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Directions in green roof research: A bibliometric study

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ABSTRACT

Green roof research is a multidisciplinary and new research area. We conducted a bibliometric quantification to assess the rate of publications in specific areas of research for this novel research area based on the scientific literature as available from the Web of Science. Bibliometric research can provide valuable information about changes in the trends within a particular area of research. For example, we found that the number of publications in this field increased in the last two decades at very similar pace to other pre-established academic disciplines. We also found that papers on green roofs were classified into 32 research areas. There was very little change in the frequency of most research areas through time. The percentages of plant sciences, forestry, marine and freshwater biology and biodiversity conservation of the total research areas classifications used each year increased significantly with time, while architecture decreased significantly with time signifying an increased interest in environmental issues and less focus on architectural issues. The distribution of publications between countries has been skewed, with the USA and the EU conducting 66% of the research, and thus allocation of research effort is focused in those continents and predominantly in temperate ecosystems. However, there has been a sharp increase in the number of countries that conduct green roof research. Our work provides a suite of indicators that can be combined to give a useful picture of the development of green roof research and identifies the challenges which lie ahead for this novel research area.

1. Introduction

The establishment of growing media and plants on the roofs of buildings has taken place since ancient times [1]. Greened roofs provide benefits far beyond the aesthetic aspect. They store rainfall, which delays runoff and promotes evapotranspiration [2]. During hot weather, green roofs reduce heat flux through the roof by evapotranspiration, physically shading the roof, and increasing the insulation and thermal mass, thereby lowering the energy demands of the building's cooling system [3–5]. They reduce pollutants such as carbon dioxide [6]. Green roof habitats show promise for providing local habitat that can support a diversity of flora and fauna [7–11]. However, it is only relatively recently that comprehensive research has been undertaken.

One of the driving forces behind the upsurge in green roof research is the need to provide a solid scientific knowledge to guide future sustainable urban design and management. Green roof research, as an interdisciplinary scientific effort, can play an active role with the integration of ideas, which are derived from a variety of disciplines, including engineering, biology, architecture and geography [12].

One way of monitoring the emergence of new fields is to examine the papers published on the topic. A more simple yet more comprehensive approach to understanding the growth of a field may be offered by bibliometric quantification [13] of a related specific term during a determined period of time. Bibliometric studies are an established tool, used to survey research areas and hundreds of such papers are already published in various fields such as Ecology [14],Medicine [15], Psychology [16] and Economics [17]. These studies synthesize existing knowledge to understand trends and understand where information may be lacking in the various fields. Using the ISI Web of Science to construct a database

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of all the papers published on green roofs in the last two decades, the objectives of this work were to (1) portray the change in the yearly rate of publication in green roofs research, (2) identify the most studied research areas in green roof research, (3) characterize some essential trends in green roof research in terms of research areas and studied systems, and (4) identify the challenges which lie ahead in green roof research. Compared to more established research areas, green roofs is a relatively young research area. However, research in this field is on-going in the last two decades and we believe that this bibliometric approach can provide a thorough and unbiased overview which will help in evaluating past directions and recognizing areas that have been overlooked.

2. Methods

We used the ISI Web of Science (http://www.isiknowledge.com) to search for peer-reviewed journal papers on green roofs. Specifically, we used the search terms "green roof*", "living roof*", gründach, "ecological roof*", "roof garden*", "turf roof*" and "sod roof*".

We searched the literature published on this database on green roofs to extract (1) the total number of publications listed each year, (2) the geographical locations of authors, and (3) research areas. Clarifying the geographical distribution of the authors allows us to categorize the climatic conditions and the ecosystems that papers are considering.

It is important to note that not all green roof research will be captured by the Web of Science. Research may be reported in websites, in languages other than English (e.g. there is an extensive literature in German starting from the early 1960s) and some conference proceedings or technical reports not indexed by the Web of Science. However, the peer-review process serves to some extent as a reasonable filter for rigorous scientific work.

A bibliographic database consisting of 300 references was produced in Endnote X2. In order to compare the yearly trend in the number of publications to another newly emerging field, we compared the trend we found for green roofs research to the trends for landscape ecology research, which is also an emerging field of research over recent decades [18,19]. A major and continuous growth in green roof research began in 1992. Therefore, we checked also the trend from 1993 to 2012 and in parallel, the corresponding trend of the first 20 years in landscape ecology research (1977–1996). We plotted the yearly change in the number of publications for these two disciplines and compared the slopes after fitting a linear trend line.

We also used the research areas categories provided by the Web of Science. These categories were assigned at the level of individual publication. Each publication can be assigned to more than one research area. For each year starting from 2001 (prior to this year, there were only one or two publications each year in green roof research) we recorded the number of articles assigned to each category. We used the country of affiliation of authors for assigning geographical distribution of papers.

For evaluating possible changes in the frequency of research areas over time, we used Spearman rank correlation coefficient [20], a non-parametric measure of correlation. It was used here to test the strength and direction of the relationship between the frequency of a research area and time. $P < 0.05$ was considered statistically significant.

3. Results

Publications on green roofs appeared only sporadically in the late 1960s and during the 1970s (Fig. 1). Until 1992 only four publications were listed by ISI. The number of papers steadily increased from the early 90 s, reaching 74 papers published in 2012.

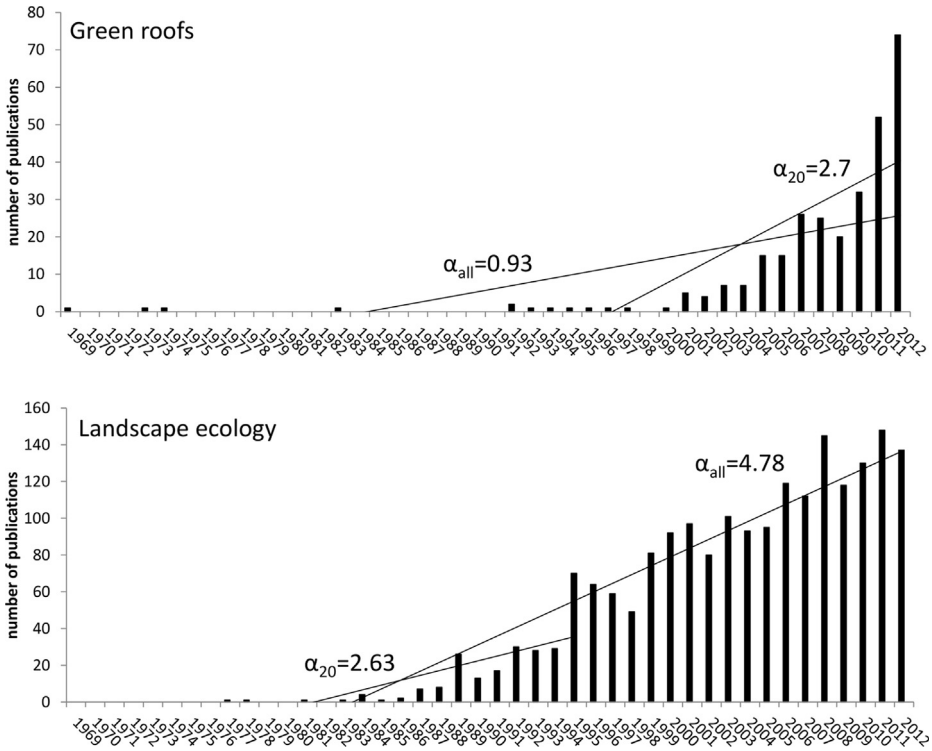

Fig. 1. Yearly rate of publication in green roofs research (upper graph) compared to landscape ecology research (lower graph). α_{all} represent the slope over all years while α_{20} represent the slope of only the first 20 years: 1993–2012 and 1977–1996 for green roofs research and landscape ecology, respectively.

Prior to 1969, we found no publication using the keywords of our search. The slope of yearly change in publications in green roofs was 0.93 and for landscape ecology it was 4.78 (Fig. 1). When comparing only the trend between 1993 and 2012 in green roofs research and the first 20 years of landscape ecology research (1977–1996), the differences between disciplines were considerably smaller, 2.7 for the former and 2.63 for the latter (Fig. 1).

Green roof research has attracted wide international interest (Fig. 2). A total of 31 countries, representing six continents are represented in the survey. However, the distribution of publications between countries is skewed. The two leading contributors were the USA (~34%) and EU countries (~33%). Asian countries contributed about 20% of publications while African countries contributed only one publication. For comparison, African countries contributed six times more publications (after standardizing to the total number of publications) to landscape ecology. Another indication for the change in distribution of the country of origin of publications is the yearly change in the number of countries (Fig. 3). Clearly there has been a sharp increase in the number of countries, increasing from one country throughout the 1990s to 24 countries in 2012. This trend is similar to the trend for landscape ecology in the first 20 years of research – increasing from one country in the late 1970s to 21 and 16 countries in 1995 and 1996, respectively. In 2012, authors from 37 countries published papers in landscape ecology. Although it is difficult from such a survey to infer the climatic conditions and the ecosystem each study represents, we conservatively estimate that most studies consider green roofs in temperate regions (Fig. 4).

The 300 papers were classified into 32 research areas (Fig. 5). This highlights the interdisciplinary nature on green roof research. The two major contributors were 'engineering' and 'environmental sciences ecology'. There was very little change in the frequency of most research areas through time. The frequency of four topics (plant sciences, forestry, marine and freshwater biology and biodiversity conservation, $r = 0.78$, 0.84, 0.66 and 0.73, respectively) increased significantly (Fig. 6). Architecture, on the other hand, decreased significantly with time ($r = -0.79$).

Thirty six percent of the articles have not yet been cited (Fig. 7). About 38% of the articles received between one and nine citations, and about 14% have been cited 20 or more times.

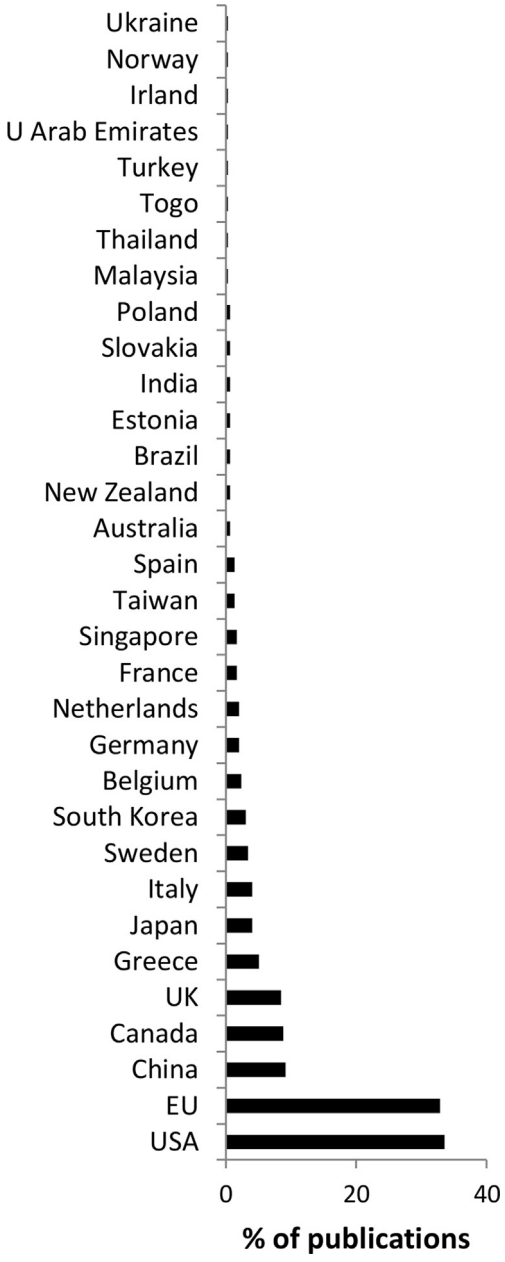

Fig. 2. Distribution of papers according to country between 2001 and 2012. We included the entire EU as a classification.

4. Discussion

This study clarifies how the status of research on green roofs has evolved during the past 20 years. It also identifies the skewed global distribution of study sites and allocation of effort in certain ecosystems and research areas. Finally, it helps identify the challenges which lie ahead.

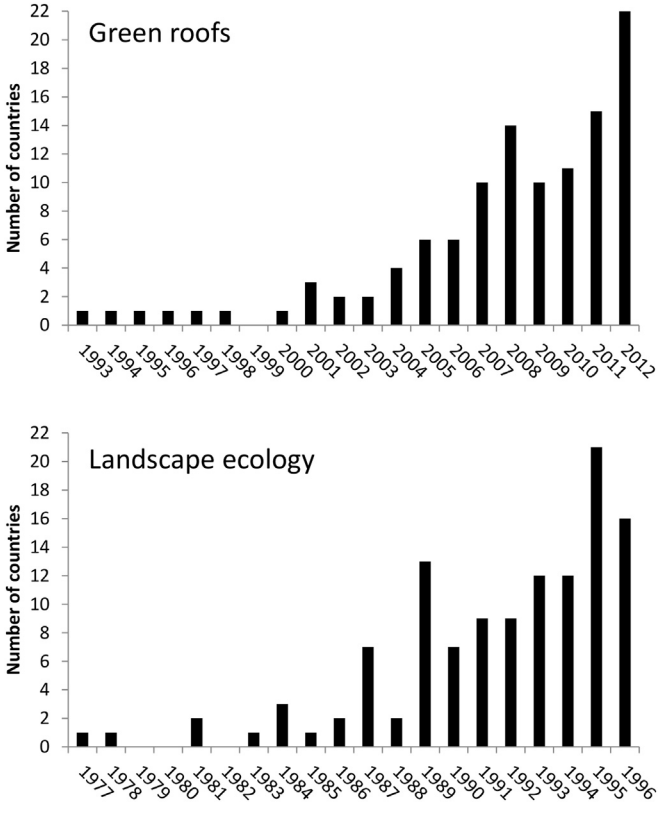

Fig. 3. Yearly change in the number of countries contributing papers on green roofs and landscape ecology in the first 20 years of research: 1993–2012 and 1977–1996 for green roofs research and landscape ecology, respectively.

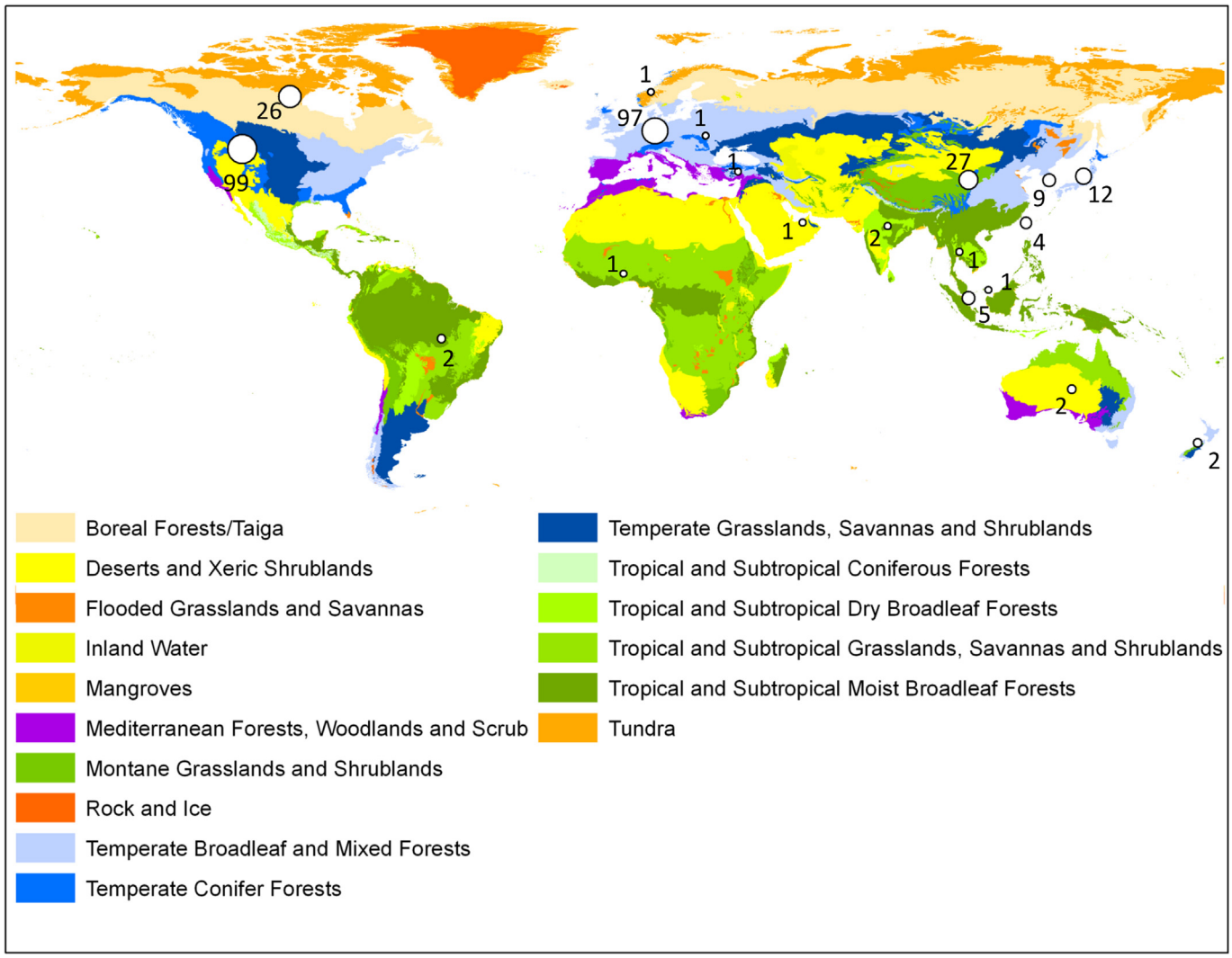

Fig. 4. Number of publications per country (between 2001 and 2012) overlaid on terrestrial ecoregions map.

When comparing the pace of change in the number of green roof publications in the first 20 years to the pace of change in landscape ecology, the picture is similar. After this period, there is a sharp increase in the number of publications and the pace almost doubles for landscape ecology. In addition, the number of countries publishing papers in landscape ecology almost doubled from 21 in the mid 90 s to 37 in 2012. These two trends illustrate the establishment of this novel research area, and potentially suggest the future increase in green roofs research once it has been firmly established as an academic discipline.

Although green roofs show promise for contributing to local habitat and species conservation, this issue has received little attention until recently, according to our survey. The results presented clearly portray a rapid growth and characterize an interdisciplinary science. This growth is probably the result of increased awareness to environmental issues and the desire to harness green roofs to mitigate environmental impacts such as managing storm water runoff [21] and urban heat islands [22].

Approximately 36% of the green roof articles have not been cited. In fact, this is a typical situation. For example, more than one fifth of the articles published in 1984 were not cited four years later [23]. This figure must be interpreted with caution. Roughly, it usually takes approximately a year for a new publication to begin to be cited. Thus, there is likely to be some underestimation for the year 2012.

Green roofs commonly support various invertebrates, including beetles, ants, bugs, flies, bees, spiders, and leafhoppers [8–11]. Green roofs have also been used by breeding birds [7]. Green roofs are also mentioned in the context of reconciliation ecology. Francis and Lorimer (2011) [24] argued that for maximizing green roof potential for supporting biodiversity, two factors need to be considered - heterogeneous designs and a landscape-scale approach. However, as seen in our survey, biodiversity research has received only a small fraction of the research effort. Many questions are yet to be fully answered, such as: how to optimize biodiversity on green roofs; how to establish a viable network of green roofs that will help to support biodiversity and serve as stepping stones to link existing habitats; and how extensive roofs can contribute to the formation of such networks. However, there is an apparent trend signifying a decrease interest in architecture issues and an increase in research in environmental issues such as plant sciences, forestry, marine and freshwater biology and biodiversity conservation. We believe that these trends are the result of how green roofs research has developed: in its beginning it addressed design and engineering issues and as it became established, it turned to other directions such as environmental and ecological issues.

The research community (as determined by the country of affiliation of authors), is dominated by the USA and countries in the

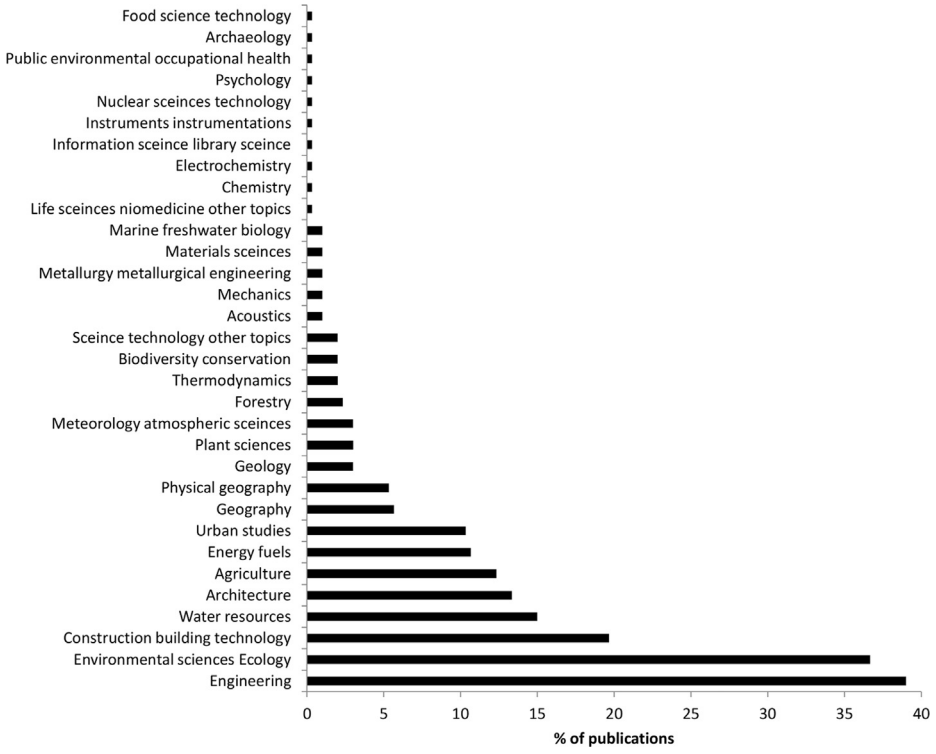

Fig. 5. Distribution of papers (between 2001 and 2012) according to research areas categories assigned by ISI.

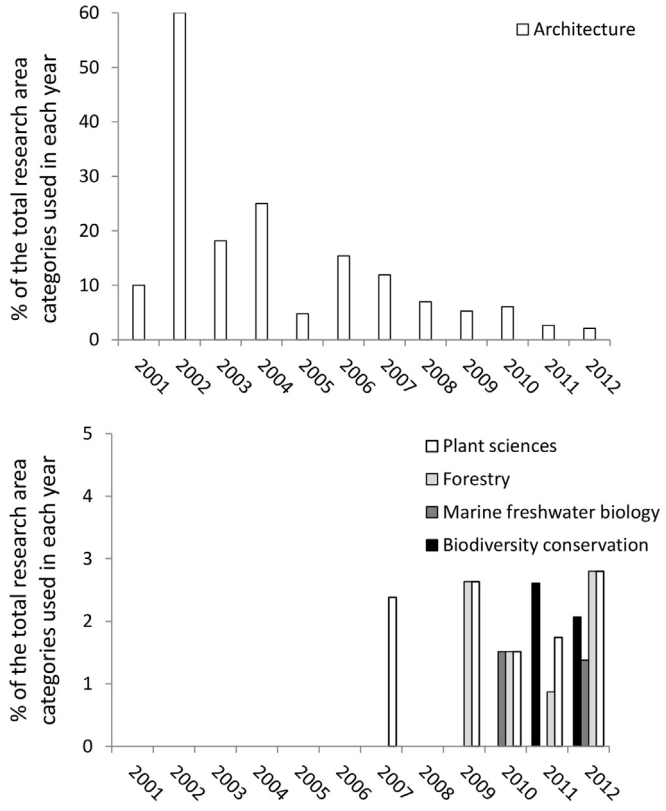

Fig. 6. Change in the percentage over time (between 2001 and 2012) of all research areas for which change over time was statistically significant.

European Union. These countries represent mainly temperate regions. Few studies have been performed in dry ecosystems. We suggest several reasons explaining this pattern. Green roofs or turf (sod) roofs in Northern Scandinavia, used for securing waterproofing in high winds, have been around for centuries [25]. The modern green roof originated during the 20th century in Germany and Switzerland, and spread to other parts of Europe, and then to North America [26]. In addition, there is a common perception that it may be difficult to make green roofs aesthetically appealing in dry climates. Lastly, North America and Europe have the largest concentration of research institutes, and thus most of the studies in most fields are expected to result from these regions.

Plant survival and growth are affected by soil depth. Shallow and therefore lightweight soils are often a desirable attribute for

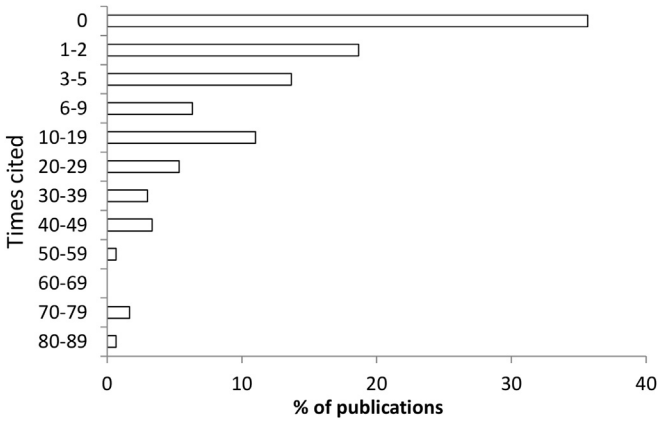

Fig. 7. Distribution of papers (between 1969 and 2012) according to the number of citations.

extensive green roofs established on lightweight structures [27]. Plant survival and coverage of the roof surface are important for aesthetics and for the different benefits from this cover such as energy savings that result from reduced roof temperatures, and runoff water captured on the roof during storms [28]. The rate of water loss from the growing medium is a crucial issue for plant survival and is expected to be a key problem in dry climates. According to our survey, this issue is now receiving more attention, in concert with an increasing interest in plant sciences as a research area.

The issue of soil moisture is a major constraint to plant survival that influences the selection of plant species to be used on green roofs. For this reason drought tolerant *Sedum* species (Crassulaceae) are the most frequently used plants on extensive green roofs [2,29]. Until recently biodiversity has been an overlooked theme in the context on green roofs, while it is a hot topic in ecology and environmental management in general [30] and possesses much potential in the context of urban ecology [31].

5. Conclusions

Green roof research has received increased attention in the last decade. It is multidisciplinary and includes both engineering and natural sciences. Our study suggests that until recently most research emphasis has been with engineering (including architecture and construction). We believe that one of the major themes that lie ahead in green roof research is the potential for green roofs to support the conservation of biodiversity. This aspect is still in its infancy and requires further investigation. Studying how green roofs function as biological systems should represent a cutting edge theme in applied ecology and an opportunity to employ methods and concepts from ecology to improve our ability to answer both basic and applied questions related to urban ecology.

In addition, more work is needed in other ecosystems apart from the ones represented in studies from the USA and the EU countries. There is a great challenge in constructing green roofs, and in particular, applying the knowledge accumulated through all green roof research to roof greening in drier regions.

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References

[1] Oberndorfer E, Lundholm J, Bass B, Coffman RR, Doshi H, Dunnett N, et al. Green roofs as urban ecosystems: ecological structures, functions, and services. Bioscience 2007;57:823–33.
[2] Mentens J, Raes D, Hermy M. Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? Landsc Urban Plan 2006;77:217–26.
[3] Jim CY, Tsang SW. Biophysical properties and thermal performance of an intensive green roof. Build Environ 2011;46:1263–74.
[4] Kumar R, Kaushik SC. Performance evaluation of green roof and shading for thermal protection of buildings. Build Environ 2005;40:1505–11.
[5] Theodosiou TG. Summer period analysis of the performance of a planted roof as a passive cooling technique. Energy and Buildings 2003;35:909–17.
[6] Li JF, Wai OWH, Li YS, Zhan JM, Ho YA, Li JZ, et al. Effect of green roof on ambient CO_2 concentration. Build Environ 2010;45:2644–51.
[7] Baumann N. Ground-nesting birds on green roofs in Switzerland: Preliminary observations. Urban Habitats 2006;4:37–44.
[8] Brenneisen S. Space for urban wildlife: Designing green roofs as habitats in Switzerland. Urban Habitats 2006;4:27–36.
[9] Coffman RR, Davis G. Insect and avian fauna presence on the Ford assembly plant ecoroof. In: Third annual greening rooftops for sustainable communities conference, awards and trade show 2005. Washington, DC.
[10] Grant G. Extensive green roofs in London. Urban Habitats 2006;4:51–65.
[11] Kadas G. Rare invertebrates colonizing green roofs in London. Urban Habitats 2006;4:66–86.
[12] Snodgrass EC, McIntyre L. The green roof manual: a professional guide to design, installation, and maintenance. Portland: OR Timber Press Inc.; 2010.
[13] Pritchard A. Statistical bibliography or bibliometric. J Document 1969;25:348–9.
[14] Liu X, Zhang L, Hong S. Global biodiversity research during 1900–2009: a bibliometric analysis. Biodivers Conserv 2011;20:807–26.
[15] Clarke A, Gatineau M, Grimaud O, Royer-Devaux S, Wyn-Roberts N, Le Bis I, et al. A bibliometric overview of public health research in Europe. Eur J Public Health 2007;17:43–9.
[16] Schui G, Krampen G. Bibliometric analyses on the emergence and present growth of positive psychology. Appl Psychol Health Well-Being 2010;2:52–64.
[17] Ramos-Rodríguez AR, Ruíz-Navarro J. Changes in the intellectual structure of strategic management research: a bibliometric study of the Strategic Management Journal, 1980–2000. Strateg Manag J 2004;25:981–1004.
[18] Li X, Mander Ü. Future options in landscape ecology: development and research. Prog Phys Geogr 2009;33:31–48.
[19] Turner MG. Landscape ecology in North America: past, present, and future. Ecology 2005;86:1967–74.
[20] Sokal RR, Rohlf FJ. Biometry: the principles and practice of statistics in biological research. Ney York: WH Freeman; 1995.
[21] Stovin V. The potential of green roofs to manage Urban Stormwater. Water Environ J 2010;24:192–9.
[22] Prado RTA, Ferreira FL. Measurement of albedo and analysis of its influence the surface temperature of building roof materials. Energy Build 2005;37:295–300.
[23] Pendlebury DA. Science, citation, and funding. Science 1991;251:1410–1.
[24] Francis RA, Lorimer J. Urban reconciliation ecology: the potential of living roofs and walls. J Environ Manage 2011;92:1429–37.
[25] van Hoof J, van Dijken F. The historical turf farms of Iceland: architecture, building technology and the indoor environment. Build Environ 2008;43:1023–30.
[26] Dvorak B, Volder A. Green roof vegetation for North American ecoregions: a literature review. Landscape Urban Plann 2010;96:197–213.
[27] Boivin MA, Lamy MP, Gosselin A, Dansereau B. Effect of artificial substrate depth on freezing injury of six herbaceous perennials grown in a green roof system. Hort Technol 2001;11:409–12.
[28] Lundholm J, MacIvor JS, MacDougall Z, Ranalli M. Plant species and functional group combinations affect green roof ecosystem functions. PloS One 2010;5:e9677.
[29] Snodgrass EC, Snodgrass LL. Green roof plants: a resource and planting guide. Timber Press; 2006.
[30] Hendriks IE, Duarte CM. Allocation of effort and imbalances in biodiversity research. J Exp Mar Biol Ecol 2008;360:15–20.
[31] Gedge D, Kadas G. Green roofs and biodiversity. Biologist 2005;52:161–9.