



# Socio-Ecological Dimensions of Spontaneous Plants on Green Roofs

Dean Schrieke<sup>1\*</sup>, Joel Lönnqvist<sup>2</sup>, Godecke-Tobias Blecken<sup>2</sup>, Nicholas S. G. Williams<sup>1</sup> and Claire Farrell<sup>1</sup>

<sup>1</sup> School of Ecosystem and Forest Sciences, University of Melbourne, Melbourne, VIC, Australia, <sup>2</sup> Department of Civil, Environmental and Natural Resources Engineering, Luleå University of Technology, Luleå, Sweden

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### \*Correspondence:

Dean Schrieke  
dean.schrieke@unimelb.edu.au

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Green roofs have the potential to provide socio-ecological services in urban settings that lack vegetation and open space. However, implementation of green roofs is limited by high construction and maintenance costs. Consequently, green roof projects often disproportionately benefit wealthy communities and can further marginalise disadvantaged communities by increasing property values and housing costs. Vegetation cover on green roofs is crucial to their provisioning of socio-ecological services. Evidence suggests that green roof plantings change over time, especially with limited maintenance, and are replaced with spontaneous “weedy” species. This is often perceived as a failure of the original green roof design intent and spontaneous species are usually removed. However, where good coverage is achieved, spontaneous vegetation could provide beneficial services such as stormwater mitigation, habitat provision, and climate regulation. While social norms about “weediness” may limit the desirability of some spontaneous species, research suggests that their acceptability on green roofs increases with coverage. As spontaneous species can establish on green roofs without irrigation and fertiliser, reduced input costs could help facilitate adoption particularly in markets without an established green roof industry. Construction costs may also be reduced in hot and dry climates where deeper substrates are necessary to ensure plant survival, as many spontaneous species are able to colonise shallow substrates and can regenerate from seed. If implemented based on socio-ecological need, green roofs with spontaneous vegetation coverage may apply less pressure to property values and housing costs than conventionally planted green roofs, increasing the resilience of urban communities while limiting gentrification.

**Keywords:** benefit, biodiversity, invasive, maintenance, management, spontaneous, weed

## INTRODUCTION

Urbanisation is an ongoing global process with serious impacts on socio-ecological processes. Urban development seals soils with impervious materials, initiates habitat loss and fragmentation and modifies natural hydrology and climate (Grimm et al., 2008). Vegetation can alleviate some of these impacts, yet disadvantaged communities are often disproportionately green space poor (Barbosa et al., 2007; Zhang et al., 2008; Dai, 2011; Wolch et al., 2014). Maintaining and expanding urban green space is therefore a significant issue facing city planners and policymakers globally. Engineered “blue-green infrastructure” (BGI), also referred to as “nature based solutions,” such as green roofs, can mitigate flooding in built up

catchments and prevent damage to waterways (Stovin et al., 2012; Viola et al., 2017), provide habitat for urban biodiversity (Wang et al., 2017), reduce urban heat island effects (Santamouris, 2014), and provide psychological benefits such as attention restoration (Lee et al., 2015). The importance of urban BGI was further illustrated by recent COVID-19 lockdowns that limited mobility and highlighted the importance of localised green space (Ugolini et al., 2020). On the whole of lifecycle scale, combined social-ecological benefits of green roofs represent a low-risk amendment with short-term net return on investment (Bianchini and Hewage, 2012). However, significant barriers to widespread adoption of green roofs include high costs associated with installation and maintenance (Shafique et al., 2018), difficulty retrofitting existing rooftops (Ziogou et al., 2018) and input demands such as irrigation in hot and/or dry climates (Williams et al., 2010; Ascione et al., 2013).

Vegetation cover on green roofs is crucial to their provisioning of socio-ecological services (Speak et al., 2013). Achieving close to 80% vegetation cover 12 months post installation is an objective of extensive green roofs (FLL, 2008; Dvorak and Volder, 2010) and bare patches are considered a failure. However, the relatively shallow substrates of extensive green roofs limit plant growth and survival (Durhman et al., 2007; Eksi and Rowe, 2019). Increased substrate depths of “intensive” green roofs can improve plant health and survival (Olly et al., 2011), but incur higher engineering and maintenance costs and are less able to be retrofitted on existing buildings (Bianchini and Hewage, 2012), hence extensive green roofs are much more common (Shafique et al., 2018). Several studies (see **Table 1**) show that, when left unmanaged, spontaneous vegetation can completely replace original green roof plantings over time. Unmanaged green roofs with spontaneous vegetation coverage could be considered an “informal green space,” a term proposed by Rupprecht et al. (2015) to classify unmanaged urban ecosystems with a history of anthropogenic disturbance that are at least partly occupied by spontaneous vegetation. Informal green space has long been a focus of urban ecology research (Sukopp, 2008) and recent studies focus on its potential to support ecosystem health (Kim et al., 2018), plant and animal biodiversity (Gardiner et al., 2013) including rare and endangered species (Kowarik, 2011; Bonthoux et al., 2014), and facilitate nature experiences for urban dwellers (Threlfall and Kendal, 2018).

Increasingly, cities undergoing densification are implementing strategies to encourage and facilitate green roof adoption (Shafique et al., 2018). Paradoxically, greening strategies can increase housing costs and property values (Ashley et al., 2018; Hamann et al., 2020), leading to gentrification and displacement of disadvantaged communities (Wolch et al., 2014). Installation of green roofs can increase rental prices in surrounding areas (Ichihara and Cohen, 2011) and the high cost of green roof construction and ongoing maintenance can mean that these projects do not benefit disadvantaged communities (Sharma et al., 2018). To avoid gentrifying processes and democratise the benefits of green infrastructure such as green roofs, a “just green enough” (Curran and Hamilton, 2012; Wolch et al., 2014) approach conceives greening projects based on socio-ecological need rather than normative design

or species conservation outcomes. This strategy prioritises installation of low maintenance green infrastructure in smaller and underutilised sites, compared to large-scale projects that are concentrated geographically and can kick-start gentrification processes (Schauman and Salisbury, 1998; Wolch et al., 2014). Should spontaneous vegetation provide functionality to green roofs like that of planted vegetation, it might embody a novel “just green enough” nature based solution. However, research on the potential for “just green enough” or other informal urban greening approaches to avoid gentrification is still in its infancy (Rupprecht and Byrne, 2017) and has not yet been explored for elevated landscapes such as green roofs. In this mini-review we discuss the socio-ecological dimensions of spontaneous vegetation on green roofs (**Table 2**) and whether spontaneous vegetation cover could help expand green roofs into areas that are funding or space limited, or whether their inherent “weediness” may make them an unwelcome addition to urban landscapes.

## ECOLOGICAL DIMENSIONS OF SPONTANEOUS GREEN ROOFS

Environmental filters such as habitat transformation and fragmentation, and human preferences shape urban vegetation communities by selecting against certain species (Williams et al., 2009). Plant traits of spontaneous species, such as woodiness, height, and seed mass, appear to increase along gradients of urbanisation, yet other traits have mixed responses associated with localised factors (Williams et al., 2015). On green roofs, factors such as substrate depth and roof age determine spontaneous plant diversity, composition, and traits (Madre et al., 2014). The species composition of spontaneous green roof vegetation also changes with competition and/or facilitation by established plants (Miller et al., 2014; Ksiazek-Mikenas and Köhler, 2018; Thuring and Dunnett, 2019) and the frequency of green roof maintenance (Madre et al., 2014; Catalano et al., 2016). Shallow green roof substrates appear to have greater cover and diversity of spontaneous species than deeper substrates (Lönqvist et al., 2021), presumably due to increased availability of bare areas or “safe sites” for colonisation by spontaneous plants (Harper et al., 1961). Maintenance and resource input is greater initially following green roof installation, and spontaneous vegetation assemblages are dominated by “ruderal” (*sensu* Grime, 1977) species (Köhler, 2006; Dunnett et al., 2008; Van Mechelen et al., 2015; Catalano et al., 2016; Ksiazek-Mikenas and Köhler, 2018). These ruderal species grow fast and can complete their life-cycles before drought occurs, allowing them to set seed and germinate rapidly in response to rainfall (Bevilacqua et al., 2015). However, as green roofs age, and in the absence of routine maintenance, ruderal species tend to disappear (Bates et al., 2013) and are replaced by more stress tolerant species which can tolerate hotter and drier conditions (Madre et al., 2014; Catalano et al., 2016; Ksiazek-Mikenas and Köhler, 2018). Yet the influence of spontaneous vegetation on green roof functionality, compared to commonly planted green roof species, is less clear.

**TABLE 1** | Vegetation coverage and species richness of spontaneous green roof plants recorded in global surveys.

Study	Location	Climate	Roof age (years)	Substrate depth (mm)	Maintenance regime	Spontaneous cover %	Spontaneous richness %
Deng and Jim (2017)	Hong Kong, China	Oceanic monsoon	1–4	50–100	No maintenance	80–95%	100%
Dunnett et al. (2008)	Sheffield	Temperate	4	100–200	High maintenance	2.5% of biomass	70%
Lönnqvist et al. (2021)	Kiruna, Sweden	Subarctic	2	63	Low maintenance	5%	28%
Lönnqvist et al. (2021)	Luleå, Sweden	Subarctic	4	26	Low maintenance	17%	28%
Lönnqvist et al. (2021)	Umeå, Sweden	Humid continental/subarctic	2	67	Regular fertilising and irrigation during drought	2%	74%
Thuring and Dunnett (2019)	Stuttgart (three sites)	Warm–temperate	~20	80–100	Very low maintenance	60%	–
Bates et al. (2013)	Birmingham	Temperate	1–2	40–120	Low maintenance	–	59–66%
Bevilacqua et al. (2015)	Lleida, Spain	Dry Mediterranean Continental	4–5	80	Minimal maintenance	6–61%	50%
Catalano et al. (2016)	Hannover, Germany	Warm-temperate, fully humid	30	50–250	No additional maintenance following installation	90% +	93–94%
Köhler (2006)	Berlin, Germany	Temperate oceanic	1–19	100	No additional maintenance following installation	1–35%	5–36%,
Köhler (2006)	Berlin, Germany	Temperate oceanic	15	100	No additional maintenance following installation	17–61%	17–76%
Madre et al. (2014)	Paris, France (115 sites)	Western European oceanic	1–42	20–600	Variable	–	41%
Olly et al. (2011)	Birmingham	Temperate	1	100–150	No maintenance	–	62%

For more than half of the surveys, spontaneous species provided more than 50% of the vegetation cover and more than 50% of species richness, regardless of maintenance regime or substrate depth. Older unmanaged green roofs typically had higher spontaneous species cover.

Cover of spontaneous species and their total contribution to species richness were estimated from published data presented for the time of survey. All surveys were conducted in colder temperate and subarctic climates, except for studies in Hong Kong (Oceanic monsoon), Lleida (Dry Mediterranean/Continental), and Paris (Western European Oceanic).

Spontaneous green roof communities can have high biodiversity, with species richness becoming greater than the original plantings if left unmanaged (see **Table 1**). Spontaneous vegetation can also provide habitat for invertebrates (Kadas, 2006; Robinson and Lundholm, 2012) and floral resources for pollinators (Bretagnolle and Gaba, 2015). Where these communities replace *Sedum* green roof vegetation, they can support greater butterfly diversity due to increased flowering continuity over the year and the presence of flowers with short corollas that are accessible to a wide range of species (Wang et al., 2017). Green roofs have also been specifically designed to promote biodiversity and habitat provision (Grant, 2006; Ishimatsu and Ito, 2013; Benvenuti, 2014). Early examples were designed to mimic “brownfield” habitats such as gravel piles (known to also host spontaneous plant species) for declining birds such as black redstart *Phoenicurus ochrurus* and lapwing *Vanellus vanellus* (Grant 2006). These roofs used construction rubble as substrates and spontaneous plant species were left to colonise them. Some spontaneous plant species of conservation interest appeared on these roofs; however, initial coverage of spontaneous vegetation did not

meet expectations and researchers eventually reseeded the roof with a locally sourced wildflower seed mix (Grant, 2006). Rare spiders and insects hosted by ground level brownfield sites were also found on these green roofs (Kadas, 2006).

Rapid urbanisation increases stormwater runoff in urban areas, polluting and damaging receiving waterways (Walsh et al., 2005). The negative health impacts associated with stormwater runoff and flooding have been shown to disproportionately affect disadvantaged communities (Patz et al., 2005). Green roofs can reduce the volume and peak flow of runoff by retaining water and releasing it to the atmosphere via evapotranspiration, mitigating downstream flooding and other socio-ecological harm (Getter, 2006). Stormwater mitigation by green roofs is influenced by a range of factors, however substrate type and depth are the primary determinants of water retention (Czemiel Berndtsson, 2010; Zhang et al., 2019), though vegetation increases rainfall retention through interception by plant canopies and evapotranspiration (Zhang et al., 2018, 2019). Research suggests that green roof plantings with high functional diversity incorporating species with higher water

**TABLE 2** | Potential trade-offs between spontaneous green roof vegetation traits and their social and ecological function.

Spontaneous green roof vegetation traits	Social function	Ecological function	Trade-off
 Prolonged flowering continuity <sup>a</sup>	Cue to care <sup>e</sup> , ecological beauty <sup>f</sup> , high preference <sup>g</sup>	Support butterfly biodiversity <sup>a</sup> , floral resource for pollinators <sup>h</sup>	No clear trade-off
 High biodiversity <sup>b</sup>	Biodiverse vegetation preferred <sup>d</sup> , acceptance increases when residents informed of ecological function <sup>i</sup>	Habitat for rare insects and spiders <sup>j</sup> , increased GR functionality <sup>k-m</sup>	Perceived messiness of naturalistic plantings <sup>l</sup>
 Fast growth/ annual lifecycle <sup>c</sup>	Accumulation of organic matter when plants senesce perceived as 'messy' <sup>i</sup>	High transpiration <sup>n</sup> may increase stormwater mitigation	Accumulation of organic matter when annual plants senesce provides arthropod habitat <sup>n</sup>
 Gaps in vegetation <sup>d</sup>	Significant negative impact on green roof aesthetic <sup>d</sup>	Gaps provide safe sites for plant colonisation <sup>o</sup>	Loss of transpiration and canopy cooling when vegetation senesces <sup>p</sup>
 Low maintenance	Reduction to green roof costs, a significant deterrent to adoption <sup>d</sup>	No fertiliser, herbicide, or pesticide application	No clear trade-off

Colours represent perceived beneficial (green) and unfavourable (red) outcomes.

<sup>a</sup>Wang et al. (2017), <sup>b</sup>Madre et al. (2014), <sup>c</sup>Schrieke and Farrell (2021), <sup>d</sup>Vanstockem et al. (2019), <sup>e</sup>Nassauer et al. (2009), <sup>f</sup>Sutton (2014), <sup>g</sup>Lee et al. (2014), <sup>h</sup>Bretagnolle and Gaba (2015), <sup>i</sup>Southon et al. (2017), <sup>j</sup>Kadas (2006), <sup>k</sup>Dunnnett et al. (2008), <sup>l</sup>Farrell et al. (2012), <sup>m</sup>Kemp et al. (2019), <sup>n</sup>Kyrö et al. (2020), <sup>o</sup>Harper et al. (1961), and <sup>p</sup>Speak et al. (2013).

use provide greater stormwater retention than commonly used monocultures of Sedum species which generally have low water use (Dunnnett et al., 2008; Farrell et al., 2012; Kemp et al., 2019). However, the role of spontaneous vegetation on green roof hydrological performance is unclear (Robinson and Lundholm, 2012). As spontaneous green roofs are likely to be more diverse than many sedum-based roofs and have also been shown to become more diverse if left unmanaged (see Table 1), they may provide greater stormwater retention. Spontaneous vegetation may improve stormwater retention on green roofs through increased functional diversity (Cook-Patton and Bauerle, 2012), high transpiration (Schrieke and Farrell, 2021) and maintenance of vegetation cover on green roofs

where the original plants have died (Dunnnett et al., 2008). Highly managed green roofs have also been shown to reduce runoff quality as they act as nutrient sources (Buffam and Mitchell, 2015) due to fertiliser use (Li and Babcock, 2014). As spontaneous vegetation can thrive with limited or no fertiliser, this type of green roof is less likely to produce poor quality water runoff.

## SOCIOLOGICAL DIMENSIONS OF SPONTANEOUS GREEN ROOFS

To our knowledge, there is no research that specifically appraises the sociological dimensions of spontaneous vegetation on green



roofs. Further, studies that have evaluated the psychological dimensions of green roof vegetation caution against generalising outcomes of ground-level social research to the context of green roofs (Williams et al., 2019). Human landscape and plant preferences are highly complex and influenced by cultural norms at neighbourhood (Nassauer et al., 2009) and individual scales (Fernandez-Canero et al., 2013; Brun et al., 2018; Nagase and Koyama, 2020). Aesthetics are an important element of landscape preference, however preference studies of green roof vegetation appear to have inconsistent findings and may vary with context. For example, while office workers in Toronto and Chicago considered green roofs planted with native prairie meadows untidy and out of place in the urban context, spontaneous vegetation was viewed with interest and curiosity (Loder, 2014). In contrast, Australian office workers preferred diverse, taller, green, and flowering vegetation on green roofs; traits associated with meadow-type vegetation (Lee et al., 2014). A similar survey conducted in Chiba, Japan, found preference for turfed green roofs (Nagase and Koyama, 2020). In all these preference studies, participants were presented with images of green roofs, or experienced these roofs directly. Whether perceptions of green roofs change when vegetation is inaccessible, not viewed closely or fully concealed is unclear.

Spontaneous vegetation can be perceived negatively due to its unpredictability, lack of human control and perception of “weediness” that challenges the static ecosystem view of green roofs (Lundholm, 2016) (Table 2). When landscapes lack easily recognisable designed elements, or “cues to care” (Nassauer et al., 2009), residents can experience feelings of social and physical isolation, hopelessness, and diminished social capital (Mair et al., 2012). As spontaneous plants replace original green roof plantings where maintenance is infrequent, this could be perceived as a lack of care and may reduce their acceptance. However, spontaneous vegetation on green roofs often has high floristic diversity (Catalano et al., 2016; Kratschmer et al., 2018) which may improve their acceptance as flowers can be perceived as a “cue to care” (Nassauer et al., 2009). Flowers were also shown in the study with Australian office workers to increase preference, regardless of the vegetation type (Lee et al., 2014). Additionally, as spontaneous vegetation on green roofs is framed within the substrate area, this may communicate a “cue to care” (Nassauer et al., 2009). Moreover, in the case of wild or naturalistic biodiverse roofs, people can appreciate “ecological beauty” when they understand their purpose (Jungels et al., 2013; Sutton, 2014). For example, Southon et al. (2017) showed improved acceptance for perennial meadows that undergo winter senescence after residents were informed about their benefits for pollinators. When the biodiversity benefits of green roof meadows were better understood, these types of roofs were perceived as more “natural” and therefore preferable to *Sedum* species monocultures (Loder, 2014). Therefore, it is possible that perceptions of spontaneous vegetation on green roofs would improve if people were informed of the potential benefits to biodiversity and stormwater retention. Finally, weed “conspicuousness” on green roofs may not matter when there is good cover, as gaps have been shown to have greater effects on aesthetics than weediness (Vanstockem et al., 2018).

## SPONTANEOUS GREEN ROOFS IN PRACTISE

To maintain designed plantings on green roofs, weeding of spontaneous vegetation is recommended (FLL, 2008). The risk of annual spontaneous species damaging water proofing membranes is limited by their shallow and non-invasive root systems. However, spontaneous green roofs would still require periodic inspection and maintenance to identify and remove woody spontaneous species to avoid membrane penetration or blocking of drains (Archibold and Wagner, 2007). Controlled disturbance, such as the cutting of the vegetation to mimic grazing, could also prevent competitive species from dominating and optimise species diversity. There are concerns spontaneous green roof vegetation could result in these plants spreading beyond the roof (Lundholm, 2015) as the distance travelled by wind dispersed seeds increases with release height, improving their ability to colonise surrounding urban landscapes. Green roof designers are therefore encouraged to plant native species in areas of conservation value (Williams et al., 2010). However, a large-scale study in France found that spontaneous vegetation that colonised green roofs had greater native species richness (86%) than the initial plantings (30%) and included rare and endangered species (Madre et al., 2014). The urban landscapes that surround green roofs are likely already populated by the typically cosmopolitan species that commonly colonise green roofs (Lundholm and Marlin, 2006). Indeed, the composition of spontaneous green roof vegetation often reflects that of the surrounding environment (Madre et al., 2014; Catalano et al., 2016). Consequently, the risk of invasion by spontaneous green roof species in these landscapes is likely to be limited and potentially lower than species used in horticulture, which is consistently identified as the source of many invasive plants (Dodd et al., 2015; van Kleunen et al., 2018). However, where green roofs are near conservation areas increased monitoring for invasive species is warranted.

Spontaneous green roofs may provide a nature based “just green enough” (Curran and Hamilton, 2012) solution that improves the health and well-being of residents while limiting associated green gentrification. Incorporating spontaneous vegetation on green roofs could reduce high initial costs associated with installation, and ongoing costs associated with plant replacement and maintenance. As spontaneous species colonise and persist on green roofs with shallow substrates (Madre et al., 2014), spontaneous green roofs could also alleviate engineering costs associated with increased weight loading and deeper substrates. Furthermore, locating these roofs in inaccessible locations or in areas where they are not overlooked could improve their acceptance. Together, these factors could facilitate adoption of spontaneous green roofs across cities and improve access to socio-ecological services in areas where urban greening is overlooked. However, there are a range of potential positive and negative functional outcomes related to spontaneous vegetation traits on green roofs (Table 2). For example, spontaneous green roofs still require maintenance and costs would be incurred for annual inspections of roofing

membranes and drainage, and the removal of woody plants to prevent damage to waterproofing membranes. Relying completely on spontaneous vegetation for good plant cover could also have drawbacks, particularly on tall buildings where height could limit propagules reaching the roof. If no or very few propagules reach the substrate, the roofs will be left with low cover and low diversity potentially leading to erosion of the substrate and reduced energy and stormwater performance. Additionally, as spontaneous vegetation can take time to establish (see Catalano et al., 2016) there may be periods of time with little to no vegetation present. In this case, direct sowing with common green roof spontaneous species could provide initial vegetation cover.

## CONCLUSION

In a rapidly urbanising world, the socio-ecological benefits of spontaneous vegetation on green roofs may outweigh other considerations associated with “weediness” or aesthetic preferences. Maintenance and input costs could be significantly reduced, and this may alleviate “green gentrification” and associated displacement of vulnerable communities by large green infrastructure projects. While the desirability of spontaneous vegetation may be limited by social and cultural norms, research suggests that their acceptability on green roofs is likely to increase with plant coverage and “cues to care” (Nassauer, 2003) such as boundaries, neat edges, and flowers. Negative perceptions of “weediness” may reduce the acceptability of spontaneous green roofs in highly visible

and accessible locations, although this could be reduced through education of their benefits. In inaccessible or less visible locations, the “weedy” perception of spontaneous vegetation may not matter, broadening opportunities for implementation. We suggest that lightweight green roofs with shallow substrates that facilitate spontaneous colonisation could deliver socio-ecological benefits at a lower cost than conventional extensive green roofs. These roofs could be delivered as part of a “just green enough” (Wolch et al., 2014) strategy, based on socio-ecological need rather than normative design or conservation outcomes.

## AUTHOR CONTRIBUTIONS

DS, JL, CF, and NW contributed to conception of the review. DS and JL wrote the first draft of the manuscript. DS wrote the second draft of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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