity to epicenters play a large role in green infrastructure adoption	Education
19	Rowe, 2011	Review pollution mitigation by green roofs	USA: Illinois, Michigan, North Carolina, California, Pennsylvania; Sweden; Estonia; Canada	Green roofs	Interdisciplinary coordination during the design and construction phases is necessary to ensure the provision of multiple ecosystem services; the valuation of services, particularly public health benefits and water quality improvement, will reduce the cost gap between green and conventional roofs	Coordination Among Actors, Provision of Ecosystem Services, Financial Incentives

Table 1. *Cont.*

Number	Citation	Study Objectives	Location(s)	Type(s) of Green Infrastructure	Summary of Results and Conclusions	Socio-Ecological Factor(s)
20	Van Shaack & BenDor, 2011	Analyze factors that influence the adoption of green building techniques in rural, transitioning, and urban counties	North Carolina, USA	LEED-certified buildings and green building techniques	Active local governments, forward-thinking educational institutions, active advocacy groups, and knowledgeable industry leaders are main factors that contribute to the adoption of green infrastructure; factors are more likely to be found in urban centers, and therefore nearby transitioning counties are more likely to adopt green infrastructure than more isolated rural counties	Education, Coordination Among Actors
21	Vandermeulen et al., 2011	Develop an economic valuation model for green infrastructure investments	Belgium	Greenways	Economic valuation can be used to convince stakeholders from a variety of disciplines to work towards the adoption of green infrastructure; investing in green infrastructure creates greater public support for policy actions to promote its use	Financial Incentives, Coordination Among Actors, Education, Laws and Policies
22	Dapolito Dunn, 2010	Demonstrate the benefits of green infrastructure for the urban poor and delineate strategies to promote the use of green infrastructure in lower income areas in order to provide utility cost savings and aesthetic improvement	USA: Seattle, WA, New York, NY, Stamford, CT, Portland, OR, Philadelphia, PA, Columbus, OH, Chicago, IL, California, Michigan, North Carolina, New Jersey	Permeable pavement, rain barrels, green roofs	The exceptional environmental benefits of green infrastructure are not highlighted frequently enough; decision-makers are possibly unaware of benefits; legal structures must be put in place to increase use	Provision of Ecosystem Services, Education, Laws and Policies
23	Smith et al., 2010	Review innovation studies and their multi-level perspectives on socio-technological transitions	International	All	A broad, interdisciplinary approach is needed to tackle sustainability issues	Coordination Among Actors
24	Thomas & Littlewood, 2010	Track progress of green infrastructure in relation to emerging strategies for spatial and economic planning to determine if green infrastructure can provide positive benefits to communities	England	All	Green infrastructure should be incorporated into local plans	Planning Recommendations
25	Carter & Fowler, 2008	Evaluate existing international and national green roof policies at a range of administrative levels	USA: Portland, OR, Chicago, IL, Minneapolis, MN, Athens, GA, Tennessee, North Carolina, Michigan, Iowa, Idaho, Washington, D.C.; Toronto, Canada; Linz, Austria; Tokyo, Japan; Basel, Switzerland; Berlin, Germany; Malmo, Sweden	Green roofs	Federal policies will positively influence the availability of funding; the incorporation of locally-gathered data on green roof performance into policy recommendations is needed because it will help decision-makers understand the benefits that green infrastructure can provide	Laws and Policies, Financial Incentives, Provision of Ecosystem Services, Planning Recommendations, Education

Table 1. *Cont.*

Number	Citation	Study Objectives	Location(s)	Type(s) of Green Infrastructure	Summary of Results and Conclusions	Socio-Ecological Factor(s)
26	Schilling & Logan, 2008	Develop strategies to convert vacant areas to green infrastructure in shrinking cities	USA: Pennsylvania, Massachusetts, New York, Maryland; Toronto, Canada	Greenspace	The conversion to green infrastructure requires the collaboration of academics, practitioners, and policy-makers; research and data on the benefits of green infrastructure are needed by policy-makers to familiarize various groups about the benefits green infrastructure can provide	Coordination Among Actors, Provision of Ecosystem Services, Education
27	Yang et al., 2008	Quantify air pollution reduction by green roofs	Chicago, IL, USA	Green roofs	Green roofs are often not considered as viable alternatives to conventional roofs because their long-term benefits are not widely known; industry standardization and a procedural guide for installation would reduce initial construction costs	Education, Provision of Ecosystem Services, Financial Incentives
28	Kosareo & Ries, 2007	Compare the lifecycle costs and benefits of green and conventional roofs	Pittsburgh, PA	Green roofs	Energy cost savings and a longer lifespan make green roofs the environmentally preferable choice and a better long-term financial investment compared to conventional roofs	Provision of Ecosystem Services, Financial Incentives
29	May & Koski, 2007	Examine state choices to adopt green building mandates and the form of their policy statements	USA: New York, New Jersey, Maine, California, Arizona, Michigan, Colorado, Rhode Island, New Mexico, Oregon, Washington, Maryland, Nevada, Pennsylvania, Arkansas	LEED-certified buildings and green building techniques	Bureaucratic presence is especially important because the use of green building practices is an issue of low salience	Laws and Policies
30	Tzoulas et al., 2007	Formulate a conceptual framework of associations between human and ecosystem health and urban greenspaces	International	All	Various groups, such as urban nature conservationists, environmental psychologists, and public health specialists should work together to encourage the adoption of green infrastructure and improve urban environments	Coordination Among Actors
31	Wong et al., 2003	Compare the lifecycle costs and benefits of green and conventional roofs	Singapore	Green roofs	Energy cost savings and runoff reduction provided by green roofs make them a better financial and environmental investment over time than conventional roofs	Provision of Ecosystem Services, Financial Incentives
32	Basiago, 1995	Define the term 'sustainability' and examine the principles underlying it	International	All	Coordination among government agencies, private parties, and environmental decision-makers is necessary to enable sustainable practices to become more commonplace	Coordination Among Actors

We identified six major factors that influence the adoption of green infrastructure: Education, Provision of Ecosystem Services, Financial Incentives, Coordination Among Actors, Laws and Policies, and Planning Recommendations (Table 1). Education and Provision of Ecosystem Services were each supported by the conclusions of 15 articles; Financial Incentives was supported by the conclusions of 14 articles; Coordination Among Actors and Laws and Policies were each supported by 11 articles; and the factor Planning Recommendations was discussed in four articles. The factor Education refers to awareness, knowledge, and understanding of the types and uses of green infrastructure, including the ecosystem services it provides, by the general public, stakeholders, and policy- and decision-makers. We classified studies as supporting the factor Provision of Ecosystem Services if they simply described the services provided by green infrastructure, compared the performance of green infrastructure to the performance of traditional infrastructure, and/or identified the need for additional research, technological development, and data collection related to the ecosystem services provided by green infrastructure. Financial Incentives includes both direct, such as grants and subsidies, and indirect, such as energy cost savings, incentives. Coordination Among Actors describes the collaboration of public and private entities and individuals at a variety of scales, from the national to the local. Laws and Policies are instruments that are mandatory and can be enforced whereas Planning Recommendations are used to encourage, rather than mandate, the use of green infrastructure.

In our hypothesized model of interactions among factors and the adoption of green infrastructure, factors may influence adoption in direct (arrows 1–6 in Figure 2) and indirect (arrows 7–17 in Figure 2) ways. In our model, Education has the greatest number of connections with other factors and adoption (10 incoming and outgoing arrows). First, a feedback relationship exists between Education and adoption (arrow 1). The use of green infrastructure in an area positively influences awareness among the general public, stakeholders, and policy- and decision-makers. This awareness and a deeper knowledge and understanding of green infrastructure may indirectly influence adoption through the creation of Laws and Policies (arrows 7 and 5), Planning Recommendations (arrows 8 and 6), and/or Financial Incentives (arrows 9 and 2). Awareness, knowledge, and understanding of green infrastructure in different groups may facilitate Coordination Among Actors (arrow 10) whereas formal undergraduate and graduate programs function to promote technological innovation in green infrastructure, which positively affects the Provision of Ecosystem Services (arrow 11). Financial Incentives, Coordination Among Actors, and the Provision of Ecosystem Services feedback to Education (arrows 9–11) by means of grants and financial aid to faculty and/or students, knowledge diffusion among groups in a coordinated network, and improved knowledge and understanding resulting from research on and development of the ecosystem services provided by green infrastructure, respectively.

Financial Incentives has the second greatest number of connections (7) in our model, followed by Planning Recommendations (6 connections), Laws and Policies and Coordination Among Actors (5 connections each), and the Provision of Ecosystem Services (4 connections) (Figure 2). In addition to the interaction mentioned above (arrow 9), Financial Incentives may be influenced by Laws and Policies (arrow 12) and the Provision of Ecosystem Services (arrow 13) and has a feedback relationship with Planning Recommendations (arrow 14). Legislated grant, subsidy, or loan programs positively affect the adoption of green infrastructure. The Provision of Ecosystem Services by green infrastructure creates indirect Financial Incentives such as a reduction in building heating and cooling expenses. The inclusion of indirect financial gains, such as credits for stormwater utility fees, in Planning Recommendations positively influences adoption whereas Financial Incentives with the aim of promoting the use of green infrastructure by municipal governments may affect the creation of Planning Recommendations. Other relationships in our model include the positive impact of the Coordination Among Actors on the creation of Laws and Policies (arrow 15) and Planning Recommendations (arrow 16) and the influence of Laws and Policies on the development of Planning Recommendations (arrow 17).

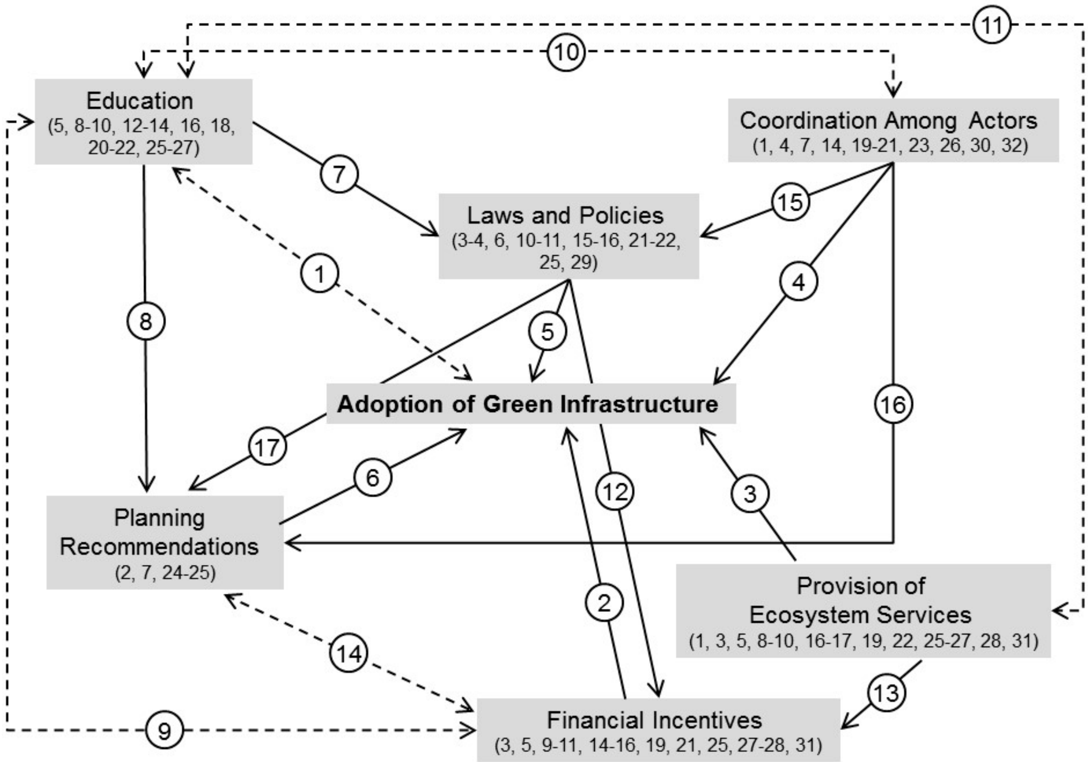

Figure 2. The socio-ecological factors that influence the adoption of green infrastructure. Hypothesized direct and indirect relationships between factors and the adoption of green infrastructure are indicated with numbered arrows. Dashed arrows represent two-way relationships and solid arrows represent one-way relationships. Numbers in parentheses under factors refer to the articles listed in Table 1.

Several patterns are apparent in the geographical distribution of studies and the associated factors that they support (Figure 3). The projects referenced in articles were located on the North American, European, African, and Asian continents (Figure 3a). Education, Coordination Among Actors, and Financial Incentives were most commonly discussed in articles originating in Africa whereas Laws and Policies and Planning Recommendations were predominantly discussed in European articles and the Provision of Ecosystems Services was predominantly discussed in North American articles. With the exception of North America, Financial Incentives was the most commonly discussed factor in articles from all continents studied. In Africa, Financial Incentives and Education were discussed in equal proportion. In North America, the Provision of Ecosystem Services was the dominant factor discussed in articles, followed by Education and Financial Incentives.

The grouping of continental locations into developing and developed regions revealed that Financial Incentives was more commonly discussed in articles from developing regions whereas Education, the Provision of Ecosystem Services, Coordination Among Actors, and Planning Recommendations were more commonly discussed in articles from developed regions (Figure 3b). In order of decreasing prevalence, Financial Incentives and Laws and Policies, the Provision of Ecosystem Services, and Education, which were equally prevalent, were the most common factors described by articles from developing regions whereas the Provision of Ecosystem Services, Financial Incentives, and Education were the most common factors described by articles from developed regions.

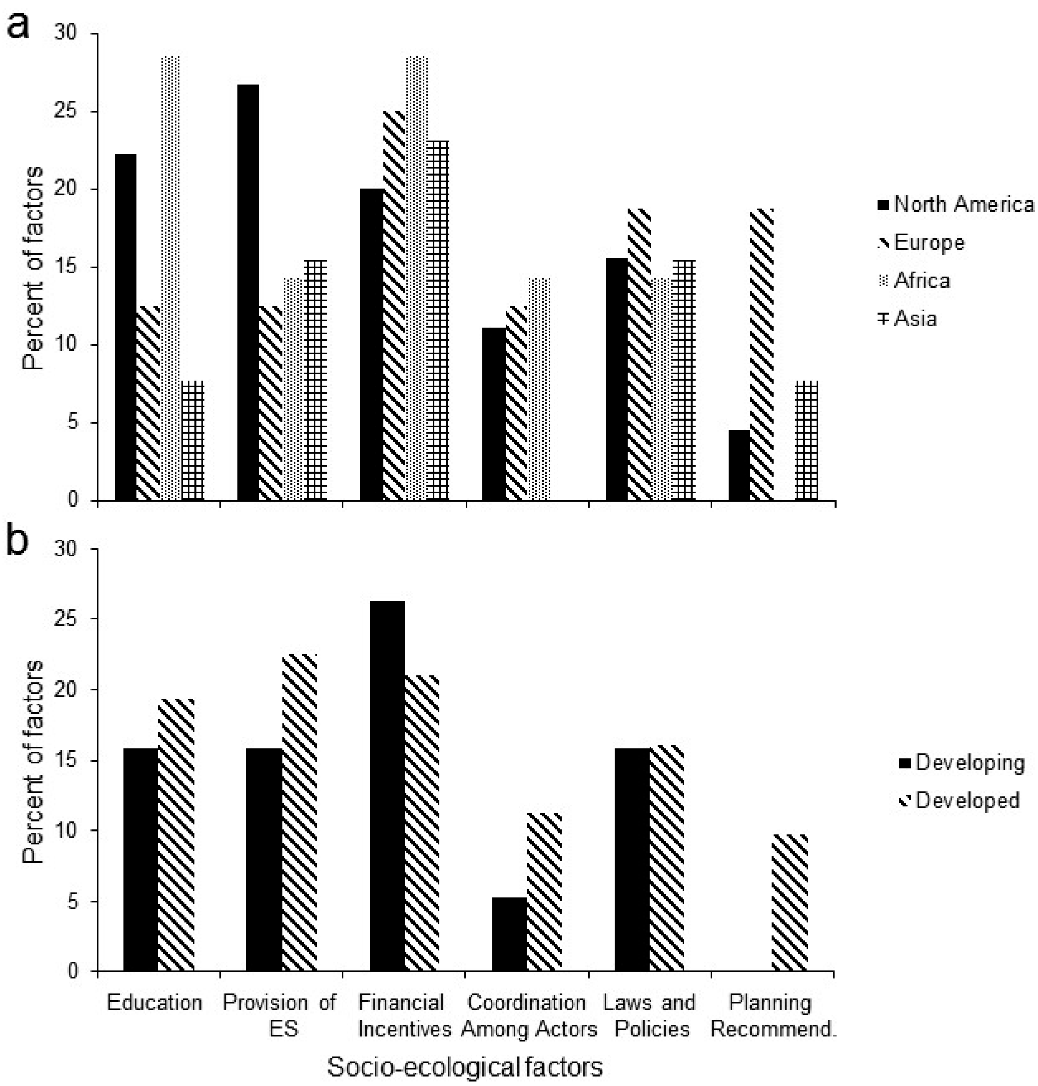

Figure 3. The percentage of the total number of socio-ecological factors that influence the adoption of green infrastructure discussed in articles represented by each factor with respect to study locations. (**a**) The percentages of factors discussed in articles from different continents; (**b**) The percentages of factors discussed in articles from different economic regions. The developing region category includes locations in Africa and Asia excluding Japan and the developed region category includes locations in North America, Europe, and Japan. ES: ecosystem services.

4. Discussion

Our review of the literature indicated that Education, the Provision of Ecosystem Services, and Financial Incentives are the most important factors influencing the adoption of green infrastructure. The importance of these three factors is supported by the fact that most of the articles that we reviewed concluded that they affected the use of green infrastructure; in the case of Education and Financial Incentives, their large number of connections in our model of adoption (Figure 2); and their dominance, in terms of the proportion of articles supporting them, regardless of the continental location or the economic development of the region of study (Figure 3). Other factors that were consistently discussed in the articles we reviewed were Coordination Among Actors, Laws and Policies, and, less frequently, Planning Recommendations.

The influence of Education on the adoption of green infrastructure may be mediated by location. Johansson [4] concluded that location played a large role in the adoption of Leadership in Energy and Environmental Design (LEED) practices. Regions bordering the Pacific Coast and New England, which are epicenters of environmental innovation in the USA, were more likely to be characterized by concern for the environment and to incorporate green building techniques in development practices. Similarly, Van Shaack and BenDor [17] concluded that counties neighboring urbanized areas, where the use of green infrastructure was common, and transitioning from rural to urban were more likely to make use of green infrastructure than more isolated counties.

This diffusion effect may translate directly or indirectly into the implementation of green infrastructure. Directly, the general public and stakeholders, including developers, may make use of green infrastructure simply because they are aware of and familiar with it. Indirectly, awareness of and familiarity with green infrastructure can influence public support and/or the attitudes of policy- and decision-makers, with consequences for the creation of Laws and Policies and Planning Recommendations. In our review, a general lack of knowledge among decision-makers of the different types of green infrastructure and their uses and benefits was found to be one of the main reasons for the lack of green infrastructure projects [44]. Awareness and a deeper knowledge and understanding of green infrastructure also influence the amount and type (direct or indirect) of Financial Incentives because the performance and benefits of green infrastructure must be known before incentives are provided. For example, in Minneapolis, USA, the stormwater fee is waived if a building has a green roof because significant runoff reduction is a widely known environmental benefit of green roofs [17].

Interestingly, Education is the only factor that we think has a feedback relationship with the adoption of green infrastructure (arrow 1 in Figure 2). Vandermeulen et al. [35] reported that investment in green infrastructure creates greater public support for policy actions that promote its use. Also, in a survey we carried out of facility managers, marketing directors, and owners of buildings with green roofs in Charlotte, USA, educational purposes was reported as the primary reason for the installation of a green roof instead of a conventional roof on a respondent's building [51]. This positive feedback is also evident in the diffusion effect we described above.

The set of articles we reviewed contained several that concluded that the ecosystem services provided by green infrastructure were a major factor influencing adoption. The lifecycle and cost-benefit analyses included in our selection of articles considered the environmental benefits that green infrastructure provides to be a major reason underlying its use [40,46]. In Los Angeles, CA, USA, a green alley program was implemented to mitigate excessive urban runoff and high air temperatures associated with the urban heat island effect and to improve city aesthetics [42]. The latter is a service that was also sought after by two-thirds of the respondents to our survey in Charlotte [51]. Other services provided by green infrastructure that may influence adoption include the removal of harmful pollutants from the air, a reduction in ambient noise levels, improved runoff quality, and a reduction in the amount of roofing materials in landfills [43,47]. In Charlotte, the respondents to our survey listed temperature reduction and stormwater management as the most desired ecosystem services provided by green roofs, followed by aesthetic improvement, noise reduction, pollution filtration, and the increased productivity of building occupants [51].

However, there is little empirical information about the magnitude of ecosystem services provided by green infrastructure and the design considerations that maximize green infrastructure performance in providing services [15]. In our review, Schilling and Logan [16] concluded that policy-makers need better data and more research in order to include green infrastructure in policy and planning reform. In Charlotte, two thirds of respondents reported plant death as a major maintenance issue on their green roofs, followed by the spread of weedy species and irrigation system difficulties [51], problems that significantly affect the performance of ecosystem service provisioning by the roofs. Pataki et al. [15] suggest that the lack of empirical information of the effectiveness of ecosystem service provisioning by green infrastructure in different biophysical and socio-political contexts is a significant impediment to adoption. As is the case with the choice of green roof plants in Charlotte, the assumed benefits of green infrastructure may not necessarily be realized in untested contexts and/or may be outweighed by unexpected costs or disservices (e.g., maintenance in the form of weeding and irrigation). In order to promote adoption, Pataki et al. [15] call for the quantification of the net effectiveness, i.e., taking into account trade-offs between ecosystem services and disservices, of specific green infrastructure applications using multiple services as decision-support criteria.

Direct and indirect Financial Incentives are likely one of the most influential factors leading to the adoption of green infrastructure because profits and cost savings are some of the main considerations for any new project, especially in its early stages. Direct financial incentives originate from public and private entities and occur at a range of scales. For example, in 2005, the City of Chicago, USA implemented a competitive grant program with the aim of encouraging the construction of green roofs that distributed $100,000 to 20 projects [29]. Indirect financial incentives are more common than direct financial incentives and therefore likely represent a stronger motivating force underlying adoption. Yang et al. [47] found that the energy cost savings associated with green roofs strongly influenced decision-makers to choose green roofing over conventional roofing. In addition, two-thirds of the respondents to our survey in Charlotte stated that indirect financial incentives, such as energy cost savings, were the factor that most influenced their decision to use a green roof rather than a conventional roof on their building [51]. The lifecycle analyses included in our selection of articles concluded that, over time, green infrastructure is a more cost-efficient approach than gray infrastructure [40,46]. In some cases, green infrastructure initially costs less than traditional infrastructure. This is the case with bioretention facilities which are a less expensive alternative to traditional pipe systems used to manage runoff and reduce pollution [38]. In other cases, green infrastructure is initially more expensive and savings are realized over the life span of the technology [19]. For example, the typical lifespan for a green roof is 40–55 years whereas a conventional roof is expected to last roughly 20 years [37]. The ecosystem services provided by green infrastructure also function as an indirect financial incentive when they are translated into monetary terms. In Philadelphia, USA, the net value of stormwater control by green infrastructure over a 40-year period is between $1.94 and $4.45 billion, about 30 times more than for gray infrastructure, valued at $0.06–$0.14 billion [44].

However, the difficulty in economically valuing the ecosystem services provided by green infrastructure and the often long time frame over which savings from the use of green infrastructure accrue remain significant barriers to adoption. Zhang et al. [49] concluded that the lack of economic quantification of services such as runoff reduction has significantly limited awareness and understanding of the benefits derived from urban greenspaces and their management in Beijing, China. As mentioned earlier, in some cases savings due to the use of green infrastructure are the result of its longer life span compared to traditional infrastructure (despite its initially higher cost). However, these savings may or may not be taken into account in deciding whether to use green infrastructure in a particular project. In Charlotte, a major indirect financial incentive that motivated one respondent to choose green roofing was the longer life span of green roofs compared to conventional roofs and the consequent reduction in roof replacement costs over time [51]. However, others considering using green infrastructure may discount long-term savings and prioritize higher initial costs in their decision-making process because they will not be present when savings are realized. For instance, a housing developer would likely consider only initial construction costs as a factor influencing their choice of infrastructure.

Partially due to the fact that green infrastructure itself is a blend of the natural and built environments, it is important to take an interdisciplinary approach and ensure that there is coordination among actors when implementing green infrastructure. Tzoulas et al. [28] concluded that the successful implementation of green infrastructure requires that urban planners, developers, politicians, and scientists participate in a collaborative process that articulates the linkages between the ecological and social systems that exist in urban areas and are affected by city planning and design. Collaborative efforts enable the necessary mix of knowledge, power, and location and can unite individual stakeholders and interest groups that have insignificant influence acting alone. Over and above the benefits of collaboration itself, coordination may be enhanced by the presence of key actors in networks. For example, leadership by non-profit umbrella organizations that link smaller groups with public and private funding and provide administrative, training, and advocacy services to smaller groups has been identified as a significant feature in successful green infrastructure programs [16]. This may be because such organizations act as bridge organizations by interacting with a large number of other organizations and occupying structurally important positions in networks [30]. In particular, the role of bridge organizations as intermediaries between public agencies and community groups builds multi-scale capacity into networks that is deemed necessary for the adoption of green infrastructure [17,23,30].

Laws and policies play a significant role in the adoption of green infrastructure because they mandate the inclusion of green infrastructure in planning and design. For example, in Toronto, Canada, all new city-owned buildings must have 50%–75% of the building footprint covered by a green roof [29]. In Basel, Switzerland, all new roofs over 500 m^2 must be green [29]. In Minneapolis, there is a zoning ordinance which requires that greenspace compose a certain percentage of a property. Interestingly, the ordinance has promoted the use of green roofs since these satisfy the requirement for greenspace and their use allows for the entirety of a property to be built up [29].

Planning Recommendations influence the adoption of green infrastructure in a similar fashion to Laws and Policies, with the exception that they cannot be legally enforced. Ellis [31] concluded that there is a need to incorporate green infrastructure into planning because it will help encourage a focus on sustainable, green practices. In fact, cities are increasingly including recommendations and suggestions about green infrastructure and greenspace in their comprehensive plans [29]. For example, the City of Portland, USA's recent Grey to Green initiative invested in the creation and maintenance of numerous green roofs, green streets, and natural areas to help mitigate a variety of environmental issues ranging from air pollution to excessive runoff [52].

A lack of standardization in industry practices and a lack of prescription in laws and policies represent potential barriers to the adoption of green infrastructure. Yang et al. [47] suggested that industry standardization would reduce the initial construction costs of green roofs, making them a more attractive option to potential users, and Veugelers [36] concluded that the lack of a single definition of clean technology hinders innovation in the field. A lack of prescription in laws and policies can significantly hinder their effectiveness because it may create loopholes by which compliance can be avoided. For example, in Portland, the green roof policy states that "all new city-owned facilities must include a green roof with 70% coverage when practical" [29]. The clause 'when practical' is not specifically defined by the city and is open to interpretation, thus reducing the likelihood of implementation of the policy.

The importance of factors affecting the adoption of green infrastructure appears to differ among continents and regions characterized by varying social, political, and economic structures (Figure 3). The Provision of Ecosystem Services, Education, Coordination Among Actors, and Planning Recommendations are more important factors in developed regions compared to developing regions. Also, the study areas of most of the articles citing Laws and Policies or Planning Recommendations were located in Europe. It may be that Laws and Policies and Planning Recommendations are particularly important in Europe and North America because they are necessary in order to incorporate green infrastructure into existing highly-developed political and administrative structures. If, in general, actions in developed regions are constrained by these structures, then any move to adopt green infrastructure must be translated into a law, policy, or recommendation that fits within the existing system. Education and Coordination Among Actors may be essential to the systemic incorporation of Laws and Policies and Planning Recommendations into existing structures. On the other hand, Financial Incentives are more important in developing than in developed regions, perhaps because they can exert strong direct influence on adoption in highly variable political and economic conditions. The focus on the Provision of Ecosystem Services in developed regions, particularly in North America, may reflect the emphasis on ecosystem services in the scientific community in those areas. Interestingly, Education, Coordination Among Actors, and Planning Recommendations were cited by very few of the articles that described projects in Asia. This may reflect the strong top-down structure of Asian societies. Finally, it is important to note that all of the differences in importance between regions and among continents discussed above are relative. In other words, the lesser importance of a factor in one region or continent compared to others does not mean that the factor is unimportant in that region or continent. In fact, the study of the contextual importance of factors affecting the adoption of green infrastructure deserves more explicit attention.

5. Conclusions

Our review represents an important early effort to synthesize current understanding of the social and ecological factors that influence the adoption of green infrastructure. We cast a wide net to find articles under the assumption that the field of green infrastructure studies is still very new and few articles might exist on any particular sub-topic (e.g., the role of political structures) or type of green infrastructure (e.g., green alleys). In fact, the majority of articles that we found were published in the last three years (Figure 1). This necessitates that a grain of salt be added to our results since the field is clearly in the early stages of emergence and development. However, we suggest that a synthesis at this point is important and necessary to identify evidence-to-date-based strategies to promote the adoption of green infrastructure and to suggest further avenues of inquiry by researchers and practitioners in the field.

Overall, Education, the Provision of Ecosystem Services, and Financial Incentives emerge as the most important factors influencing the adoption of green infrastructure, both directly and indirectly. We suggest that professional educators at all levels should incorporate material on green infrastructure, particularly with respect to the ecosystem services it provides, into their curricula. This suggestion also applies to professionals from non-profit organizations, which play an important role in public education, both by providing materials to teachers and in informing the general public. Government agencies at all levels should invest in public education programs, in advance of or in conjunction with any direct financial incentives for particular green infrastructure initiatives. Because of the positive feedback between adoption and education, any new green infrastructure project should incorporate a public education component to maximize the geographic spread of awareness and understanding. In addition to their educational efforts, public and private entities must prioritize green infrastructure in their budgets and funding decisions. Research and development funds should be made available to study the ecosystem services provided by green infrastructure, particularly those that result in indirect financial incentives. Research and development should also focus on maximizing the performance of green infrastructure in different bio-geographical and socio-political environments and the development of industry design and implementation standards and a standard methodology for ecosystem service valuation.

Finally, we call for a great many more studies that explicitly investigate the social and ecological conditions surrounding the use and performance of green infrastructure in various parts of the world, especially in developing regions experiencing high rates of urbanization. It is our hope that such an emphasis will significantly advance our understanding of how green infrastructure can be successfully implemented on a global scale.

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