Edible green infrastructure: An approach and review of provisioning ecosystem services and disservices in urban environments

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Abstract

Recently published green infrastructure, nature-based solutions, and ecosystem disservices (ED) literature have focused primarily on the supply of urban *regulating* and *cultural* ecosystem services (ES). Other literature on urban and peri-urban agriculture has mostly studied the role of localized, intensive agricultural practices in providing food to inhabitants. The aim of this review is to raise awareness and stress the knowledge gap on the importance of urban *provisioning* ES, particularly when implementing an edible green infrastructure (EGI) approach as it can offer improved resilience and quality of life in cities. We compiled and systematically analyzed studies on urban ES and ED related to a number of EGI typologies. Our systematic review of the relevant literature via an EGI framework, identified more than 80 peer-reviewed publications that focused on ES and food production in urban areas. An EGI approach can contribute socially, economically, and environmentally to urban sustainability and food security. However, such benefits must be weighed against ED trade-offs, including: potential health risks caused by human exposure to heavy metals and organic chemical contaminants often present in urban surroundings. We conclude with recommendations and guidelines for incorporating EGI into urban planning and design, and discuss novel areas for future research.

1. Introduction

The world's population is rapidly increasing and will top 9.7 billion by 2050 (United Nations, 2015). By 2025, two thirds of the world's population will be concentrated in urban areas, increasing the importance of providing not only environmental quality and livable spaces but food security and resilient food systems (Haberman et al., 2014). This advanced rate of urbanization has coincided with global environmental degradation, increased consumption of natural resources, habitat loss, and overall ecosystem change (Daily, 1995; McDonald et al., 2013; McNeill, 2000). A cause-and-effect reproach from escalating global population brings to the forefront the need to re-examine how urban spaces are developed, used, and urban inhabitants fed (Ackerman et al., 2014). Recent research has focused on the use of *regulating* and *cultural* ecosystem services (ES) and ecosystem disservices (ED), green infrastructure (GI) and nature-based solutions (NBS) for improving upon environmental, social, and economic conditions in cities (Haase et al., 2014). This literature has rarely focused on systems integration for food cultivation and the benefits of *provisioning* ES in relation to urban areas (Cameron et al., 2012). Below, we expand upon the historical traditions of urban agriculture by examining rarely incorporated studies on GI, ES, and NBS (Lin et al., 2015; Lovell, 2010).

Our review provides background justification and scope into integrating commonly used GI, ES, ED, and urban agriculture concepts. We then explore the relevant literature to better characterize different types of edible green infrastructure (EGI) and their related ES and ED. We further our research by discussing recommendations for promoting the design, planning, and management of sustainable EGI. At present, GI and ES are promoted as concepts that have the potential to improve environmental planning in urban areas (Hansen and Pauleit, 2014). More recently, NBS is an approach that improves upon the livability and resilience of cities in retrospect to climate change. Although these concepts are apparently used interchangeably, below we refer to urban GI as hybrid infrastructure of green and built systems (e.g. urban forests, wetlands, parks, green roofs, and walls that together can contribute to ecosystem resilience) and human benefits through their ecological processes or ES (Demuzere et al., 2014; Russo et al., 2016). These benefits or ES are also referred to as NBS when GI is incorporated into urban management, planning, design, and sociopolitical practices and policies for climate change mitigation and adaptation. Indeed, urban GI has been found to contribute positively to outdoor and indoor environments (Russo et al., 2016; Wang et al., 2014), while providing many relevant ES − including important health benefits (Coutts and Hahn, 2015). As such, GI delivers measurable ES and benefits that are fundamental to the concept of a sustainable city (Ahern et al., 2014).

Urban and peri-urban agriculture and forestry (UPAF), on the other hand have been studied and can be considered a set of experiences and practices for implementing the GI approach in and around cities (Eigenbrod and Gruda, 2015; Escobedo et al., 2011). UPAF systems focus on agro-forestry production and agro-ecological practices (e.g. production of vegetables, mushrooms, fruits, crops, aromatic and medicinal herbs, and ornamental plants) as well as the raising of animals (e.g. livestock and aquaculture) in and around urban areas (FAO, 2016). Whereas GI, as stated earlier, is closely related to ES and human wellbeing, with particular focus on *regulating*, *cultural*, and *supporting* services such as biodiversity and nature conservation (Breuste et al., 2015; Tzoulas et al., 2007). Very few studies have integrated UPAF as part of GI and ES frameworks (Coronel et al., 2015; Di Leo et al., 2016). To our knowledge, studies on UPAF have focused mostly on issues relating to livelihoods, poverty reduction, environmental pollution, health risks, and urban policy (Lwasa et al., 2014).

Studies have documented that urban soils often have increased levels of potentially toxic elements (PTEs) such as Zn, Pb, Zi, and Cu that are of primary concern in food production in cities, mostly due to their potential long-term effects to human and animal health (Lu et al., 2016). The balance between food supply and its demand correlates with sustainability and environmental health, while maintaining the factor of human health, fundamental to future challenges and long-term goals (Boye and Arcand, 2013). In this paper, we define EGI as a sustainable planned network of edible food components and structures within the urban ecosystem which are managed and designed to provide primarily *provisioning* – as opposed to highly studied urban "*cultural*" (e.g. recreation, increased property premiums, and aesthetics) and "*regulating*" (e.g. air and water pollution removal, temperature regulation, and flood regulation) – ES. To this end, EGI can include allotment gardens, rooftop gardening, edible landscaping, and urban forests. It can also include non-timber forest products in unmanaged and remnant peri-urban landscapes (McLain et al., 2014). The EGI concept does however emphasize UPAF practices that focus on sustainable techniques that yield food, while protecting the environment and its associating human communities. Note, the scope of this research does not include intensive urban-agricultural practices such as commercial farming, biomass feedstock, aquaculture, and livestock in urban areas (Eigenbrod and Gruda, 2015).

In developing this review, we found it necessary to examine facets of the urban landscape, specifically, food supply. For example, a city's footprint requires vast areas and transportation networks to deliver the necessary food products that urbanites have largely become depend upon, this includes: large amounts of food, complex and extended food delivery systems, and associated energy use often supplied great distances from the end consumer (Deelstra and Girardet, 2000). The results are emission of greenhouse gasses (Grewal and Grewal, 2012) and negative socioeconomic impacts. But, to our knowledge, few cities produce a sufficient supply of the food they consume, and thus depend largely on distant areas to meet demand (Eigenbrod and Gruda, 2015; Gerster-Bentaya, 2013). Low income urban dwellers are particularly vulnerable to adverse food price shocks, as they are largely net food buyers and depend mostly on accessible markets for their food supplies, thus, more localized agriculture supplies may play a substantial role in reducing urban poverty and food security issues (Zezza and Tasciotti, 2010). The aim is to raise awareness and specify a gap in the knowledge-base of urban *provisioning* ES, particularly when implemented using an EGI approach. Specifically, the objectives of this review are to: (1) identify different typologies of urban EGI, (2) synthesize findings on ES and ED of EGI from relevant literature, and (3) provide indicators and technical guidelines regarding the design, planning, and management of sustainable EGI.

As pointed out, most of the GI and ES literature has focused on *cultural* and *regulating* urban ES with only scant references to their food providing components and related co-benefits (i.e. *provisioning* ES) (Escobedo et al., 2011; Haase et al., 2014). Given the need for improved urban living spaces, food security, climate change mitigation, socioeconomic equity, and sustainable resource use, we propose that the EGI approach can indeed provide both a lens and set of practices to address mismatches in ES provision, food security, poverty alleviation, and issues of inequality in urban areas.

2. Methodology

A systematic literature search was conducted using the following electronic journal databases: Science Direct, Web of Knowledge, Scopus, ProQuest, Sage, Directory of Open Access Journals, Google Scholar, and Google. We specifically searched for the following English language keywords including “urban agriculture benefits”, “green roof + food”, “urban + provisioning ecosystem services”, “edible green wall”, “urban forestry food production”, “school gardens”, “edible forest garden”, “historic gardens”, “edible botanic gardens”, “food + botanic gardens”, “edible community gardens”, “allotment garden”, “urban soil contaminants”, “edible green walls”, “ecosystem disservices + urban agriculture”, and “botanic gardens ecosystem services”. Once the literature was compiled, publications were systematically analyzed so as to identify those that presented specific findings on urban ES, NBS, and ED related to EGI, as previously defined, using strategic and critical reading methods (Matarese, 2013; Renear and Palmer, 2009).

From this original compilation of the literature we then identified and analyzed the identified literature and relevant information regarding different urban EGI components (e.g. green roofs, urban forest, and domestic gardens) which were then summarized and presented in the results and discussion sections. As part of the systematic review process, we also identified past and existing terminology related to GI and UPAF and we synthesize and updated it so as to provide a way forward with the EGI framework. In addition, we identified the related ES and ED indicators and metrics related to these EGI components. Overall, we identified more than 6700 articles, reviews, and grey literature in our initial literature review. To better focus our review, we filtered out articles published before 1989 and omitted articles on *cultural* ES or those that did not discuss the nexus between ES and food production in urban and peri-urban areas, leaving us with approximately 175 publications that included literature published in the form of books and technical reports.

Once these were filtered, we compiled and discussed findings and their implications for development of management and planning guidelines for city-based food production and policy uptake in different cities worldwide. We conclude with specific recommendations and guidelines for incorporating EGI into urban planning and design. Note that, in this review, all chemical element names are referenced by their element symbols.

3. Results

After initial filtering out of non-relevant publications, we identified approximately 80 peer-reviewed publications that were related to our definition of EGI. The geographical distribution of EGI-related studies varied according to different typologies. For example, approximately, 70% of the studies relating to ES of “edible urban forests and edible urban greening” were from the USA. Conversely, there was only one review paper on “edible forest gardens” in which one co-author was from an American institution while 50% of the studies were from peri-urban and rural areas in Sri Lanka and Indonesia. The majority of studies on ED of EGI were from the USA (28.6%), the UK (16.7%) and Italy (11.9%) – see Fig. 1.

The scientific journals “Urban Forestry and Urban Greening” and “Landscape and Urban Planning” published most of the identified articles. When analyzed according to discipline, most of these were in the applied sciences (i.e. agriculture and forestry, ecology, and food science) and social sciences (i.e. urban studies and planning, human geography, and urban sociology). However, a few studies such as that of Lin et al. (2015), focused on ES and urban agriculture inclusive within our scope of EGI research typologies.

Using the results from our finalized literature, we identified the most commonly reported EGI types and their characteristics that matched our definition. As shown in Fig. 2, these sites can be found across a vast array of contexts (e.g., countries, regions, climates, and urban land uses). We also used the literature to identify key urban ES associated with EGI and their related quantitative and qualitative indicators (Table 1). Following commonly applied typologies

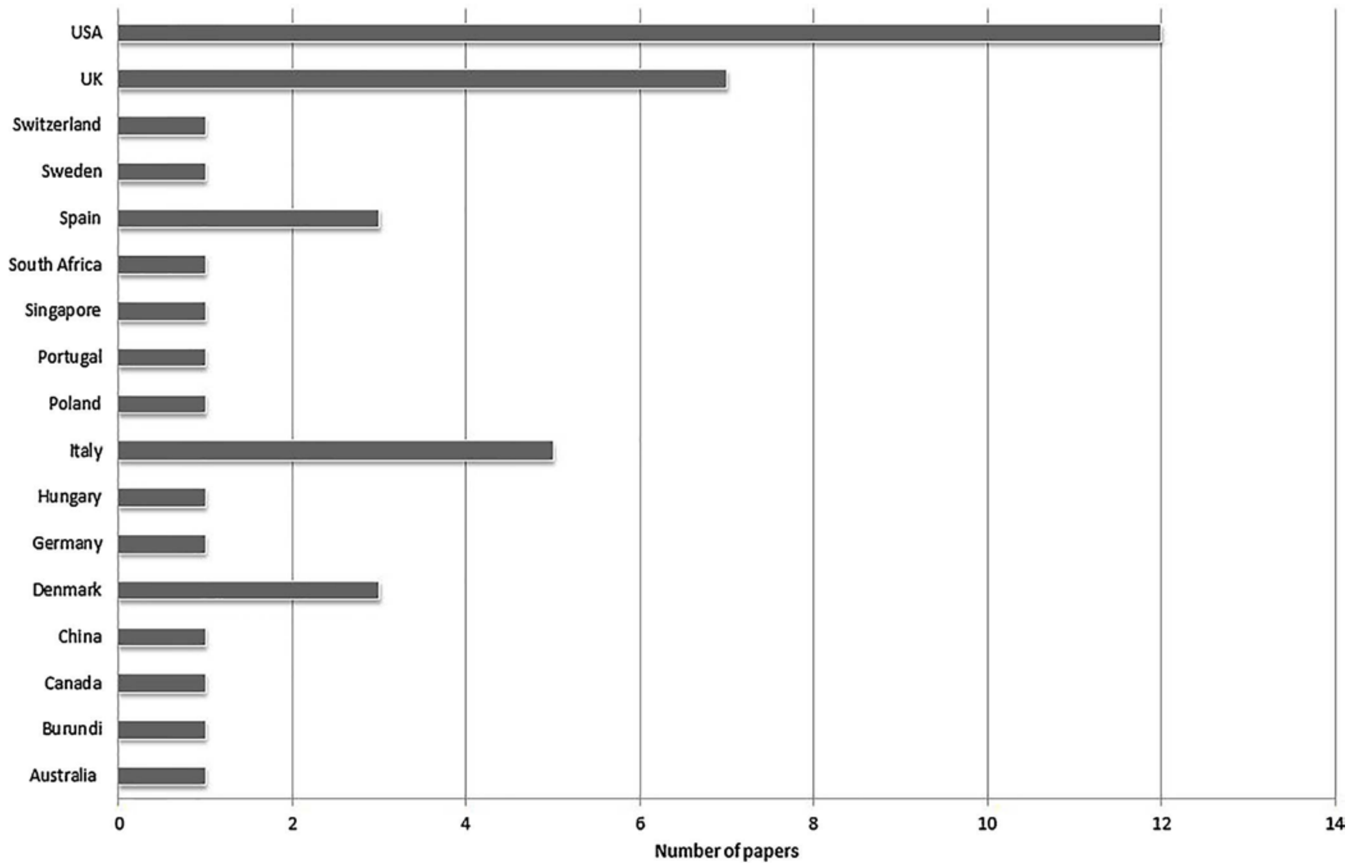

Fig. 1. Geographic distribution of papers on ED from EGI.

(e.g. Millennium Ecosystem Assessment, 2005), we organized ES into four categories: (1) *provisioning* services, (2) *regulating* services, (3) *cultural* services and human wellbeing, and (4) *habitat* or *supporting* services following both Escobedo et al.'s (2011) and Hasse et al.'s (2014) typologies for urban ES. Given the typology we assembled from the literature, we also present identified ED as seen in Table 2. For each EGI type, we synthesized the relevant literature with a geographic focus while updating the scientific jargon and correlating terminology. It should be noted, urban and peri-urban landscapes are known to support fiber, forage, and other non-human consumptive products (McLain et al., 2014); hence, since the number of studies on *provisioning* ES are still limited a breakdown of the varying EGI typologies is presented in Fig. 3.

4. Discussion

Several cities, international and non-governmental organizations (NGOs), and research institutions have provided guidelines for the design and management of different types of EGI (City of Vancouver, 2009; COST Action TU1201, 2017; EPA, 2011; SITES, 2017). In particular, in North America there were many examples of English-language policies for developing city-based food production systems – see Table 3 (CoDyre et al., 2015). According to these guidelines and policy programs, the main concerns are site safety and environmental quality related to food production and potential for contamination from both in-ground and airborne sources. Sustainable and environmentally-friendly practices have also been developed, for example: use of organic permaculture-based agricultural methods, water harvesting techniques, and composting systems. Most of this literature frequently specifies city planners to develop a context-specific list of nondesirable or not recommended plants due to allergenic potential or other possible negative effects to human health (Cariñanos et al., 2014; Lorenzoni-Chiesura et al., 2000).

A more in-depth examination of the EGI typologies is provided and is based upon one macro-category, EGI and urban agriculture as well as eight sub-classifications: (1) edible urban forests and edible urban greening, (2) edible forest gardens, (3) historic gardens and parks and botanic gardens, (4) school gardens, (5) allotment gardens and

Fig. 2. Examples of EGI types for urban areas in different international and geographical contexts: (a) domestic garden in Italy, (b) rooftop kitchen garden in Italy, (c) an allotment garden in Finland, (d) date palm streetscape in the United Arab Emirates (e) an urban agriculture lot in Germany, (f) sour-orange street trees in Greece, (g) a riparian urban-agricultural zone in Japan, and (h) vegetables in the Summer Garden park in Saint Petersburg, Russia.

community gardens, (6) domestic and home gardens, (7) edible green roofs and vegetable rain gardens, and (8) edible green walls and facades. The following will detail each EGI typology and present key research findings identified during the review process as well as specific ES points relating to each classification.

4.1. ***EGI and urban agriculture***

In this systematic and analytical literature review, we have introduced a new concept of EGI that enhances ES in urban areas and applies agro-ecological and UPAF-based management practices that makes cities more sustainable and resilient. This concept, to some degree, overlaps with urban agriculture; however, it stresses a non-EGI inclusive position in terms of farming practices. For example, Ackerman et al. (2014) defined urban agriculture in the form of green infrastructure, urban farms, and community food gardens that help reduce urban heat island effects, mitigate urban storm water impacts, and lower the energy use associated with food transportation. Overall, we found that several articles stated the principal benefits of urban agriculture and EGI in cities were related to the production of food in close proximity to its consumers (Eigenbrod and Gruda, 2015; Gerster-Bentaya, 2013; Lee et al., 2015; Lovell, 2010). This benefit is particularly significant as it can reduce food transportation from remote farming areas and, therefore, reduce food mileage and subsequent pollution emissions (Lee et al., 2015).

Lee et al. (2015) illustrates that for the 51 km^2 greater metropolitan area of Seoul, South Korea, the implementation of urban agriculture would reduce annual CO_2 emissions by 11.7 million kg. This offset value is the same amount of annual CO_2 sequestered by 20 km^2 of pine forests and 10.2 km^2 of 20-year-old oak forests. Similarly, EGI could provide employment opportunities and thus contribute to reducing unemployment and poverty alleviation in cities as well as create stronger ties within the community (Thornbush, 2015). Other publications documented some of the limitations or costs associated with EGI, and we refer to these as ED. The controversy related to the detrimental effects on human health caused by the consumption of food produced in urban sites is regularly discussed and emphasized via the uptake and eventual accumulation of trace metals in plant tissue. This process differs according to crop type, species, and plant parts (Säumel et al., 2012; von Hoffen and Säumel, 2014; Warming et al., 2015). We have found robust implemented urban EGI systems that takes into account trace metals can assist in counterbalancing external food resources (Chen et al., 2015; Olowoyo and Lion, 2016; Säumel et al., 2012).

4.2. *Edible urban forests and edible urban greening*

Edible urban forests and urban greening have been generally defined under the term urban food forestry and refers to “the intentional and strategic use of woody perennial food producing species in urban edible landscapes to improve the sustainability and resilience of urban communities” (Clark and Nicholas, 2013). The difference between conventional forms of UPAF and urban food forestry is its focus and use of perennial woody plants for fruit and nut production (see “food trees”, Clark and Nicholas, 2013). McLain et al. (2012) identified an alternative view of urban forests as places where people inhabit nature through the production of edible landscapes. Poe et al. (2013) highlighted that urban forests in Seattle, USA contain non-timber forest products that provide a variety of wild food products, medicine, and materials for the wellbeing of urban residents. von Hoffen and Säumel (2014) found that the consumption of non-vegetable fruits growing on inner-city sites in Berlin, Germany did not pose a risk to human health.

Nevertheless, fruit trees in cities are indeed high-maintenance dependent crops, requiring pruning, fertilization, and adequate water to produce fruits that can then be consumed – incurring greater overall costs. Still, a co-benefit that compensates fruit producing trees is they can counteract allergenic pollen production and minimize specific ED to human health (Escobedo et al., 2011). Lafontaine-Messier et al. (2016), for example, investigated and evaluated the financial potential of the establishment of food trees in two urban public parks of Villa El Salvador, Peru with the help of local inhabitants. They found that the use of food trees in public green areas appeared to be a financially viable alternative for both the municipality and its inhabitants.

4.3. *Edible forest gardens*

An edible forest garden is another relatively new concept with origins in North America and, more recently, in the UK dating back a quarter century (Crawford, 2010). This garden typology, also referred to as a “multi-strata system”, has been introduced in tropical Asia and Africa, Central America, and temperate and subtropical China. An edible forest garden can be described as being a perennial polyculture that mimics a forest ecosystem (Jacke and Toensmeier, 2005). A simple forest garden generally contains three levels: (1) an overstory layer of tree crowns, (2) a middle canopy level composed of shrubs, and (3) a ground layer composed of herbs, vegetables, and flowers (Jacke and Toensmeier, 2005).

Edible forest gardens have the potential to provide several ES in cities; however, the majority of studies did not relate to our urban EGI concept due to where they had been conducted (i.e. rural tropical, temperate, and subtropical areas) (Crawford, 2010; Kaya et al., 2002; Perera and Rajapakse, 1991; Salafsky, 1994; Wiersum, 2004). Keeping within our EGI framework, edible forest gardens represented low-maintenance landscapes with dense vegetation which cover and reduce water requisites, inhibits weeds, and improves soil quality through the production of organic matter (Hemenway, 2009). We did not however identify any publications reporting relevant ED from these forest gardens.

4.4. *Historic gardens and parks and botanical gardens*

Historic gardens are architectural structures whose components are primarily horticultural and plant-based, which mean they are perishable and renewable (ICOMOS, 1982). These gardens are intended to provide humans with existential, recreation, and recuperation activities, and cognitive experiences in a setting that can contribute to an overall renewed awareness for a variety of cultural benefits (i.e. *cultural* ES). These cultural benefits also include garden related design, construction, and maintenance and can thus generate income and employment from their upkeep (Brandt and Rohde, 2007). The importance of botanical gardens is based on their status as centers for the study and understanding of plants and their use in the medicinal sciences. Botanical gardens’ maintenance costs often exceed revenues thus making their continued existence regularly questioned (Garrod et al., 1993). Botanical gardens do however provide multiple cultural, social benefits, and relating functions (Ward et al., 2010). Regrettably, they have historically contributed to the introduction and dispersal of alien and often invasive plants to local urban environments (Galera and Sudnik-Wócikowska, 2010; Reichard and White, 2001).

Table 1
ES indicators for different EGI types reported in scientific papers.

EGI Typology	ES	Indicators	No. of Papers	Reference
Edible urban forests and edible urban greening, urban food forestry	Provisioning services Food production, medicinal resources	Production of food (kg/ha)	8	Clark and Nicholas (2013); Lafontaine-Messier et al. (2016); McLain et al. (2012, 2014); Mullaney et al. (2015); Niemelä et al. (2010); Poe et al. (2013); Richardson and Moskal (2016)
	Regulating services Carbon sequestration, air pollution, stormwater runoff reduction	Carbon sequestration (kg/year), air pollution removal (tons/ha), % runoff volume reduction	4	Dobbs et al. (2011); Escobedo et al. (2011); McLain et al. (2012); Niemelä et al. (2010)
	Cultural services and human well-being Aesthetic, stress reduction	Human Well-Being Index	3	McLain et al. (2012); Niemelä et al. (2010); Poe et al. (2013)
	Habitat or supporting services Biodiversity, soil formation	Shannon H diversity index, % organic matter of top soil	5	Clark and Nicholas (2013); Dobbs et al. (2011); Escobedo et al. (2011); McLain et al. (2012); Niemelä et al. (2010)
Edible forest gardens	Provisioning services Food production, medicinal resources	Production of food (kg/ha)	9	Belcher et al. (2005); Bisseleua and Vidal (2008); Galhena et al. (2013); Kumar and Nair (2004); Kumar (2011); Perera and Rajapakse (1991); Salafsky (1994); Torquebiau (1992); Wiersum (2004)
	Regulating services Carbon sequestration, air pollution, stormwater runoff reduction	Carbon sequestration (kg/year), air pollution removal (tons/ha), % runoff volume reduction	5	Galhena et al. (2013); Kumar and Nair (2004); Kumar (2011); Mattsson et al. (2015); Torquebiau (1992)
	Cultural services and human well-being Aesthetic, stress reduction	Human Well-Being Index	4	Corazon et al. (2012); Galhena et al. (2013); Kumar and Nair (2004); Torquebiau (1992)
	Habitat or supporting services Biodiversity, soil formation	Shannon H diversity index, % organic matter of top soil	8	Bisseleua and Vidal (2008); Galhena et al. (2013); Kaya et al. (2002); Kumar (2011); Kumar and Nair (2004); Mattsson et al. (2015); Perera and Rajapakse (1991); Torquebiau (1992)
Historic gardens and parks and botanical gardens, School gardens	Provisioning services Food production, medicinal resources	Production of food (kg/ha)	3	Apostolides et al. (2015); Heyd (2006); McLain et al. (2014)
	Regulating services Carbon sequestration, air pollution, stormwater runoff reduction	Carbon sequestration (kg/year), air pollution removal (tons/ha), % runoff volume reduction	1	Donaldson (2009)
	Cultural services and human well-being Aesthetic, stress reduction	Human Well-Being Index	4	Fleszar and Gwardys-Szczesna (2009); Hardwick et al. (2011); Heyd (2006); Ward et al. (2010)
	Habitat or supporting services Biodiversity, soil formation	Shannon H diversity index, % organic matter of top soil	5	Donaldson (2009); Hardwick et al. (2011); Maunder (1994); Oldfield (2009); Ward et al. (2010)

Table 1 continued

EGI Typology	ES	Indicators	No. of Papers	Reference
School gardens	Cultural services and human well-being Aesthetic, stress reduction	Human Well-Being Index	10	Blair (2009); Cutter-Mackenzie (2009); Fleszar and Gwardys-Szczesna (2009); Graham and Zidenberg-Cherr (2005); Guitart et al. (2014); Hutchinson et al. (2015); Lineberger and Zajicek (2000); Miguel and Ivanovic (2011); Ozer (2006); Skelly and Bradley (2007)
Allotment gardens (UK) and community gardens (USA)	Provisioning services Food production, medicinal resources	Food production (kg/ha)	10	Bellows (2004); Breuste and Artmann (2015); Dennis and James (2016); DeSilvey (2003; Lin et al. (2015); McLain et al. (2014); McPhearson et al. (2013); Saldivar-tanaka and Krasny (2004); Speak et al. (2015); Wiltshire and Azuma (2000)
	Regulating services Carbon sequestration, air pollution, stormwater runoff reduction	Carbon sequestration (kg/year), air pollution removal (tons/ha), % runoff volume reduction	5	Dennis and James (2016); Lin et al. (2015); Matteson and Langellotto (2010); Pawelek et al. (2009); Speak et al. (2015)
	Cultural services and human well-being Aesthetic, stress reduction	Human Well-Being Index	15	Alaimo et al. (2008); Barthel et al. (2010); Bellows (2004); Breuste and Artmann (2015); Dennis and James (2016); DeSilvey (2003); Egli et al. (2016); Hawkins et al. (2013); Kingsley et al. (2009); Lin et al. (2015); Saldivar-tanaka and Krasny (2004); van den Berg et al. (2010); Wakefield et al. (2007); Wiltshire and Azuma (2000); Wiltshire and Azuma (continued on next page) (2000); Wood et al. (2016)
	Habitat or supporting services Biodiversity, soil formation	Shannon H diversity index, % organic matter of top soil	4	Dennis and James (2016); Matteson and Langellotto (2010); Pawelek et al. (2009); Speak et al. (2015)
Domestic gardens	Provisioning services Food production, medicinal resources	Food production (kg/ha)	5	Calvet-Mir et al. (2012); Cameron et al. (2012); Cilliers et al. (2013); Lin et al. (2015); Rowe (2009)
	Regulating services Carbon sequestration, air pollution, stormwater runoff reduction	Carbon sequestration (kg/year), air pollution removal (tons/ha), % runoff volume reduction	5	Cameron et al. (2012); Cilliers et al. (2013); Davies et al. (2011); Lin et al. (2015); Tratalos et al. (2007)
	Cultural services and human well-being Aesthetic, stress reduction	Human Well-Being Index	5	Calvet-Mir et al. (2012); Cameron et al. (2012); Cilliers et al. (2013); Lin et al. (2015); Rowe (2009)
	Habitat or supporting services Biodiversity, soil formation	Shannon H diversity index, % organic matter of top soil	2	Bigirimana et al. (2012); Davies et al. (2009)
Edible green roofs and vegetable raingardens	Provisioning services Food production, medicinal resources	Food production (kg/ha)	8	Aloisio et al. (2016); Astee and Kishnani (2010); Lin et al. (2015); Orsini et al. (2014); Richards et al. (2015); Tanaka et al. (2016); Whittinghill et al. (2013); Whittinghill and Rowe (2012)
	Regulating services Carbon sequestration, air pollution, stormwater runoff reduction	Carbon sequestration (kg/year), air pollution removal (tons/ha), % runoff volume reduction	8	Lin et al. (2015); Oberndorfer et al. (2007); Orsini et al. (2014); Richards et al. (2015); Tanaka et al. (2016); Ugai (2016); Wang et al. (2014); Whittinghill et al. (2014b)

Table 1 continued

EGI Typology	ES	Indicators	No. of Papers	Reference
	Cultural services and human well-being Aesthetic, stress reduction	Human Well-Being Index	1	Orsini et al. (2014)
	Habitat or supporting services Biodiversity, soil formation	Shannon H diversity index, % organic matter of top soil	2	Francis and Lorimer (2011); Orsini et al. (2014)
Edible green walls and facades	Provisioning services Food production, medicinal resources	Food production (kg/ha)	2	Mårtensson et al. (2016); Al-Kodmany (2014)
	Regulating services Carbon sequestration, air pollution, stormwater runoff reduction	Carbon sequestration (kg/year), air pollution removal (tons/ha), % runoff volume reduction	3	Manso and Castro-Gomes (2015); Raji et al. (2015); Al-Kodmany (2014)
	Habitat or supporting services Biodiversity, soil formation	Shannon H diversity index, % organic matter of top soil	2	Francis and Lorimer (2011); Al-Kodmany (2014)

Table 2
ED from different EGI types reported in scientific papers.

EGI Typology	ED	No. of Papers	Reference
Edible urban forests and urban greening	Risk of vegetables and soil contaminated by heavy metals and pollutants	1	von Hoffen and Säumel (2014)
	Allergies	3	Cariñanos et al. (2014); Dobbs et al. (2011); Escobedo et al. (2011)
	Fruit fall problems	1	Dobbs et al. (2011)
	Maintenance costs	1	Escobedo et al. (2011)
	Water consumption	1	Pataki et al. (2011)
	Water pollution from fertilizers and chemical inputs	1	Escobedo et al. (2011)
	Volatile organic compounds	4	Dobbs et al. (2011); Escobedo et al. (2011); Paoletti (2009); Russo et al. (2016)
	Invasive species	1	Escobedo et al. (2011)
School gardens	Risk of vegetables and soil contaminated by heavy metals and pollutants	1	Warming et al. (2015)
Allotment gardens (UK) and community gardens (USA)	Risk of vegetables and soil contaminated by heavy metals and pollutants	12	Alexander et al. (2006); Antisari et al. (2015); Bretzel et al. (2016); Izquierdo et al. (2015); Kim et al. (2014); Leake et al. (2009); McBride et al. (2014); Mitchell et al. (2014); Nathanail et al. (2004); Papritz and Reichard (2009); Samsøe-Petersen et al. (2002); Warming et al. (2015)
	Over application of chemicals	1	Bretzel et al. (2016)
Domestic gardens	Risk of vegetables and soil contaminated by heavy metals and pollutants	6	Alexander et al. (2006); Alloway (2004); Hough et al. (2004); Leake et al. (2009); Moir and Thornton (1989); Szolnoki et al. (2013)
	Water consumption	2	Domene et al. (2005); Syme et al. (2004)
	Invasive species	1	Bigirimana et al. (2012)
	Allergies	3	Otang et al. (2015); Paulsen et al. (2014); Tavares et al. (2006)
Historic gardens and parks and botanic gardens	Risk of vegetables contaminated by heavy metals and pollutants	1	Orecchio (2010)
	Invasive species	2	Galera and Sudnik-Wócikowska (2010); Reichard and White (2001)
	Maintenance costs	1	Garrod et al. (1993)
Green roofs and vegetable raingardens	Risk of vegetables contaminated by heavy metals and pollutants	1	Ye et al. (2013)
	Water consumption	2	Astee and Kishnani (2010); Whittinghill and Rowe (2012)
	Water pollution from fertilizers and chemicals	4	Aloisio et al. (2016); Oberndorfer et al. (2007); Pataki et al. (2011); Whittinghill et al. (2014a)
Edible green walls and facades	Installation costs	2	Mårtensson et al. (2016); Al-Kodmany (2014)

In terms of ED, a study conducted by Orecchio (2010) did find high concentrations of polycyclic aromatic hydrocarbons (PAH) in the Botanical Garden of Palermo, Italy. These PAHs have been classified by the International Agency for Researches on Cancer as probable or possible human carcinogens. The authors point out that levels were higher than the maximum concentrations allowed by Italian legislation for green areas and were nearly two to three times higher than samples obtained from adjacent urban reference sites and about 20 times higher than those of rural sites. Such an example points out the potential to human health regardless of recreational benefit.

4.5. *School gardens*

School gardens can positively contribute to a child's education and their ability to identify fruit and vegetables and thus increase their awareness of, and willingness to, eat healthier fruits and vegetables (Hutchinson et al., 2015; Lineberger and Zajicek, 2000; Miguel and Ivanovic, 2011). Moreover, they have the potential to conserve agro-biodiversity and positively influence the diets of urban school children (Guitart et al., 2014). Garden-based learning also positively impacts academic performance and fruit and vegetable consumption (Berezowitz et al., 2015). The use of school gardens as a teaching and learning resource to introduce basic biological principles increases the effectiveness of the educational process. In particular, they can: (1) provide students an opportunity for direct contact with nature, (2) develop students' talents and interests as well as teach them to conduct ecological and phonological observations, (3) teach them to recognize plants and animals, and (4) help acquaint them with the necessary knowledge for growing, fertilizing, and tending plants (Fleszar and Gwardys-Szczesna, 2009).

In a secondary school in New York, USA, Wansink et al. (2015) measured the change in vegetable selection and plate waste when school-grown salad greens were incorporated in the cafeteria's school lunch program. When the cafeteria menu included salads consisting of food grown by students, the percentage of those who selected salads with their meals increased from 2 to 10% and on average students ate two-thirds of their salads. In addition, negatively the increased salad selection amounted to an increase in discarded plastic plate waste. We did not find papers that focused on other *provisioning* ES provided by school gardens and note this as an important area for future research.

4.6. *Allotment gardens and community gardens*

Allotment gardens were reported to provide important ecosystem functions such as pollination, seed dispersal, and pest regulation (Barthel et al., 2010). Barthel et al. (2010) found that allotment gardens can serve as "communities-of-practice, where participation and reification interact and socio-ecological memory is a shared source of resilience of the community by being both emergent and persistent". Middle et al. (2014) explored the potential of integrating community gardens into standardized and under-utilized public park landscapes and, as such,

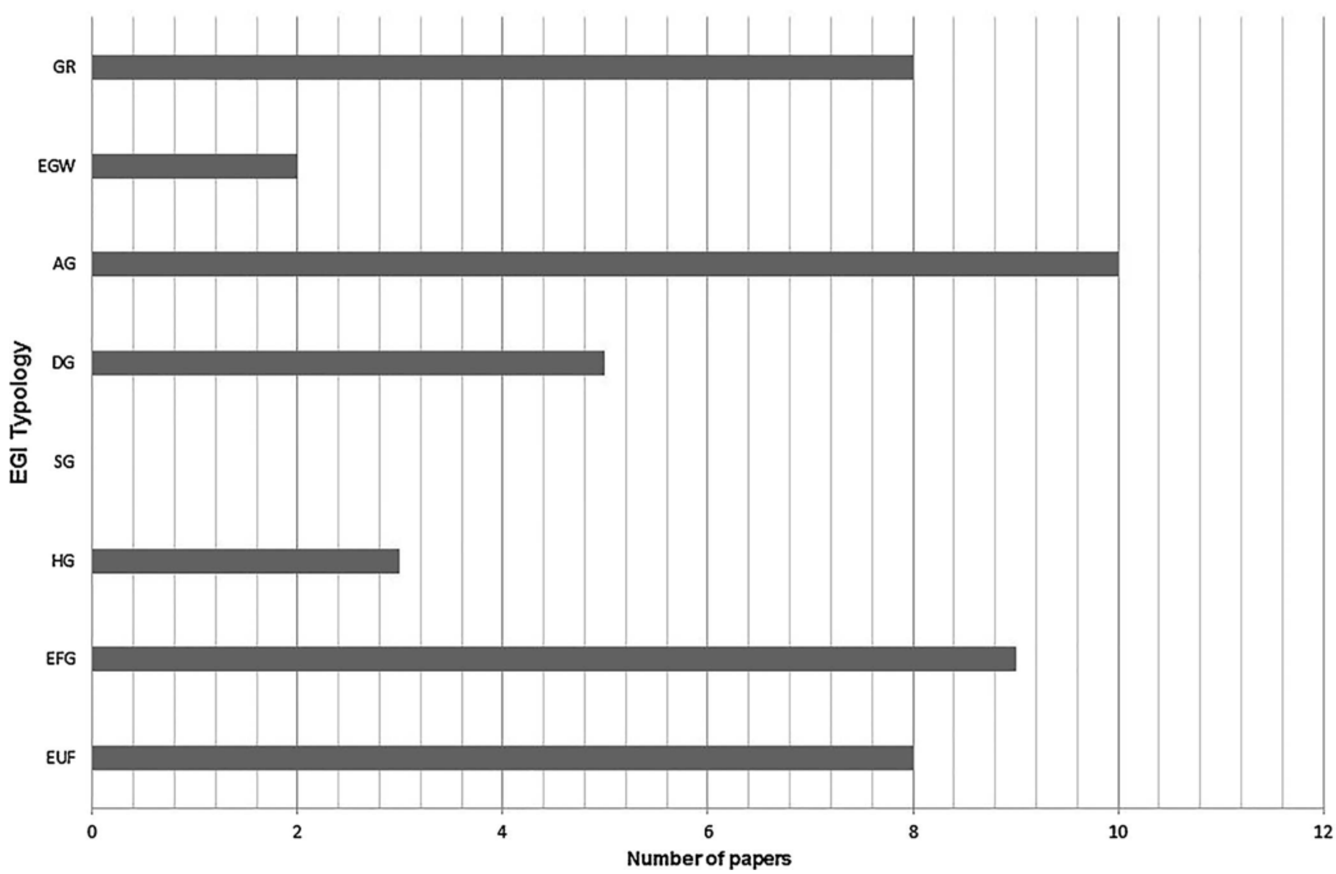

Fig. 3. Number of articles on provisioning ES by different EGI typologies (GR = green roofs, EGW = edible green walls, AG = allotment gardens, DG = domestic gardens, SG = school gardens, HG = historic gardens and botanical gardens, EFG = edible forest gardens, EUF = edible urban forests).

Table 3
Examples of English-language policy guidelines emphasizing city-based food production.

City, Country	Policies and guidelines	Online Reference
Yarra, Australia	The Council established the *Urban Agriculture Advisory Committee* with the aim to provide the Council with information about proposed urban agriculture initiatives and to generally support and encouragecommunity gardening networks in Yarra.	http://www.yarracity.vic.gov.au/environment/Community-gardens/
Victoria, Canada	The City of Victoria recognizes community gardening as a valuable community recreational activity that contributes to health and well-being, positive social interaction, community development, environmental education, connection to nature, protection, and the use of open space and economical, nutritious food production and food security.	http://www.victoria.ca/assets/Departments/Parks~Rec~Culture/Parks/Documents/community-garden-policy.pdf
Minneapolis City Council, USA	The Minneapolis City Council adopted The Homegrown Minneapolis Report in June 2009 with a variety of recommendations related to improving the growth, processing, distribution, consumption, and waste management of healthy, locally grown foods within the city.	http://www.minneapolismn.gov/cped/planning/cped_urban_ag_plan
Las Cruces City Council, USA	The objective of the plan is to provide informed recommendations to advance and guide the city's efforts to support and expand food and agriculture activities within Las Cruces.	http://www.las-cruces.org/~/media/lcpublicwebdev2/site%20documents/article%20documents/community%20development/planning%20and%20revitalization%20docs/urban%20ag/ua%20policy%20plan%20draft%202516.ashx?la=en

represent an innovative approach for providing ES and green space functionality. Community gardens can also have the potential for "nutrition intervention approaches" for increased fruit and vegetable intake (Alaimo et al., 2008). Similarly, Hawkins et al. (2013) stated that participating in allotment gardening practices and being physically active within the garden itself was beneficial in terms of relaxation and stress management. Indeed, allotment gardening can play a key role in promoting mental wellbeing and usefulness as a preventive health measure (Wood et al., 2016).

In terms of ED, Warming et al. (2015) offer an example where they calculated the hazard quotients (HQs) associated with soil ingestion, vegetable consumption, measured trace-element concentrations, and tolerable intake for five common crops cultivated in allotment gardens, school gardens, and a university garden in Copenhagen, Denmark. They found that HQs for trace elements (i.e. As, Cd, Cr, Cu, Ni, and Zn) did not pose health risks. However, exposure to Pb-contaminated sites can lead to unacceptable risks not caused by direct vegetable consumption but rather by unintentional soil ingestion.

In the USA, Mitchell et al. (2014) conducted analyses for heavy metals in 564 soil samples from 54 New York City (NYC) community gardens and found that in 70% of the gardens at least one sample exceeded health-based guidance values. In another study, paired vegetable-soil samples were collected from seven community gardens in NYC and ten gardens and urban farms in Buffalo, NY. All samples were analyzed for Pb, Cd, and Ba and the authors found that soil and vegetable metal concentrations did not correlate while vegetable concentrations varied by crop type. Also Pb was below health-based guidance values, comparatively, both for US EPA and EU food standards in virtually all fruits. Specifically, 47% of root crops and 9% of leafy greens exceeded guidance values; while, over half the vegetables exceeded 95% of market basket concentrations for Pb and soil particle adherence was more important than Pb uptake via roots (McBride et al., 2014).

In Madrid, Spain pseudo-total and gastric-bioaccessible concentrations of Ca, Co, Cr, Cu, Fe, Mn, Ni, Pb, and Zn were determined in a total of 48 samples collected from six community urban gardens with different characteristics (Izquierdo et al., 2015). A conservative risk assessment with bioaccessible concentrations in two scenarios, that is, adult urban farmers and children playing in urban gardens revealed acceptable levels of risk. It demonstrated large differences between urban gardens depending on land use history and proximity to high traffic areas, especially near the city center. Only in the worst-case scenario, in which children who used gardens as recreational areas and ate the products grown there, did the risk exceed the limits of acceptability (Izquierdo et al., 2015). Contaminant concerns in com- munity gardens have often been alleviated by the use of raised beds, which can be considered an easy and effective best management practice for reducing soil contamination risk (Kim et al., 2014).

4.7. *Domestic gardens*

Domestic gardens are an important component of urban GI and have the potential to make significant contributions to urban biodiversity (Zhang and Jim, 2014). Domestic gardens provide a large set of ES, *provisioning* being the most obvious while *cultural* services are the category reported as most valued (Calvet-Mir et al., 2012). Little information has specifically identified the role of the domestic garden in *regulation* services such as climate change mitigation via carbon sequestration, but the effectiveness of garden plants and soils for carbon offsetting will strongly depend on design (i.e. types of vegetation, density, biomass, and coverage). In addition, according to Cameron et al. (2012) they can provide stormwater regulation services to the urban matrix and alleviate related urban soil quality problems.

Research by Moir and Thornton (1989) in 94 domestic gardens and municipal allotments in nine British towns and cities found that the geometric mean of soil Pb concentration were five times higher than values previously found on agricultural soils, while the mean Ca concentration was similar. Szolnoki et al. (2013) determined heavy metal concentrations in urban garden soils in Szeged, Hungary and found that Cu, Zn, and Pb concentrations were considerably greater in the topsoil whereas in Ni, Co, Cr, and As they did not accumulate. A principal component analysis revealed the geogenic origin of Ni, Co, Cr, and As differentiated two groups of anthropogenic metals (i.e. Pb, Zn, Cd, and Cu) thereby indicating the different sources of these heavy metals. For example, Cd exceeded the “B” limit value in some gardens due to point sources and its concentrations were slightly greater in the topsoil. Thus, the accumulation of heavy metals differed according to crop plant species and cultivars as frequently reported in much of the literature (Alexander et al., 2006). Alexander et al. (2006) furthered their research by pointing out highly significant differences in metal content between cultivars of different vegetables. Similarly, some edible species commonly grown in domestic gardens such as *Allium sativum* L., *Mangifera indica* L., *Anacardium occidentale* L., *Daucus carota* L., *Lactuca sativa* L. *Brassica oleracea* L., *Carica papaya* L., *Musa paradisiaca* L., *Citrus limon* (L.) Osbeck, *Citrus sinensis* (L.) Osbeck, *Capsicum annuum* L., *Pastinaca sativa* L., *Solanum tuberosum* L., and *Solanum lycopersicum* L. can cause allergic contact dermatitis to some people (Otang et al., 2015; Paulsen et al., 2014; Tavares et al., 2006).

4.8. *Edible green roofs and vegetable rain gardens*

The installations of green-roof systems are popular and have been promoted worldwide, especially in the USA, Europe, and Asia (Li and Yeung, 2014). Whittinghill et al. (2014b) has compared the carbon content of nine in-ground and three green roof landscape systems of varying complexity to determine their carbon sequestration potential. They found that landscape systems containing more woody plants, such as shrubs (65.67, 78.75, and 62.91 kg m^{-2}) and herbaceous perennials and grasses for the in-ground and green roofs (68.75 and 67.70 kg m^{-2}) respectively had higher carbon content than other landscape systems. However, a vegetable and herb garden and vegetable green roof contained only moderate carbon densities (54.18 and 11.03 kg m^{-2}). Carbon life cycle analyses have often found that the high maintenance, high chemical and energy inputs associated with green roofs can lead to overall net C emissions (i.e. ED) (Blackhurst et al., 2010; Bozorg Chenani et al., 2015).

In Asia, Astee and Kishnani (2010) found that Singapore’s public housing estates were suitable for rooftop farming and the implementation of a nationwide program that could result in a 700% increase in domestic vegetable production. This amount could satisfy domestic demand by 35.5% and reduce food imports while also decreasing Singapore’s annual carbon emissions footprint by 9,052 metric tons. Orsini et al. (2014) explored the production capacity of rooftop gardens in Bologna, Italy and found that rooftop gardens could provide more than 12,000 t $year^{-1}$ of vegetables to Bologna, satisfying 77% of the inhabitants’ requirements. In addition, vegetable raingardens often referred to as green-roof systems could also be integrated to further augment food production and reduce urban stormwater runoff (Richards et al., 2015).

Conversely, the literature also reported that green roof runoff, relative to atmospheric precipitation inputs, might contain higher concentrations of nutrient pollutants such as N and P (Oberndorfer et al., 2007). Oberndorfer et al. (2007) and Pataki et al. (2011) demonstrate a gap in the research and conclude that further investigations are needed to confirm these findings. Additionally, Whittinghill et al. (2014a) compared three green-roof vegetation types (i.e. unfertilized *Sedum* and native prairie species mixes, a fertilized vegetable, and herb species mix) on stormwater runoff quantity over three growing seasons and runoff quality during one growing season. They found that the prairie covered green roofs had the greatest reduction in runoff; almost half that of *Sedum* or vegetable producing green roof treatments. The edible vegetation type had no effect on runoff nitrate-nitrogen (NO_3^-) concentrations, but NO_3^- concentrations decreased over the course of the growing season. Runoff P concentrations also decreased over time in the *Sedum* and prairie treatments, which were lower than P concentrations from the vegetable green roof throughout the growing season. Overall, the authors found that vegetable production with careful nutrient management would not have a negative impact on stormwater retention or runoff water quality. There are several papers on cost-effectiveness and life cycle assessment of green roofs (Blackhurst et al., 2010; Bozorg Chenani et al., 2015; Peri et al., 2012) which did not utilize edible plant species.

4.9. ***Edible green walls and facades***

Research on edible plant species in these EGI types is limited and recent (Larcher et al., 2013; Mårtensson et al., 2016). Edible plants in living wall systems have been reported to improve the local environment and the potential for *provisioning* ES in terms of harvestable goods (Mårtensson et al., 2016). In terms of their cost efficacy, Mårtensson et al. (2016) state the installation costs of living wall systems is often expensive, which means that they are installed on high profile buildings so as to add more aesthetic visual effects to the urban landscape. Recently, facade technology integration has been extensively implemented and planned throughout major cities in China, and to a lesser extent North America, the Middle East and Europe (Al-Kodmany, 2014). Al-Kodmany (2014) points out their enhancement of environmental performance and dramatic visual effect promote a range of technical provisions that accommodate vertical urban farming, aesthetics, efficient thermal performance, daylight penetration, and interior environment control. In addition, they can form a vital system that can improve the holistic approach to buildings offering an ever-growing need for combined food, housing, and integrated sustainable solutions. Facade design have been found in skyscraper exoskeletons and innovative skins reshaped to support ecological and agro-green design principles.

5. **Conclusion: recommendations for incorporating EGI**

We found increased concerns in the reviewed literature regarding the suitability of possibly contaminated urban land and its use for food growing systems. But guidelines exist and regularly recommend against growing crops less than ten meters from busy roads, particularly in countries where lead-based fuels are still used (Deelstra and Girardet, 2000). Another commonly reported guideline is using buildings and large masses of woody vegetation as barriers between crops and roads as a means of reducing trace metal contamination (Säumel et al., 2012).

Proper planning guidelines indicate that when designating an area as suitable for EGI, that knowledge of past site history, existing soil properties and distance from possible nearby sources of pollution, especially traffic, be taken into account in order to prevent crop contamination. Similarly, the overuse of chemicals needs to be prevented (Bretzel et al., 2016). Exceedingly high heavy metal concentrations in urban grown fruits and vegetables must be strictly related to specific safe zones in the city where plants are going to be grown. As such, when plants are cultivated near pollution-emission sources (e.g. main roads or factories), risks of heavy metal contamination are increased approximately 1.5-fold when fruits and vegetables are grown 10 m from the road as compared to 60 m (Antisari et al., 2015).

Our review identified a commonly reported need for more detailed and region-specific education tools, information and clearing houses on products, best agriculture practices, and techniques so as to implement and promote rooftop agriculture practices worldwide (Ugai, 2016). Examples of more effective governance instruments and experiences are also needed to better identify successful approaches for integrating city-based food production into urban sector policies and urban land use planning instruments, and to facilitate the development of safe and sustainable urban agriculture (FAO, 2007). Future research should also address the application of climate-smart agriculture practices (Dubbeling, 2014; Scherr et al., 2012) for the design, planning, and management of urban GI and NBS to mitigate climate change effects, increase food security, and provide sustainability-based guidelines.

We note that a main limitation of our literature review was that we examined only relevant English language literature. For example, a search for the Spanish language term "*agricultura urbana*" (i.e. urban agriculture in

English) for articles in agricultural, applied social sciences, biological sciences, exact earth sciences and engineering in the Scientific Electronic Library Online (SCIELO) – a search engine focusing on scientific literature from Latin America and emerging countries – returned 64 publications from throughout Latin America. Cities in emerging counties such as Rosario, Argentina and others in Brazil and Cuba have established EGI policies and are regularly used as study sites for relevant Spanish and Portuguese language articles, reviews, and books that would indeed fit our criteria (Coronel et al., 2015; Madaleno, 2000; Miguel and Ivanovic, 2011). Similarly, a search for French, Chinese, Arabic, and Russian language scientific literature would have likely produced relevant publications from France, Africa, Middle East, Asia, and Eastern Europe (Bellows, 2004; Crawford, 2010; Di Leo et al., 2016).

In this review, we have highlighted that EGI together with the beautification of a city, contribute to not only urban food production but nutritional, socioeconomic, and environmental co-benefits (Madaleno, 2000). However, poor urban agricultural practices can have a negative effect on air pollution by-way-of associated pesticide use, odors, smoke and dust emissions, allergenic pollens, and residue production. Nitrogen compounds emitted from agricultural sources in particular affect air quality in two primary ways, that is: (1) NH_3 emissions resulting from fertilizers, and (2) NO_x from fuel combustion in agricultural equipment (Dale and Polasky, 2007). Woody plant selection can also affect volatile organic compound emission and subsequent O_3 air pollution (Escobedo et al., 2011). We note that most reviewed literature has not taken into account ED and this would be a timely topic for future research.

With the ever increasing demand for livable space we conclude that ES and NBS from EGI, in conjunction with proper agricultural and urban design practices, is opportune for urbanization-related research and interlinking environmental food security norms and policies. This research extends to establish relevant resilient food security systems and to promote the use of edible gardens, roofs, walls, and facades. Our review shows that the urban potential for ES provision from an EGI framework, via the developed indicators and our proposed typology, indicate a research gap in which unknown or a little amount of examination indicates the socio-ecological benefits of such an agenda. Results from this novel research could be used for developing sustainable urban agricultural practices and community participation programs for policy uptake. As discussed, several cities have already integrated different types of EGI into their urban management plans. Management and planning must take into account context-specific geographic (e.g. climatic zones), social (e.g. community development, educational benefits, and equity), and economic (e.g. employment opportunities and inexpensive food sources) requirements. Recommendations can further be extended to incorporate the potential EGI benefits for sustainability-based living and raise societal awareness of food sources and quality (i.e. organically grown fruits and vegetables). Future research should continue to focus on EGI food quality protection from contamination and other possible opportunities from hydroculture practices.

We propose that EGI is a rather novel concept that intertwines environmental, social, and economic co-benefits and locates food sources closer to city-dwellers thus increasing food security and lessening food transport distances. It reinforces low-energy and chemical input practices, less human consumption of processed foods, and teaches people from all socioeconomic levels the equitable benefits of locally grown food. An EGI approach can thereby play a vital role in providing city planners and policy makers further justification for green space conservation and utility. Findings from our review indicate that implementing, incorporating, administering, and promoting an urban EGI approach will require context-specific expertise, information, and knowledge offered via local governments and NGOs alike. It will need to integrate interdisciplinary practices and experiences from diverse fields such as urban agriculture, UPAF, landscape design, horticulture, agronomy, urban planning, civil engineering, and others.

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