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What happens to nitrogen and phosphorus nutrient contributions from green roofs as they age? A review

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ABSTRACT

Green roofs (GR) have gained widespread popularity in cities due to their multiple benefits. This review synthesizes the latest knowledge around GR ageing and the associated changes in nutrient runoff quality from GRs. Most GR studies have focused on water quality trends for the first 10 years. Information about nutrient levels in runoff, vegetation, and substrate for older GRs (>10 years) is extremely limited and based on monitoring at snapshot points in time, rather than continuously over time, mainly for GRs in Europe, UK and the USA. Nitrogen (N) and phosphorus (P) levels in GR runoff are initially high, especially in the first-year post-installation (NO_3: 0.08-100 mg/L, PO_4: 0.01-13 mg/L) and subsequently decline to lower concentrations over time (NO_3: 0.05-7 mg/L, PO_4: 0.01-1.2 mg/L for GRs over 10 years old). Green roof substrate received most research attention but there is growing interest in how vegetation and microbiome characteristics change with time. The review provides a conceptual model of GR ageing that includes the impacts of seasonal changes and other disturbances (e.g., fertilizer applications, extreme events) on nutrient runoff quality. Recommendations for GR design and management are also provided. Future areas of research should focus on long-term holistic monitoring of all GR components across more climate zones, especially arid and tropical climate zones. Studies comparing GRs of different ages are encouraged. Ageing experiments conducted under controlled laboratory conditions complement field monitoring studies and provide a continuous timeline of changes in GR components and runoff quality as they age.

1. Introduction

As the world population gravitates towards urban centres, city expansion has resulted in environmental problems that include increased flood risk, poor water and air quality, biodiversity loss and increase in urban heat. Nature-based solutions are widely implemented in cities across many regions to mitigate some of the negative environmental impacts; starting in Europe in the 1960s, then the United States, Hong Kong, Singapore, and most recently, as part of the Sponge City movement in China (Xiao et al., 2014, Vijayaraghavan, 2016, Nguyen et al., 2019). Green roofs are an example of a popular nature-based solution that has been implemented in urban areas, which now also includes rooftop agriculture (e.g., Harada et al., 2018). With the widespread implementation of GRs and rooftop agriculture across cities, their associated water quality impacts are of concern to the sustainability and liveability of urban environments.

While GRs neutralize rainfall and remove trace metals (e.g., Bliss et al. 2009; Van Seters et al. 2009; Vijayaraghavan et al. 2012, Vijayaraghavan and Joshi, 2014, Lim et al., 2021), many studies found that GR runoff quality contain high levels of nitrogen (N) and phosphorus (P) (e.g., Hathaway et al., 2008, Gregoire & Clausen, 2011, Malcolm et al., 2014, Beecham & Razzaghmanesh, 2015, Harper et al., 2015, Zhang et al., 2015, Gong et al., 2019, 2020, Castro et al., 2020, Lim et al., 2021), sometimes higher than other vegetated systems such as woodland, grassland, rain gardens and constructed wetlands (e.g. Barr et al., 2017). Mitchell et al. (2017) found that phosphate concentrations from the GR in the first-year post-installation was close to concentration levels from wastewater but decreased to values similar to agricultural systems (i.e., alfafa field) in its 4th year. The poorest nutrient runoff quality occurs in the early stages of the GR's lifespan (e.g., Vijayaraghavan et al. 2012, Harper et al. 2015, Kuoppamäki & Lehvävirta, 2016, Lim et al., 2021) but water quality generally improves with time as the substrate and vegetation stabilize (e.g., Köhler & Schmidt, 2003, Aitkenhead-Petersen et al., 2011, Gregoire & Clausen, 2011, Razzaghamanesh et al., 2014, Beecham & Razzaghamanesh, 2015, Todorov et al., 2018, Kuoppamäki et al., 2021).

Current information about the water quality performance of older GRs (> 10 years of age) are based on snapshot monitoring at a particular

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stage of their lives, often in comparison with younger GRs (e.g., Mitchell et al., 2017, Okita et al., 2018, Todorov et al., 2018, Akther et al., 2020). The limited evidence shows conflicting water quality impacts from these older GR systems. Some older GRs (>20 yrs) were releasing nitrate in their runoff (Mitchell et al., 2018, 2021) while a 43-year-old GR, monitored by Speak et al. (2014) in the UK removed N and P nutrients at the same rate as younger GRs located elsewhere (e.g., Todorov et al., 2018, Akther et al., 2021). These inconsistent findings are due to the unique vegetation and substrate characteristics, climatic conditions and management activities associated with different GRs.

Variations in GR runoff quality over time are due to changes in the properties of the substrate, vegetation, and soil microbiome (Berndtsson, 2010, Buffam and Mitchell, 2015, Mitchell et al., 2017). Fig. 1 provides a visual comparison of changes in GR vegetation over a period of 9 months. Rapid vegetation growth occurred initially but the brown color of the grass in its 9th month indicates unhealthy growth due to lack of water and nutrients. While the substrate is considered the main source of nutrients lost from the GR, the vegetation and soil microbiome also play important roles in the nutrient dynamics within the GR (Berndtsson, 2010, Rowe, 2011, Buffam & Mitchell, 2015, Vijayaraghavan, 2016). These components interact in complex ways with each other (e.g., Thuring & Dunnett, 2014, Mitchell et al., 2021).

Most of the current understanding about GRs relates to the substrate component as they are the main source of nutrient losses in GR runoff (e.g., Hathaway et al., 2008, Whittinghill et al., 2015, Mitchell et al., 2017). Comprehensive reviews by Kazemi & Mohorko (2017), Jennett & Zhang (2018) and Vijayaraghavan et al. (2019) provide the latest knowledge and understanding of substrates properties and their impact on runoff quality. A common theme in these reviews is the importance of characterizing substrate properties and careful selection for use on GRs. More recently, reviews about the GR soil microbiome acknowledge the role these living organisms play in GR vegetation dynamics (e.g., John et al., 2017, Fulthorpe et al., 2018). The review by John et al. (2017) focuses on how mycorrhizal fungi improve plant diversity, drought resilience, runoff quality, plant nutrient use efficiency and carbon sequestration on GRs. Thuring and Grant (2016) provide a review of the research and practice of temperate GR biodiversity linking soil and plant ecology with urban fauna. Buffam and Mitchell (2015) provide a comprehensive review of the nutrient cycling processes in GRs and alluded to the important issue of GR ageing and its impact on nutrient levels in runoff. Their review included a conceptual model of the long-term nutrient cycling dynamics. This review draws from Buffam and Mitchell (2015)'s work and focuses specifically on GR ageing and contributes to the body of work by a) synthesising existing information about trends in nutrient runoff quality over time and b) collating and assessing information relating to the temporal changes in GR components and how these may be related to runoff quality and c) updating the conceptual model of GR ageing with new information reviewed in this study. A holistic consideration of GR components and runoff quality is important and necessary for the improved design and maintenance activities required at different stages of their lifespan. As such, the review includes information relevant to GR ageing that are published in various fields including hydrology, soil science, microbiology, ecology and urban planning. In this review, GRs less than 5 years of age are considered young due to the fact they exhibit considerable variability in runoff quality (e.g., Buffam et al., 2016, Karczmarczyk et al., 2018, Lim et al., 2021). GRs over 10 years are considered old in this paper. This review also focuses on GRs with vegetation that are not designed for the purposes of rooftop farming as rooftop farming is a relatively new phenomenon.

The literature used for this review included only literature published in English and sourced from academic databases that included the ISI Web of Science, Science Direct and Google Scholar. The literature included mostly academic papers published in journals, dissertations, books and government reports. The keywords used to search for the articles include green roof, nutrients, nitrogen, phosphorus, vegetation, substrate, fungi, microbiome. There was no restriction on the literature publishing period and literature published up to 2022 were considered in this review.

2. Understanding nutrient losses from green roofs

This review is structured around nutrient pathways as they enter and leave the GR (Fig. 2). Nutrients enter the GRs from external sources such as the atmosphere, urban greenery, wildlife and through maintenance activities such as fertilizer applications (Wang et al., 2017a). Losses of nutrients in runoff occur when nutrient stocks in the GR are greater than vegetation uptake and substrate storage and vary over time depending on the nature of changes in the various GR components (Buffam and Mitchell et al., 2015). The uptake, transformations and release of nutrients are a result of complex interactions between the living (vegetation, community of living organisms) and non-living (substrate) components. Some important processes include the decomposition of organic matter, nutrient storage via adsorption and nitrification activities (e.g., Mitchell et al., 2017, John et al., 2017).

2.1. Nutrient losses in green roof runoff over time

2.1.1. Temporal changes in nutrient levels in green roof runoff

Table 1 summarises the results of studies that compared the runoff quality of GRs of various ages. Table 2 summarises available knowledge about nutrient runoff for older GRs (> 8 years of age), mainly from GRs in northern Europe (UK, Germany, Sweden) and the USA. Fig. 3 (concentration) and Fig. 4 (mass flux) shows nutrient losses from GRs at different stages of their development over time. Both figures are based on data compiled from studies that report nutrient concentration/mass flux. These studies do not necessarily measure all nutrient forms presented in the figures so the temporal trend for each water quality variable has to be viewed on its own. For example, some studies report nitrate concentrations and not TN concentrations and vice versa. The same can be said for phosphate and TP. Despite these limitations, Figs. 3 and 4 provide a long-term view of changes in nutrient concentrations and fluxes over time. There is more information about nutrient concentrations in GR runoff than for nutrient fluxes. There is no information

Fig. 1. Visible changes in vegetation (cynodon grass) and substrate over a 9-month period for a modular extensive green roof system in Singapore. These green roofs were not irrigated nor fertilized.

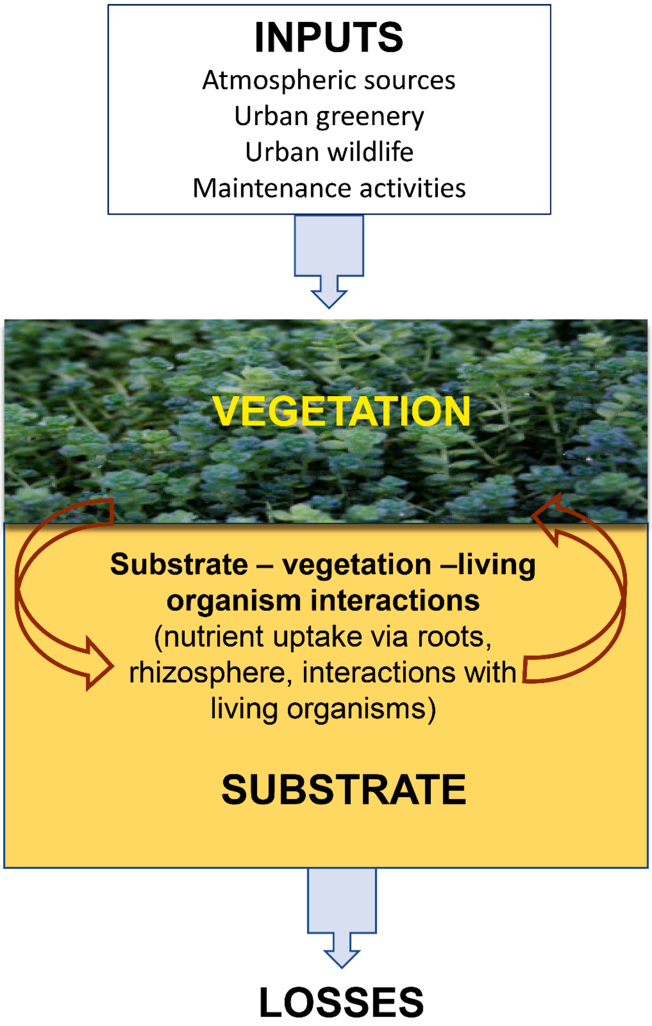

Fig. 2. Conceptual diagram of a green roof structure showing the components (substrate, vegetation, and living organisms) and pathways of nutrient inputs and losses from green roofs.

about nutrient fluxes for old GRs (>10 years).

For both nutrients, the worst water quality occurs in the first 5 years, especially the first 12 months after installation (NO_3: 0.08-100 mg/L, PO_4: 0.01-13 mg/L) (Figs. 3 and 4). This is due to the decomposition of organic matter in the substrate and leaching from the substrate (e.g., Vijayaraghavan et al. 2012, Harper et al. 2015, Kuoppamäki & Lehvävirta, 2016, Lim et al., 2021). During this initial phase, both nitrate and phosphate exceed USEPA water quality guideline values (nitrate: 10 mg/L, phosphate: 0.05 mg/L for freshwater entering lakes, 0.1 mg/L for flowing waters, Litke, 1999) (Fig. 3). The magnitude of poor water quality is illustrated in Mitchell et al. (2017)'s study where phosphate concentrations from the GR in the first-year post-installation was close to concentration levels from wastewater but decreased to values similar to agricultural systems (i.e., alfafa field) in its 4th year. Yet there are also studies which highlight positive phosphorus retention, such as Köhler et al. (2002), where P retention increased from 26 to 80% in the first and 4th year. Fig. 5 presents plots of nutrient concentrations and mass flux for the initial 4 years, highlighting the poor runoff quality and the variable nature of nutrient levels of a sedum-covered extensive GR in Syracruse, USA during this period (Todorov et al., 2018). Todorov et al. (2018)'s study is one of the few studies that report both concentration and mass flux for a relatively long monitoring period of 4 years. The sedum covered extensive GR is typical of most GRs constructed, albeit differences in substrate composition. Most of the nutrients exhibited declines in concentrations over the 5-year period, except for nitrate and TP which showed delayed peaks in the 3rd year. Phosphate concentrations are consistently above the USEPA freshwater standards for flowing waters (0.1 mg/L) for the first 3 years, whereas TP concentrations exceed the USEPA guideline values for the entire monitoring period. Concentrations of all nitrogen fractions in GR runoff were below the USEPA guideline value for drinking water (10 mg/L). The temporal trends of nutrient fluxes shows that nitrogen fluxes and TP flux from the GR are lower than a traditional roof, wet and dry deposition. However, the phosphate flux is higher than the traditional roof for the first 3 years (Fig. 5). This study shows that even though nutrient concentrations are higher relative to other inputs, the nutrient fluxes are generally lower, except for phosphate. This highlights the need for more flux information to have a better understanding of the water quality impact of GRs on downstream systems.

With time, nutrient concentrations in runoff decline; nitrate and phosphate levels for GRs over 10 years of age are 0.05-7 mg/L and 0.01-1.2 mg/L respectively (Fig. 3). However, there are indications of increased nitrate and phosphate concentrations for old GRs (>10 years). Increases in nitrogen, especially for nitrate, are most likely related to nitrifying activities (e.g., Mitchell et al., 2018, 2021), but concentration values are below USEPA guideline values for drinking water by this stage (Fig. 4). The concentrations of TP for old GRs decline to levels below the USEPA guideline values for flowing waters, based on data from 2 studies (e.g., Berndtsson et al., 2009, Speak et al., 2014). Nutrient concentrations in the runoff of a 43-year-old GR in Manchester were equivalent to or below those recorded for a bare roof and rainfall indicating that this GR has reached equilibrium conditions at that age (Speak et al., 2014). Furthermore, the lack of significant year-to-year variability in the phosphorus levels for a 11-year-old GR suggests that it had achieved equilibrium conditions (e.g., Mitchell et al., 2017). More data are required to see if the low concentrations reported in these studies are indeed representative of old GRs in general. There is no data for nutrient fluxes leaving old GRs, which presents a significant knowledge gap in our understanding of temporal changes in nutrient fluxes leaving these green infrastructures.

Short-term fluctuations in nutrient levels also occur due to seasonal changes in temperature and rainfall, with most research focused on temperature-related changes (Buffam et al., 2016, Mitchell et al., 2017, Todorov et al., 2018, Gong et al., 2020). Higher nutrient levels were observed during summer (e.g., Buffam et al., 2016, Kuoppamäki & Lehvävirta, 2016, Mucha et al., 2018) and less so for winter (e.g., Zhang et al., 2014, Harper et al., 2015). Transitional periods between seasons, particularly from dry to wet, may result in shock nutrient inputs into urban waterways due to the first flush of N and P (e.g., Vijayaraghavan et al., 2012, Todorov et al., 2018, Lim et al., 2021). Seasonal trends changed with age; the timing of seasonal peaks in nutrient release shifted as young GRs matured in age from their first to fourth year, likely due to changes in plant activity and changes in microbial decomposition rates with temperature changes (Mitchell et al., 2017, 2021).

Management activities, especially fertilizer applications, generally have a negative impact on GR runoff regardless their age (e.g., Emilsson et al., 2007, Teemusk and Mander, 2011, Buffam et al., 2016, Whittinghill et al., 2016, Okita, 2018, Akther et al., 2020, Kuoppamäki et al., 2021). So far, fertilizer additions resulted in fast responses with spikes in nutrient levels (Emilsson et al., 2007, Whittinghill et al., 2015, Buffam et al., 2016). The duration of negative water quality impacts is variable, depending on the type of nutrient (N, P) and other factors such as the type of fertilizer, concentration levels, frequency of application, substrate and vegetation characteristics of each GR (Malcolm et al., 2015, Whittinghill et al., 2015, Kuoppamäki et al., 2021). Slow-release fertilizer applications on young GR plots resulted in poor water quality that lasted up to 2 months after application (Malcolm et al., 2015). Fig. 6 shows that the initial impact of fertilizer applications for GRs in Michigan varied depending on the vegetation type for a young GR (1 yr old). Sedum and prairie GRs were not much affected by fertilizer applications,

Table 1

Nitrogen and phosphorus nutrient levels (concentration, mass flux) in the runoff of GRs of different ages.

	Substrate	GR age	Concentration (mg/L)					Mass flux (mg/m^2)				
			NO_3^--N[1]	NH_4^+-N	TN	PO_4^{3-}-P[1]	TP[2]	NO_3^--N	NH_4^+-N	TN	PO_4^{3-}-P	TP
Malcolm et al. (2014)	Commercial substrate (EnviroTech GR): 85% expanded slate & 15% compost. Fertiliser added.	newly installed	-	-	19.4	-	3.2	-	-	53.1	-	8.7
		2 yr old	-	-	3.5	-	2.5	-	-	13.3	-	51.2
Mitchell et al. (2017)	Commercial substrate (Tremco) (Ohio, USA)	First year	-	-	-	2.2	-	-	-	-	620-2180	-
		5 yr old	-	-	-	0.9		-	-	-	160-550	-
	Commercial substrate (Roofmeadow) (Kentucky, USA)	8-12 yr old	-	-	-	< 0.5	-	-	-	-	-	-
Okita et al. (2018)	Loamy sand	6 months	-	-	-	3.72	4.98	-	-	-	-	-
		6 yr old	-	-	-	1.89	2.15	-	-	-	-	-
Todorov et al. (2018)	Light weight mineral aggregates, organic components & compost	newly installed	0.21	0.18	4.46	0.22	1.52	0.11	0.24	2.59	0.31	0.74
		3.7 years	0.55	0.1	1.89	0.01	0.48	0.12	0.04	0.83	0.03	0.07
Akther et al. (2020, 2021)	A commercial substrate (ZinCoblend-SI)	1st year	3	0.8	-	1.5	-	-	-	-	-	-
		4-5 yr old	0.01	0.25	0.07	0.2	0.51	-	-	-	-	-
Speak et al. (2014)	Mineral substrate	43 yr old	0 - 7	-	-	0 - 1.15	-	-	-	-	-	-

[1] The US EPA recommended freshwater standards for NO_3^- and PO_4^{3}- are 10 mg/L and 0.05 mg/L respectively (refer to Vijayaraghavan et al., 2012).

[2] The USEPA recommended freshwater standards for total phosphorus are 0.05 mg/L for streams that enter lakes and 0.1 mg//L for flowing water (Litke, 1999)

Table 2

Summary of key findings related to nutrient runoff quality from older GRs (>8 years of age).

Authors/ Location of study	Age of GR (at time of study)	GR characteristics	Purpose of study	Key findings
Berndtsson et al. (2006) Malmo & Lund, Sweden	1, 2 yr GR (constructed 2001 & 2002) 8, 9yr GRs (constructed 1994 & 1995 respectively)	Extensive roof Sedum-moss	GR runoff quality (metals, nutrients)	GRs generally release metals and phosphorus but retained nitrogen. Oldest roof retained phosphate. Younger roofs released more TN.
Speak et al. (2013, 2014) Manchester, UK	43yr old roof (constructed 1970)	Extensive roof Mineral substrate Grasses and invasive weed	Rainfall retention Nutrient and trace metal retention performance of old GR	Rainfall retention variable (37-73%) but relatively high for an old system when monitoring conducted over a wet period. GR removed nitrate and phosphate but released trace metals; Cu, Pb, Zn. Legacy pollution from substrate storage of trace metals over time.
Mitchell et al. (2017) Ohio, Kentucky, USA	1-5 yr GR (constructed 2010) 8-12 yr GR (constructed 2003)	Extensive roof Commercial substrate Sedum vegetation	Comparative study of phosphorus dynamics from GRs of different ages	Younger roofs displayed greater variability in P concentration and mass flux over the monitoring period. Older roof displayed minimal variability in mass flux over the same period. Older roof had attained steady state conditions
Mitchell et al. (2021) Sweden	2 and 22 years in (constructed between 1994 and 2014)	Extensive roof Commercial substrate following FLL (2002) guidelines Sedum-moss vegetation	Study of GR nutrient content and vegetation communities Comparative study between young (2 yr) and older (22yr) GRs	Substrate depth, substrate N and total N stock (substrate + plant) increased with roof age. No sign of achieving steady state conditions Total and substrate stock of C and P were not related to age. Substrate stock of C, N and P was relatively greater than the vegetation stock; this ratio increased with roof age. Older GRs had more bryophytes. Lichens found for GRs greater than 15 years of age.
Thuring & Dunnett (2014) Stuttgart, Germany	20-33yrs (Constructed between 1977 & 1991)	Extensive sedum-based vegetation Mineral-based substrate	Vegetation composition	Decreased soil pH over time Substrate depth decreased over time More soil organic content over time Floristics most influenced by organic C and P *magnitude of change unknown as there were no measurements conducted when the GRs were first installed.

where phosphate concentrations post-fertilizer applications were below the USEPA guideline values for flowing waters (0.1 mg/L, Litke, 1999). The vegetation and herb GRs experienced delayed peaks in nitrate (5 weeks after first application) and phosphorus (3 weeks after second application) levels. These concentration levels were above the USEPA guideline values for flowing waters. Emilsson et al. (2007)'s study compared the impacts of a) fertilizer type (controlled-release, controlled-release and conventional) and three levels of fertilizer concentrations (low, medium, high) on runoff quality. The high applications resulted in elevated nutrient concentrations which subsequently

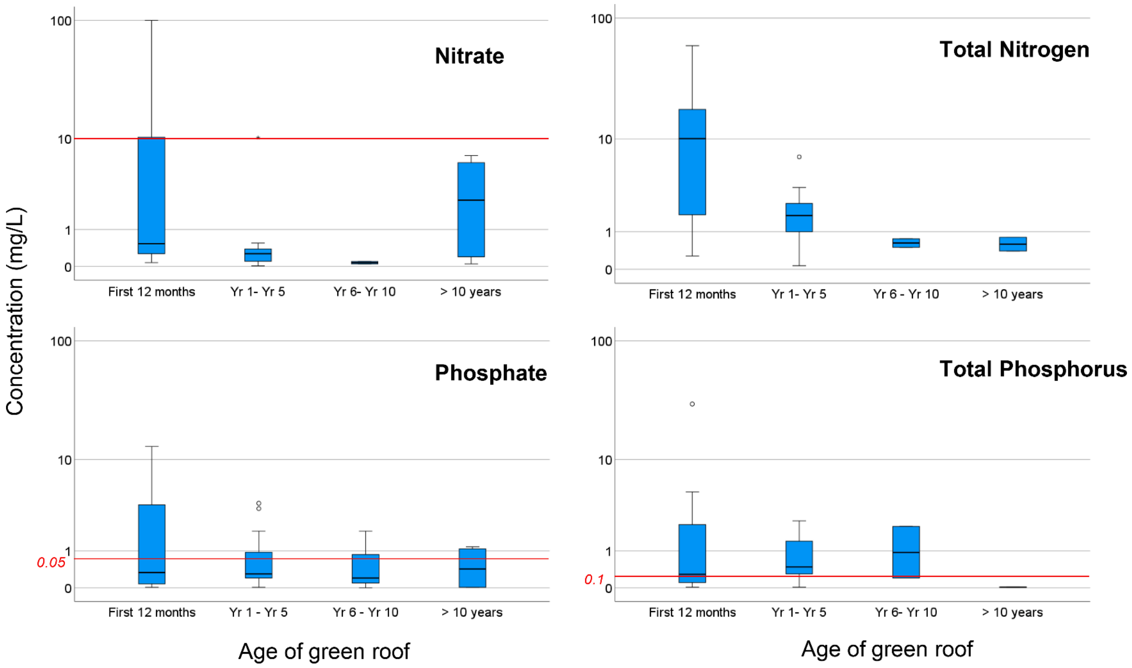

Fig. 3. Boxplots of nitrogen and phosphorus concentrations in GR runoff at different stages of their development; first 12 months (n= 18 studies), Year 1 to 5 (n= 17 studies), Years 6 to 10 (n= 3 studies) and when they are over 10 years of age (n= 2 studies). The US EPA recommended freshwater standards for NO_3^- and PO_4^{3-} are 10 mg/L and 0.05 mg/L respectively (refer to Vijayaraghavan et al., 2012). The USEPA recommended freshwater standards for total phosphorus are 0.05 mg/L for streams that enter lakes and 0.1 mg//L for flowing water (Litke, 1999). The greatest variability in nutrient concentrations occur in the first 12 months after installation.

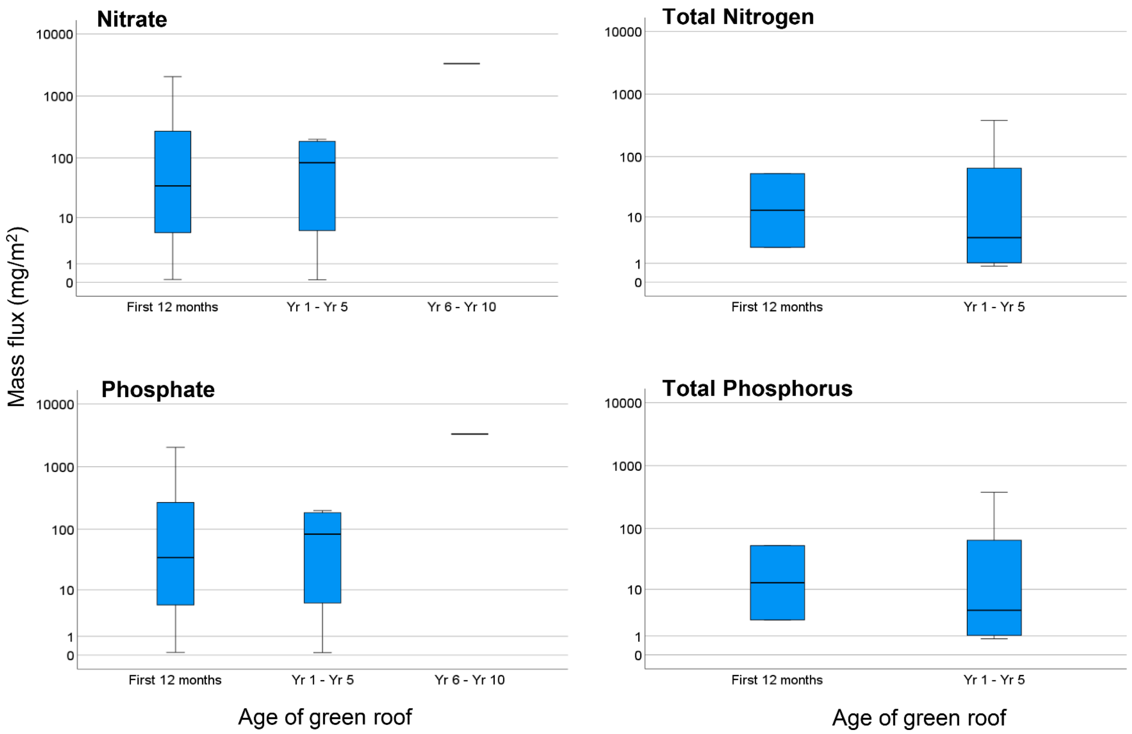

Fig. 4. Boxplots of nitrogen and phosphorus mass flux in GR runoff at different stages of their development; first 12 months (n= 6 studies), Year 1 to 5 (n= 6 studies), Years 6 to 10 (n= 1 study). There is no published information about the nutrient mass fluxes leaving GRs older than 10 years of age.

declined exponentially over time. The low and mid fertilization treatments showed delayed peak concentrations in the 2nd or 3rd week, with the delay more pronounced for phosphorus than nitrogen (e.g., Emilsson et al., 2007). In another study, fertilizer additions to a 6-yr-old GR resulted in increased levels of phosphorus (TP, PO_4) but had minimal impact on nitrogen (TN) (Kuoppamäki et al., 2021). Inconsistencies in these results reflect differences in substrate, vegetation composition in additional to fertilizer characteristics for young GRs which are most likely still experiencing changes in their substrate, vegetation, and community of living organisms, whereas the impacts of fertilizers on

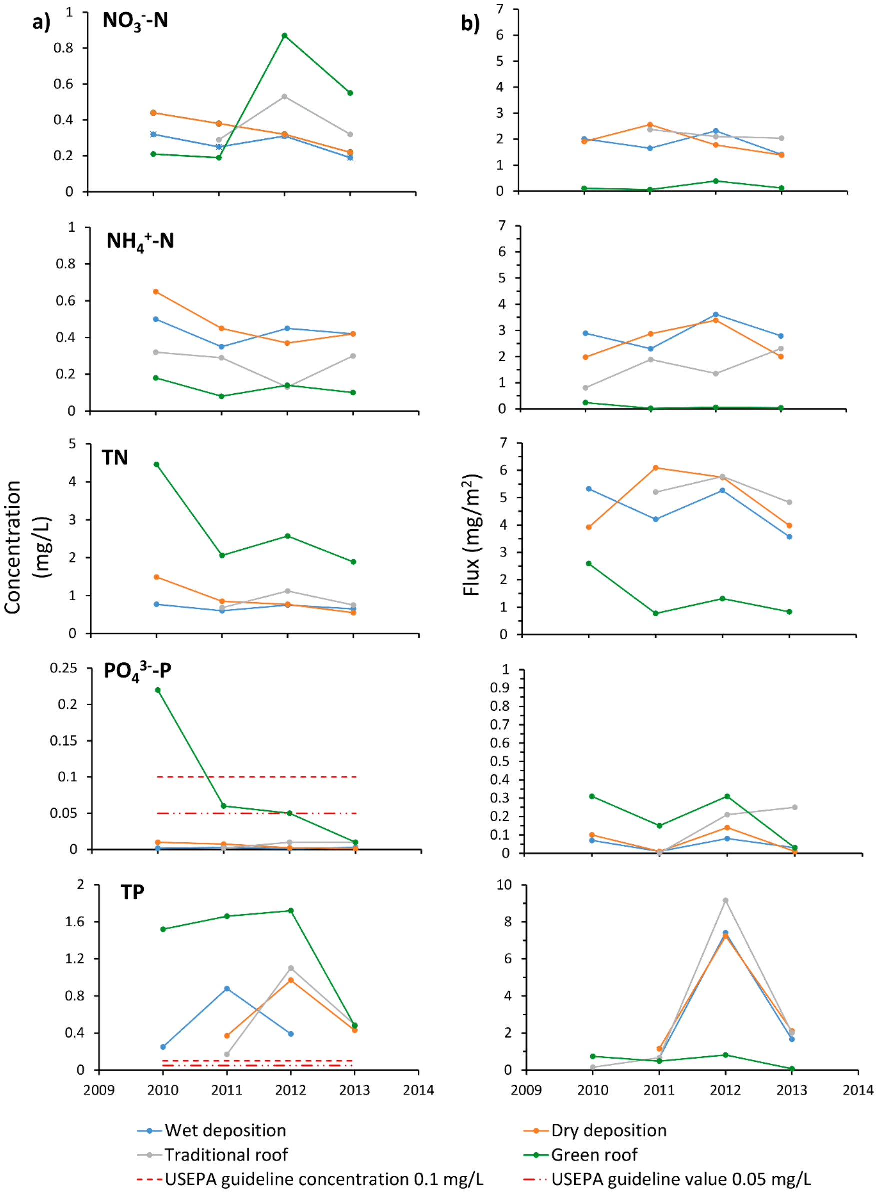

Fig. 5. Temporal changes in nitrogen and phosphorus concentrations and mass flux in GR runoff compared against wet and dry deposition and runoff from a traditional roof, for the first 4 years post-installation. Delayed peaks in nitrate (NO_3^--N) and total phosphorus (TP) are recorded in the 3rd year after the GR was installed, with the former likely due to nitrification (data from Todorov et al., 2018). USEPA freshwater standards for nitrate and phosphate are 10 mg/L and 0.05 mg/L respectively (Vijayaraghavan et al., 2012). The USEPA freshwater standards for total phosphorus are 0.05 mg/L for streams that enter lakes and 0.1 mg/L for flowing waters (Litke, 1999).

older GRs may be less dramatic and require further study.

2.1.2. *Temporal changes in water retention by GRs*

Nutrient losses from GRs are closely tied to water retention in the following ways: a) reduce runoff lost from GRs (e.g., Kuoppamäki et al., 2021), b) increase residence time for nutrient processing within the substrate and vegetation uptake and c) affect the plant and community of living organisms (Buffam & Mitchell, 2015).

Water retention can be high, between 40 to 80% of annual rainfall, and is dependent on vegetation and substrate characteristics (Bengtsson et al., 2005; Driscoll et al., 2015, Carpenter et al., 2016). Most research showed an increase in rainfall retention over time, ranging between 12 to 25% over the first 7 years, due to increased substrate porosity and infiltration rates as vegetation matures (e.g., Speak et al., 2014, De-Ville et al., 2017, 2018a,b, Yang & Davidson, 2021). A 5-yr old GR substrate had more than 3 times the water holding capacity of the original substrate (Getter et al., 2007). A rare study of GRs 20 years of age in Mexico City found that they still retained between 31 to 81 percent of rainfall (event-basis) for a range of events over a 2-year monitoring period (Arellano-Leyva et al., 2021). These retention rates fall within the average rainfall retention of 62% (per-event), based on a global review of GR literature published between 2005 and 2020 (Zheng et al., 2021).

The water retention performance of GRs depends on the way substrate and vegetation characteristics evolve over time, and their subsequent interactions with each other. In a study comparing a 6-month and 6-year-old GR, Okita et al. (2018) found that the older GR produced more runoff during events occurring in the dry season because of poorer vegetation coverage (invasive weed species senesced during the dry season), shallower root depth and more compacted substrate (6-year GR dry bulk density: 0.72 g/cm^3, 6-month GR: 0.65 g/cm^3). Cracks that develop in dry substrates also provide preferential pathways for nutrient rich water to move through the substrate quickly (e.g., Bouzouidja et al 2018b, Zhang et al., 2018).

2.2. *Changes in green roof components over time*

2.2.1. *Substrate*

Green roof substrates are materials, consisting of aggregates, organic

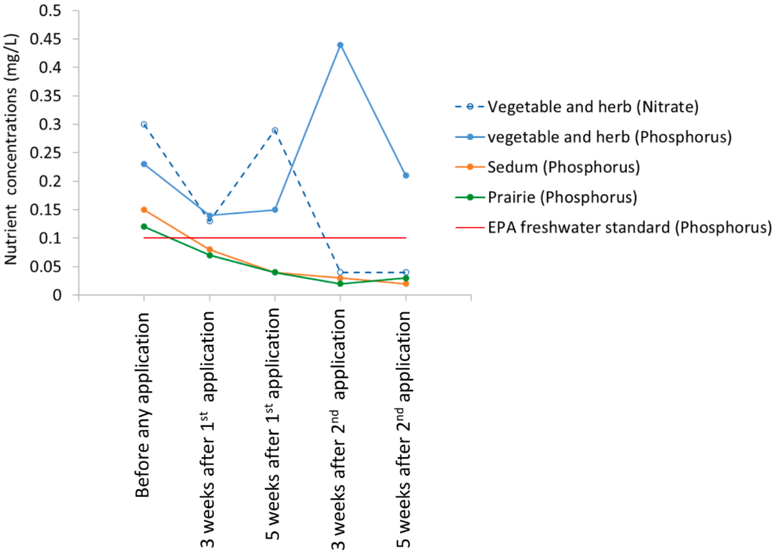

Fig. 6. Nutrient concentrations (nitrate, phosphorus) in the first 125 ml of runoff from a young GR (1 year) before any fertilizer was applied and subsequently 3 and 5 weeks after the first and second application of fertilizer. Three vegetation types were planted including a vegetation and herb garden, sedum mix, and native prairie mix planted on a commercial substrate in Michigan, USA. Data for the graph was obtained from Table 4 of Whittinghill et al. (2015).

matter[1] and commercial fertilizers designed to support vegetation by providing nutrients and water in a harsh roof environment. Most pedogenesis occur in the first year of installation due to root development and weathering. The homogeneous material slowly develops into a more layered profile with time (Schrader & Böning, 2006, Emilsson et al., 2007, Buffam et al., 2016, Mitchell et al., 2017, Bouzouidja et al., 2018a, De-Ville et al., 2018a).

Substrate properties that promote water retention include the water holding capacity (WHC), permeability and porosity. Other properties such as the cation, exchange capacity, surface area, pH and electrical conductivity (EC) are important for nutrient retention. Plant survival and development over time are affected by substrate composition, depth and water retention properties (e.g., Rowe et al., 2006, Getter et al., 2009, Nagase & Dunnett, 2011). For example, reductions in water holding capacity as the GR ages can result in reductions in plant biomass (e.g., Rowe et al., 2006, Azeñas et al., 2018). Nutrient retention is also affected by changes in substrate properties that affect nutrient adsorption kinetics and the availability of adsorption sites, especially for phosphorus (see Kazkemi & Morko, 2017, Mitchell et al., 2017).

The physical properties that have received most research attention include depth, textural properties, maximum water holding capacity and hydraulic conductivity. These properties affect nutrient retention indirectly by controlling the volume of water retained, its residence time, as well as the supply of air to the soil microbiome and roots (e.g., Getter et al., 2007, De-Ville et al., 2018a, b, Chai et al., 2018). For chemical properties, there is relatively more information about changes in substrate organic matter levels and pH than nutrient stocks. Table 3 provides key results of these studies for various physical and chemical properties of GR substrates.

Substrate depth affects plant growth and cover; deeper substrates contain more nutrients and water (e.g., Van Woert et al., 2005, Dunnett et al., 2008, Getter et al., Thuring et al., 2010, 2009, Rowe et al., 2012, Thuring & Dunnett, 2014, Gabrych et al., 2016). In some cases, substrate depth was more important than growing media composition for the growth and survival of GR plants (e.g., Molineux et al., 2015, Papafotiou et al., 2013, Ondoño et al., 2016, Kazemi & Mohorko, 2017), especially in arid climates (e.g., Ondoño et al., 2016) and protects plant roots from heat stress (e.g., Savi et al., 2016). Fortunately, information related to substrate depth extends to over 20 years where evidence from older GRs in Germany experienced reductions in substrate depth between 60 to 70% of their original depth (Table 3).

Changes in particle size distribution occur over time, with the finer textural classes increasing at least in the first 7 years of the GR lifespan (Table 3). Over a period of 5 years, De-Ville et al. (2017) found that the <0.63 micro fraction increased approximately 1.5% for two different substrates (i.e., LECA, crushed brick). In another study, Yang and Davidson (2007) found that the <0.05 size fraction increased from 5.9% to 8.4% over a period of 7 years (Yang & Davidson, 2021). There are studies that did not find any trend in the particle size distribution over a period of 4 years for a GR in NE France (Bouzouidja et al., 2018a, Table 3). For substrate pore size, Köhler & Poll (2010) report a 10% increase in pore size over 10 years. There is also evidence to show that the hydraulic conductivity decreases while the maximum water holding capacity increases over time (Table 3). For example, water holding capacities increased between 12.9% (De-Ville et al., 2017) and 50% (Getter et al., 2007) over a period of 5 years (Table 3).

Amongst the chemical properties, organic matter is one of the most studied properties of substrates because it is the main cause of elevated nutrient levels in runoff. It affects many aspects of GR functioning including substrate depth, water retention (Kazemi & Mohorko, 2017) and nutrient cycling processes including nitrogen mineralisation and soil pH levels (Thuring & Dunnett, 2014). The levels of organic matter at different stages of the GR lifespan depend on vegetation characteristics (e.g., Emilsson, 2008) and climate conditions, where higher biodegradation rates occur for wet climates and highly irrigated GRs (Kazemi & Mohorko, 2017). The levels of organic matter in GR substrates generally increase over time, largely due to the breakdown of plant biomass and additions from neighbouring vegetation (Bilderback et al., 2005, cited in Rowe et al., 2006, Emilsson, 2008, Thuring & Dunnett, 2014, Kazemi & Mohorko, 2017) (Table 3). For example, soil organic matter doubled over a 5-year period from 2.3% to 4.3% for experimental GR treatment modules established on sandy substrates in Michigan, USA (Getter et al., 2007). Yang and Davidson (2021) found that organic matter levels increased from 2.7% to 4.3% for a GR using the *Roofmix* substrate (WeCare Denali) when it was first installed and sampled again 7 years

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[1] The amount of organic matter added is often based on guidelines such as the 'FLL Guidelines' produced by the *German Landscape* Research, *Development* and Construction Society (*Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V.*). These guidelines suggest adding 4-12% organic matter into GR substrates (Whittinghill et al., 2016). They are designed to last 20 to 25 years (FLL, 2008, Jennett & Zhang, 2018).

Table 3
Summary of key changes in the physical and chemical properties of GR substrates as they evolve over time.

Substrate property	Increase with time	Decrease with time	No change
Physical properties			
Depth	Increasing approximately 1 mm/yr. Info based on regression modelling using data from roofs between 2 and 22 years of age in Sweden (Mitchell et al., 2021)	For German GRs between 20 to 33 years of age (Thuring & Dunnett, 2014), substrate depth generally decreased from recommended initial values of 200mm: GR age 20-21 years: 200 mm to 76.6mm GR age 22-23 years: 200 mm to 74.5 mm GR age 24-25 years: 200 mm to 57.5 mm GR age > 26 years: 200 mm to 61.6 mm	
Bulk density	Increased from 0.79 to 0.89 g/cm^3 over 7-yr period (Yang & Davidson, 2021)	Decreased from 800 kg/m^3 to 789 km/m^3 over 2.5-year period (Bouzouidja et al., 2018b)	
Pore size/pore volume	Doubled over a 5yr period from 41% to 82% (Getter et al., 2007) 10% increase over 10yrs (Köhler & Poll, 2010) Macro and microporosity increased slightly over 4-yr period (Bouzouidja et al., 2018a) Total porosity increased from 51.2% to 55.1% over 7-yr period (Yang & Davidson, 2021)	Porosity decreased from 72% to 70% over 2.5- year period (Bouzouidja et al., 2018b) Mesoporosity decreased from 0.11 cm^3/cm^3 to 0.02 cm^3/cm^3 over 4-yr period (Bouzouidja et al., 2018a) Air-filled porosity decreased from 12.6% to 9.3 (% vol) (Yang & Davidson, 2021)	Total porosity no change over 4-year period (Bouzouidja et al., 2018a)
Particle size distribution (PSD)	Comparison of virgin and 5-year-old substrate for <0.063mm size fraction (De-Ville et al., 2017): Light expanded clay aggregate substrate: increased from 0.66% to 1.57% Crushed brick-based substrate: Increased 0.38% to 1.41% Increased from 5.9% to 8.4% over 7-year period for particles <0.05 diameter (Yang & Davidson, 2021)	Decrease in % of <2mm particle size fraction over 4-yr from 18.2% to 12.5% (Bouzouidja et al., 2018a)	
Maximum water holding capacity	Increased from 17% to 67% over 5 yrs (Getter et al., 2007) Comparison of virgin and 5-year-old substrate (De-Ville et al., 2017): Light expanded clay aggregate substrate: Increased 21.2% to 28.5% Crushed brick-based substrate: Increased from 27.4% to 33.3% Increased from 39% to 46% over a 7-yr period (Yang & Davidson, 2021)		
Hydraulic conductivity		Comparison of virgin and 5-year-old substrate (De-Ville et al., 2017): Light expanded clay aggregate substrate: decreased from 179 mm/min to 44.3 mm/min Crushed brick-based substrate: decreased from 38.7 mm/min to 22.9 mm/min	No change over 7-yr period (0.02 cm/s) (Yang & Davidson, 2021)
Chemical properties			
pH		GR study in Sweden from first year to age 3.5 year (Emilsson, 2008): Substrate A: decrease from 7.49 to 6.8 Roof soil: decrease from 7.35 to 7.12 German roofs 20-33 years old (Thuring & Dunnett, 2014): Substrate pH values ranged from 5.1 to 7.2 (recommended value is 6.5). German GRs 3-8 years old (Buttschardt, 2001): pH range between 5.8 and 7.6. Older roofs had lower pH values. German roofs 8-12 years of age (Schrader & Boning, 2006): pH values range for older GRs were lower than younger systems. Substrate studies for a 7-year period (Jauch & Fischer, 2000): pH values decreased towards acid values Substrate studies for 16-year period (Liesecke, 2006): pH values drop significant in first few years. Lime additions can counteract pH declines (Köhler & Poll, 2010). 20-year GRs in Mexico City (Arellano-Leyva et al., 2021): pH values were between 4.8 and 4.9	
Organic matter	Doubled over a 5 yrs from 2.3% to 4.3% (Getter et al., 2007) GR study in Sweden from first year to age 3.5 year (Emilsson, 2008): Substrate A: increase from 1.02 to 1.45% Roof soil: increase from 5.3% to 8.3% Values ranged between 72 and 189 mg/L, above FLL recommended value of 65 mg/L for German GRs > 20 years old (Thuring & Dunnett, 2014) %OM increased from 5.0% to 6.8% over 3-year period (GR age: from 10yrs to 12 years of age) (Mitchell et al., 2017)	%OM decreased from 8.4% to as low as 6.3% over 3-year period (GR age: from 3yrs to 5 years of age) (Mitchell et al., 2017)	No significant difference for 20-year-old German GRs and 100-year old systems (Köhler & Poll, 2010) No statistically change over first 5 yrs of GR lifespan (Mitchell et al., 2017)

(*continued on next page*)

Table 3 (*continued*)

Substrate property	Increase with time	Decrease with time	No change
	Increased from 2.7% to 4.3% over 7 yrs (Yang & Davidson, 2021)		
Carbon	Organic carbon from older GRs 0.5% -5% higher than younger GRs (Schrader & Böning, 2006)	Organic carbon decreased from 5.0% to 2.1 % over 4-yr period (Bouzouidja et al., 2018a)	
Nitrogen	Over a 4-year period (age 3 to age 7, Whittinghill et al., 2015): %N increased from 0.03% to 0.12% for GRs planted with mats of pre-grown vegetation Over 3-year period (Mitchell et al., 2017): %N increased from 0.21 and 0.25% over 3-year period (GR age: from 3yrs to 5 years of age) %N increased slightly from 0.15% to 0.21% (GR age: from 10yrs to 12 years of age) Total N increase from 0.13% to 0.54% over 4 yrs (Bouzouidja et al., 2018a) N stock in substrate increased with age (Mitchell et al., 2021)	GR study in Sweden from first year to age 3.5 year for N total (Emilsson, 2008): Substrate A: decrease from 68.6 to 28.98 mg/100g dry soil Roof soil: decrease from 219.3 to 201.4 mg/100g dry soil Over a 4-year period (age 3 to age 7, Whittinghill et al., 2015): %N decreased from 0.04% to 0.01% for GRs planted with seeds of meadow plants.	
Phosphorus	GR study in Sweden from first year to age 3.5 year for P (Emilsson, 2008): Roof soil: increase from 1.74 to 2.96 mg/100g dry soil Over a 4-year period (age 3 to age 7, Whittinghill et al., 2015): P levels increased from 0.4 g/kg to 0.67 g/kg for GRs planted with mats of pre-grown vegetation on biochar and plantings of meadow seeds. Over 3-year period (Mitchell et al., 2017): %P increased slightly from 0.024% to 0.031% (GR age: from 10yrs to 12 years of age)	GR study in Sweden from first year to age 3.5 year for P (Emilsson, 2008): Roof soil: decrease from 1.48 to 1.17 mg/100g dry soil Over 3-year period (Mitchell et al., 2017): %P decreased from 0.049% to 0.030% (GR age: from 3yrs to 5 years of age)	

References for Buttschardt (2001), Jauch & Fischer (2000) and Liesecke (2006) are found in Thuring and Dunnett (2014). These articles were published in German and information from these studies were cited from Thuring and Dunnett (2014).

later (Table 3).

Substrate pH generally decreased as GRs aged, for both young (pH: 5.8-7.6, GRs 3-8 years old) and older German GRs (pH: 5.2-7.2, GRs 20-33 years old) (Buttschardt, 2001, cited in Thuring and Dunnett, 2014). The pH values of 20-year-old GRs in Mexico City ranged between 4.8 and 4.9 (Arellano-Leyva et al., 2021). For some old German GRs (>20 years), increases in substrate pH (6.2 to near neutral) occurred due to improvements in rainfall quality (less acidic) and lime additions to GRs (Köhler & Poll, 2010). Decreasing substrate pH can increase soil organic content due to its effect on microbial activity which are essential to nutrient cycling and decomposition as well as other chemical processes such as reduction/oxidation, sorption/desorption processes in the substrate (Berendse, 1998, cited in Thuring & Dunnett, 2014, Buffam and Mitchell, 2015, Hoch et al., 2019, Vijayaraghavan et al., 2021). For example, the optimal conditions for *Rhizobium* bacteria, which help stimulate biological nitrogen fixation, are when pH values >5 (Handreck & Black, 2010, cited in Thuring & Dunnett, 2014).

Nutrient stocks in substrates vary over time largely related to changes in vegetation (Table 3). Old GRs have lower nutrient content in the substrate compared to younger systems (e.g., Mitchell et al., 2017, 2021). At the initial stages, nutrient levels in the substrate were found to be dependent on both vegetation type and the establishment method used. In a study of Finnish GRs, the temporal pattern of nitrogen stocks in the 3rd and 7th year varied depending on the plant establishment method, with mats showing an increase while plantings with meadow seeds resulted in the opposite trend (Fig. 7). Leaching losses and low nutrient uptake by vegetation are other causes for decreases in substrate nitrogen content (e.g., Emilsson, 2008). Evidence for older GRs suggests increasing substrate N stocks; an increase from 0.15% to 0.25% over a 3-year monitoring period (Mitchell et al., 2017, Table 3). A 22-year-old GR in Sweden was accumulating N in the substrate at a rate of 2.9 ± 1.1 gN/m^2/yr due to contributions from N fixing vegetation and other living organisms (Mitchell et al., 2021, Table 3). Tracking the GR living biome over time will identify the location and main transformation pathways, especially nitrogen, for individual GRs as they age (e.g., Mitchell et al., 2018, 2021, Jauni et al., 2020).

Much less is known about phosphorus dynamics in GR substrates and the way they change over time including dominant fractions and rates of change at different stages of development. The literature reports both increases and decreases in substrate phosphorus stock (Table 3). Kuoppamäki et al. (2021) found that phosphorus stocks in the substrate mostly increased between the third and seventh year of their study GRs (Fig. 7). For GRs > 10 years of age, the % phosphorus in the GR substrate increased slightly from 0.024% to 0.031% over a 3-year period for a GR in Kentucky USA but levels were lower than a younger GR 10 years its junior (%P in substrate: 0.03-0.049%) (Mitchell et al., 2017, Table 3). Adsorption kinetics and availability of binding sites control phosphorus levels in the substrate and a better understanding of these processes is needed to account for trends in GR runoff (e.g., Speak et al., 2014, Mitchell et al., 2017, Jennett & Zheng, 2018).

The inorganic fraction tends to be dominant for younger substrates due to their engineered nature but as the substrates age and receive more nutrients from the breakdown of plant matter, the organic fractions become dominant, at least for nitrogen (e.g., Schrader & Böning, 2006, Berndtsson et al., 2009, Buffam et al., 2016). For phosphorus, the inorganic form dominates, regardless of GR age (Mitchell et al., 2017, 2021). The knowledge of nutrient stocks and fraction composition in substrates and how they change over time is important, especially to determine fertilizer application strategies. Research has so far shown that fertilizer additions led to the temporary storage of nutrients within the substrate while excess amounts are leached out (e.g., Emilsson et al., 2007, 2008).

2.2.2. Vegetation

Nutrient release in GR runoff is mediated by plant activity, namely the balance between plant uptake and additions from dead vegetation matter, nitrifying plants and other living organisms. Plants also affect the water-balance of GRs via canopy interception, water uptake and loss through transpiration (Rowe, 2011). The ability of the vegetation to survive and cover the GR determines its nutrient retention performance, especially in the first two years after installation (Savi et al., 2015, Kazemi & Kohorko, 2017). Mature and diverse vegetation retain more

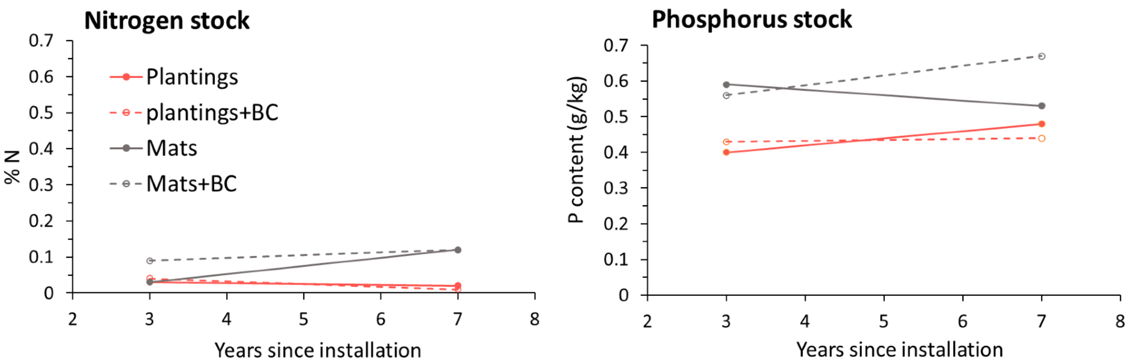

Fig. 7. Nutrient content in the substrate of green roofs in Finland in their third and seventh year. Plantings refer to seeds of meadow plants grown on green roofs. Mats refer to a 40mm-thick layer of pre-grown vegetation installed on the green roofs. BC refers to substrates amended with biochar. Graphs plotted from data taken from Table 2 of Kuoppãmaki et al. (2021).

water and nutrients (e.g., Emilsson et al., 2007, Nagase & Dunnett, 2012, Johnson et al., 2016, Jauni et al., 2020, Mitchell et al., 2021), whereas unhealthy or dead vegetation have caused high nutrient levels in GR runoff due to poor uptake or nutrient release during decomposition of dead plant matter (e.g., Aitkenhead-Peterson et al., 2011). Hence, the trajectory of vegetation dynamics (composition, areal coverage) affects the N and P nutrient performance of GRs at different stages of their development.

Initially, the vegetation may exhibit short spurts of rapid growth but die subsequently due to reductions in nutrients and water (boom and bust syndrome) (Monterusso et al., 2005, Rowe et al., 2006, Dunnett, 2008, Emilsson, 2008, Bates et al., 2015, see Fig. 1). The surviving vegetation is often colonised by other vegetation (e.g., Dunnett et al., 2008, Köhler & Poll, 2010, Rowe et al., 2012, Whittinghill et al., 2015, Catalano et al., 2016, Thuring & Dunnett, 2014, 2019, Aloisio et al., 2019, Jauni et al., 2020, Grullón-Penkova et al., 2020). For both extensive and intensive GRs installed in Puerto Rico, Grullón-Penkova (2020) reported that that only 6 species survived from the original 26 planted species (succulents, herbs, grasses, vines) over a 4-year monitoring period for young GRs that received minimal maintenance.

Thuring & Dunnett (2014, 2019) are one of the few papers that surveyed old GRs (>20 years) in Germany. They reported that less than half of the original planted vegetation (wildflower seedings, sedum cuttings) remained and was replaced by ruderals (e.g., grass, moss) that covered almost 100% coverage (Thuring & Dunnett, 2019). The vegetation cover had developed into a multi-layered meadow with a groundcover of sedum interspersed with taller herbaceous species and grasses. For other old unmanaged GRs in Hannover, Germany, spontaneous colonisation increased species composition and assemblage from 5 to over 80 species over a period of 30 years (Catalano et al., 2016). Colonisation also reduced GR species (e.g., Kinlock et al., 2016, Jauni et al., 2020) and exhibited seasonal trends (e.g., Emilsson, 2008). Over time, GR vegetation develops into assemblages that are unique to each roof with vegetation development broadly determined by stressors, the occurrence of disturbance events, competition and strategies for plant dispersal and regeneration, seedbank and propagule sources (Thuring & Dunnett, 2019).

A variety of factors affect vegetation development over time, including substrate depth (Dunnett et al., 2008, Getter and Rowe, 2009), water content (e.g., Monterusso et al., 2005, Rowe et al., 2006, Emilsson, 2008), solar radiation levels (e.g., Getter et al., 2009) and the soil microbiome, especially if nitrogen fixers are present (e.g., Mitchell et al., 2018, 2021). In a survey of nine old GRs in Germany, ranging between 20 and 33 years of age, Thuring & Dunnett (2014) found that soil organic content, soil phosphorus and pH levels were the main determinants of vegetation characteristics. Low pH values, often found for older substrates, inhibit microbial activity and lowered cation exchange capacity (Thuring & Dunnett, 2014). Interestingly, shade was more important than age in determining species richness for Swedish GRs of various ages (2 to 22 yrs) during the autumn (e.g., Mitchell et al., 2021). There is a growing body of work examining the factors surrounding vegetation change, particularly the role of spontaneous colonization (invasive, non-invasive species) on GRs (Aloisio et al., 2019, Catalano et al., 2019, Jauni et al., 2020). For example, some studies reported reduced GR species richness due to colonization by non-native invasive species (e.g., Kinlock et al., 2016, Jauni et al., 2020).

Research has also shown the plant establishment methods determine the nature of vegetation changes in the initial period after installation (e. g., Emilsson & Rolf, 2005, Emilsson et al., 2007, Emilsson, 2008, Mitchell et al., 2021). Emilsson & Rolf (2005) compared 3 different plant establishment techniques (e.g., prefabricated vegetation mats, succulent shoots, plug plants) and found that installing established vegetation (i. e., prefabricated vegetation mats) resulted in a succulent dominated vegetation cover one year after installation. However, there was no significant difference in the vegetation characteristics by the third year. Vegetation cover in the third year was determined the species mix found in the original vegetation planted and colonisation by other plants (Emilsson, 2008). The evolution of vegetation reflects not only the establishment methods, but the initial mix of plant species installed on GRs and colonisation dynamics, which are often aided by urban wildlife and neighbouring vegetation.

An important aspect of changing vegetation characteristics is their nutrient demands which varies with plant type and stage of growth. Knowledge of plant nutrient needs have implications for substrate design and fertilizer applications in terms of the type, concentration and frequency of applications. Early studies in this area showed that fertilizer applications resulted in root growth and an increase in leaf biomass. Furthermore, the preferential storage of nutrient stored in the biomass changed with age. Young GR plants store N in their biomass whilst older plants exhibited higher storage of P in their biomass (e.g., Emilsson et al., 2007). Mitchell et al. (2021) further found that plant N increased with roof age but plant biomass, plant nutrient pools and plant diversity had no relationship with age. These results suggest that the plant community may not be the dominant component controlling nutrient dynamics as GRs age but that other factors such as the community of living community have an increasingly important role, especially for nitrogen (e.g., Mitchell et al., 2018, 2021).

2.2.3. Other living organisms

Healthy GR vegetation depend on a diverse soil biome and associated living organisms. Our current knowledge of their population evolution is based on studies conducted at fixed points along the GRs lifecycle (e.g., Dunnett et al., 2008, Mitchell et al., 2017; Rumble and Gange, 2013, Rumble et al., 2018, Hoch et al., 2019) or over a period of several years (e.g., Jauni et al., 2020, Kuoppamäki et al., 2021). The living organisms found on GR systems include bacteria, archae (Mitchell et al., 2018), fungi (e.g., McGuire et al., 2013, Hoch et al., 2019, John et al 2017) and soil animals such as collembolans, nematodes and enchytraeids (e.g., Schrader & Böning, 2006, Jauni et al., 2020, Barra & Johan, 2021, Kuoppamäki et al., 2021). These organisms can increase plant diversity and aid substrate pedogenesis (McGuire et al. 2013, John et al., 2017, Mitchell et al., 2018). Bacteria and archae mineralize organic matter and carry out nitrification and N-fixation, a process aided by exudates released by plant roots (Buffam et al., 2016, Rumble et al., 2018). In addition, mycorrhizal fungi help plants access nutrients, especially phosphorus, due to their large surface area (higher P adsorption sites) (e.g., Van der Heijden, 2010, McGuire et al., 2013, John et al., 2017, Hoch et al., 2019). Fulthorpe et al. (2018) provide a good summary of the role living organisms play in the GR ecosystem.

Young GRs tend to have a low taxa of living organisms, due to treatment processes that remove unwanted viruses and bacteria from the substrate (Fulthorpe et al., 2018). During this initial stage, the community of living organisms is determined by the existing vegetation. Hoch et al. (2019) found that the vegetation communities could be classified by the bacterial and fungal communities for 99% of the time for a GR in New York City. Subsequent changes in the microbial community occur due to colonization, especially from neighboring vegetation (e.g., Buffam et al., 2016, Mitchell et al., 2017), wind and urban wildlife such as animals (e.g., Dunnett et al., 2008, John et al., 2017, Mitchell et al., 2018 Rumble et al., 2018, Jauni et al., 2020). The diversity of living organisms in GR substrates likely increases with proximity to other urban greenery. Factors that determine the diversity and abundance of the community of living organisms include water availability and substrate depth (e.g., Payne et al., 2014, Dunnett et al., 2008, Barra & Johnson, 2021). In a 5-year study conducted on GRs in dry nutrient-stressed conditions, Dunnett et al. (2008) found that deeper substrates resulted in greater survival of living organisms while there was a greater diversity of these organisms for the shallow substrate. Importantly, these living organisms play a significant role in the nitrogen budget of old GRs through their nitrifying activities which have been found to increase substrate N levels (e.g., Mitchell et al., 2018, 2021). There is clearly a need for more understanding around the changes that occur for the communities of living organisms, the factors that control their abundance and diversity as well as their role in nutrient transformation processes as GRs age. Filling these knowledge gaps is crucial for designing management activities related to fertilization.

2.2.4. *Complex synergisms and interactions between the substrate-vegetation-living organism complex*

The substate-plant-soil microbiome complex exists where living and non-living components of the GR system interact with each other. The location of nutrient pools are found here and nutrient transformation processes occur in this complex (Buffam & Mitchell, 2015). Vegetation can act as a nutrient source (dead matter) and sink (uptake). Porous GR substrates facilitate fungal growth that may increase drought resistance, but such properties may also facilitate drying, creating stressful conditions for both vegetation and the community of living organisms (McGuire et al., 2015).

These interactions and feedback processes change over time as the substrate, vegetation and community of living organisms evolve. Compensatory behavior complicates GR runoff dynamics over time. An example is where changes in substrate properties that have negative impacts on water and nutrient retention (e.g., reductions in pore size) are offset by changes in other substrate properties that may have a positive effect, such as increases in organic matter content (e.g., Buffam et al., 2016). The resultant impact on runoff quality depends on whether the positive or negative impacts outweigh the other.

The transport pathways for nutrient movement also differ for nitrogen and phosphorus. Nitrogen levels in GR runoff exhibit more variable temporal patterns because wash-off is the dominant process (Akther et al., 2020, 2021) whereas factors such as temperature, substrate composition (e.g., pH, texture) and antecedent moisture conditions control phosphorus release through their effect on microbial mineralization, desorption, or weathering (Buffam et al. 2016, Kuoppamäki et al., 2021). Akther et al. (2020) used a semi-physically based model that incorporated buildup and washoff processes to model nutrient levels in GR runoff. This model outperformed an empirical regression model in predicting the temporal behavior of nitrogen for both field and laboratory column experiments. The model failed for phosphorus because it did not incorporate temperature effects, which was important for phosphorus transformations and transport. While GR nutrient modelling work is still in its infancy, Akther et al. (2020)'s work highlights the important factors that control nutrient transformation processes. Coupling both hydrologic and nutrient models together with long-term monitoring will be key to improved understanding and modelling of GR nutrient dynamics over time.

2.3. *Changes in the external inputs of nutrients to green roofs*

Inputs of nutrients to GRs include the urban environment (urban greenery, wildlife), atmospheric inputs and maintenance activities (Fig. 2). Out of these three sources, it is likely that maintenance activities associated with fertilizer additions have the greatest impact on nutrient levels in GR runoff (Emilsson et al., 2007, Emilsson, 2008, Whittinghill et al., 2015) (see Section 2.1.1).

Nutrient inputs from neighbouring urban greenery and wildlife are known to occur but not quantified in GR nutrient budgets. Birds have been known to pull out plug plants installed on GRs (e.g., Berndtsson et al., 2006, Emilsson, 2008, Thuring & Grant, 2016) as well as disperse seeds to other GRs, changing their vegetation composition (e.g., Teemusk & Mander, 2011, Sutton, 2015) and add nutrients through their excrement.

Finally, atmospheric inputs of nutrients are small relative to additions from fertilizers and the urban environment, as nutrient concentrations in rainfall are generally lower than runoff concentrations (e.g., Mitchell et al., 2017, Lim et al., 2021). Atmospheric inputs, both wet and dry, affect the acidity of GRs and add nitrogen. But their relative inputs depend on rainfall properties (e.g., Teemusk & Mander, 2007, Todorov et al., 2018, Kuoppamäki & Lehvävirta, 2021) and varies with season, likely a reflection of the atmospheric sources of water and their trajectory of cloud movement (e.g., Lim et al., 2021). Dissolved organic carbon in rainfall also affects nitrogen dynamics and the nature of these interactions deserve further attention in future work (e.g., Carpenter et al., 2016). Changes in air quality over time, such as reductions in acid rainfall, have been known to affect nutrient transformation processes due to their impact on substrate acidity (e.g., Köhler & Poll, 2010). However, it is the occurrence of extreme events and climate change that will have the most impact on GRs in the future.

2.4. *Impact of extreme hydrometeorological conditions and climate change*

Climate conditions affect GR nutrient dynamics via its control on temperature and rainfall inputs (e.g., Buffam et al., 2016, Todorov et al., 2018, Gong et al., 2019, 2020). Currently, most of our understanding of GR nutrient dynamics originates from research in temperate and cold climate zones (Akther et al., 2018). Even then, there is limited knowledge about how GRs develop over time in those climatic zones. There is now some work conducted in dry climates (e.g., Razzagamanesh et al., 2014, Beecham & Razzagamanesh, 2015, Savi et al., 2015, 2016) and the tropics (e.g., Vijayaraghavan et al., 2012, Demarco et al., 2020, Lim et al., 2021) that include old GRs (>20 yrs, Grullón et al., 2020, Arellano-Leyva et al. 2021). Grullón et al. (2020)'s study showed that the old GR in Puerto Rico experienced a reduction in the number of plant species and Arellano-Leyva et al. (2021) found that rainfall retention was still high (approximately 60%). Despite high precipitation and humidity typical of tropical areas, water availability for plants is still an issue that needs to be addressed especially with global warming.

The lack of water and high temperatures associated with extreme events such as droughts and heatwaves have a negative impact on GRs (e.g., Kuoppamäki & Lehvävirta, 2016, Kuoppamäki et al., 2021), especially extensive systems with a shallow substrate. Higher temperatures accelerate biogeochemical processes and changes the water balance of GRs (e.g., Klein and Coffman, 2015). Drying substrates instigates cell dehydration and die-off, causing a negative impact on plants and microbial communities (Payne et al., 2014). The impact of drought stress was found to be species-dependent and varied seasonally (e.g., Vanuytrecht et al., 2014). Fowdar et al. (2021) conducted biofilter column experiments with 4 species of plants, native to China and Australia and subjected them to cold and dry conditions. Plant response was species-dependent, nutrient removal performance varied for N and P (greater impact for phosphorus) and temperature had a greater effect than water availability on nutrient removal. A more diverse plant mix increases the system resilience to more variable climate conditions. A study of drought-resistant Mediterranean and sub-Mediterranean flora found that substrate temperature had a greater impact than water availability during drought periods (Savi et al., 2016). Plant survival during such events depends on their physiological traits and age. In a study using 15 shrubs from a range of climates (dry, mesic, wet), Du et al. (2019) found that plant survival during dry periods was determined by physiological traits associated with leaf shedding, water storage in plant tissue and recovery from embolism. Another impact of climate change is higher CO_2 levels which have a greater impact for intensive roofs with a wider range of vegetation composition and structures.

The evidence so far suggests that diverse vegetation taxa and community of living organisms increase resilience under a variable climate (Nagase & Dunnett, 2010, MacIvor et al., 2011, Fowdar et al., 2021), minimizing vegetation loss during and after climate-related extreme events (e.g., Nagase & Dunnett, 2010, Johnson et al., 2016, Hoch et al., 2019, Tran et al., 2019, Kuoppamäki et al., 2021). To study the impact of vegetation diversity on plant survival after dry periods, Nagase & Dunnett (2010) conducted a greenhouse experiment and found that a diverse plant mix had better survival rates than monoculture plantings. Native plants may also be more resilient to climate change (e.g., Sutton et al., 2012). Clearly the impact of climate change depends on whether the change is associated with warming or cooling, plant physiological traits and their relative sensitivity to temperature changes and water availability and that a diverse vegetation community, that includes natives, may increase GR resilience to such events. Old GRs where the vegetation characteristics have evolved to be quite complex (e.g., multi-layered meadow vegetation, Thuring & Dunnett, 2019) will respond differently to systems of similar age but with unhealthy vegetation cover. Future work needs to address how old GRs with different substrate, plant and community of living organism respond to the extreme events and climate change.

3. Conceptualising temporal change and associated water quality impacts

The existing knowledge so far reveals that nutrient levels in the runoff of young GRs are high and variable. The main nutrient source is the substrate and leaching are the main pathways of nutrient loss. Changes to the substrate occur rapidly while the vegetation and community of living organisms play a secondary role in nutrient dynamics as they are still establishing (Johnson, 2014, cited in Buffam and Mitchell, 2015, Buffam et al., 2016).

As GRs age, nutrient levels in the runoff decrease and become less variable. The substrate is no longer the dominant source of nutrients. Nutrient losses are now controlled by vegetation characteristics, the community of living organisms and maintenance activities involving fertilizer applications (Berndtsson et al., 2006, Speak et al., 2014, Mitchell et al., 2017, 2021). Notable changes in the substrate include variations in the depth (e.g., shallower with age), water retention properties and organic matter content. Changes in the vegetation characteristics and community living organisms are determined by colonisation dynamics (e.g., Emilsson, 2008, Mitchell et al., 2018, 2021).

To describe the changing nature of nutrient levels in GR runoff, Buffam and Mitchell (2015) developed a 3-compartment model that describes the variation in nutrient stocks and fluxes as a function of changing inputs and outputs over time. This model is shown in Fig. 8 for periods when the GR acts as a nutrient source (output greater input), sink (output less than input, retention) and when steady state conditions are achieved (inputs equal outputs). Assuming constant inputs, the authors hypothesized that GRs are initially sources of both N and P nutrients. Over time, nutrient outputs decline exponentially as they get used up by vegetation or lost via leaching (e.g., Akther et al., 2021). As vegetation mature, the GR starts to retain nutrients (act as a sink) and achieve steady state conditions when inputs equate outputs. Steady state conditions are achieved for nitrogen first (Fig. 8).

Both field and laboratory results corroborate the general trends described in Buffam and Mitchell (2015)'s model (e.g., Seidl et al., 2013, Buffam et al., 2016, Mitchell et al., 2017, Akther et al., 2021). Nutrient levels in the outflow of laboratory leaching experiments initially decline exponentially but become progressively linear by the 4th or 5th year (Akther et al., 2021). The initial 'source' period can last up to 3 years or more (e.g., van Seters et al., 2009, Toland et al., 2012, Malcolm et al, 2014, Chai et al., 2018, Gong et al., 2020) and the duration of poor water quality lasted longer for phosphorus than nitrogen as shown in Fig. 8 (e.g., Akther et al., 2020). The relatively lack of year-to-year variability in the phosphorus levels of runoff from an 11-year-old GR suggests that it had achieved equilibrium (e.g., Mitchell et al., 2011).

Given the limited availability of long-term data, water quality models are used to examine if GRs achieve steady state conditions. Using linear mixed models, Mitchell et al. (2017) highlighted the long-term impact of phosphorus release from GRs (11 years) before runoff concentrations were similar to input concentrations. Seasonal variability was modelled by adding sine and cosine components to the exponential curve that is generally used to describe the decline in runoff quality. The modelling exercise showed the important interactions between seasonal responses and age-related factors that cause changes in the timing of seasonal peaks and the magnitude of their variability. The high level of variability in runoff quality over time presents challenges for water quality models that have fixed model structures and parameters, which may not capture changing dominant processes in nutrient transformations and transport pathways governing nutrient release from GRs.

One limitation of Buffam and Mitchell (2015)'s conceptual model is that it fails to capture short-term fluctuations in runoff quality caused by seasonal changes in temperature and rainfall (e.g. Buffam et al., 2016, Todorov et al., 2018), nor delayed increases due to additional inputs originating both internally (e.g., work of nitrifying bacteria, Mitchell et al., 2018, 2021) and externally (e.g., droughts, fertilizer additions, e.g., Emilsson et al., 2007, Emilsson, 2008, Kuoppamäki et al., 2021). Fig. 9 is an updated conceptual model that includes new information about short-term variations in nutrient runoff based on field and laboratory experiments. Notable increases in nutrient flux due to seasonal plant activities result in periods when GRs act as a temporary nutrient source or sink (e.g., Buffam et al., 2016, Mitchell et al., 2017, Todorov et al., 2018, Gong et al., 2020). Fertilizer applications, vegetation death and subsequent decomposition as well as contributions from nitrifying bacteria and archae cause delayed increases in nutrient flux, such that steady state conditions are not attained (e.g., Mitchell et al., 2017, 2021). Instead, the GR continues to act as a source of nutrients for an extended period that can exceed 10 years, especially for phosphorus (e.g., Buffam et al., 2016, Mitchell et al., 2017, 2021) (Figs. 3, 4 and 9b).

Fig. 10 illustrates temporal changes in the nutrient stocks found in the substrate and vegetation components of GRs. To simplify things, the model assumes constant inputs and a general exponential decline in nutrient flux over time for both N and P (Fig. 10a). The nutrient pool associated with the community of living organisms (e.g., soil microbes)

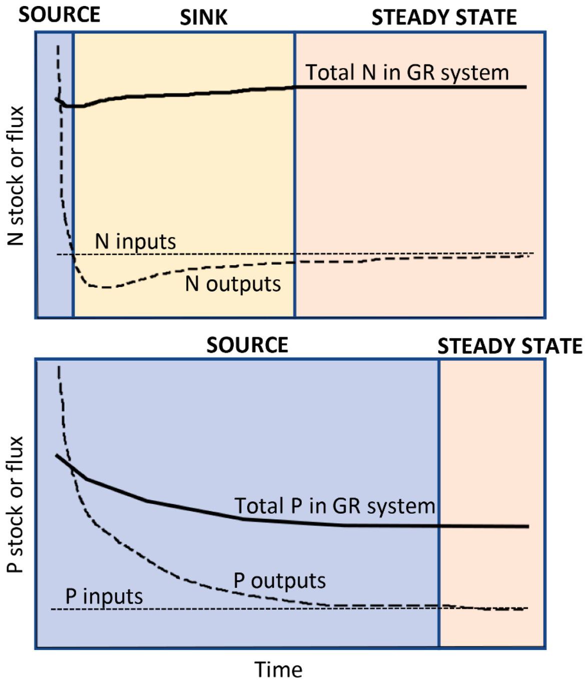

Fig. 8. Three-compartment model describing changes in GR nutrient flux and stocks over time (from Buffam & Mitchell 2015). The blue shading represents periods of time when GRs act as nutrient sources (Outputs> inputs). The yellow shading shows when GRs are nutrient sinks (outputs< inputs) and the peach shading shows when GRs have achieved steady state conditions. Steady state occurs when nutrient inputs into the GR system equals losses. Graph not drawn to scale.

is ignored and treated as a temporary conduit that links the substrate and vegetation nutrient pool. The GR lifespan is divided into the initial post-installation phase where both substrate and vegetation properties are rapidly changing. This is then followed by a period when the vegetation is established and starts retaining nutrients. Finally, the mature GR is one where both vegetation and substrates are established, with less fluctuations in their properties, unlike young systems. The substrate nutrient stock (brown shading) generally declines over time as nutrients are used up by vegetation (Fig. 10b). Leaching occurs when substrate stocks exceed vegetation nutrient demands, reducing substrate stocks. The nutrient stock in vegetation (green shading) increases as they mature (e.g., Emilsson et al., 2007, Nagase & Dunnett, 2012, Johnson et al., 2016, Mitchell et al., 2021) (Fig. 10b).

Fertilizer additions and the occurrence of extreme events (e.g., heatwaves, droughts) disrupt the general trend shown in Fig. 10b. Fertilizer applications increase substrate nutrient stocks temporarily, followed by an increase in the vegetation nutrient stock (e.g., Emilsson et al., 2007, Fig. 10c). The vegetation stock increases when an extreme event causes plants to die and decompose (Fig. 10d). Substrate stocks experience a delayed increase in nutrient stock (Fig. 10d), which causes a delayed spike in nutrient losses (Fig. 10a). The nature and magnitude of disturbance determines whether the vegetation nutrient stock recovers to the pre-disturbance levels and the duration of the recovery period.

These disturbances and nutrient additions from dead vegetation matter, nitrogen-fixing organisms and fertilizer applications delay the progression to steady state conditions (Buffam & Mitchell, 2015, Mitchell et al., 2021). It is not clear if mature GRs in Europe have achieved steady state conditions due to the limited monitoring conducted at all stages of their development (e.g., Berndtsson et al., 2009, Speak et al., 2014, Thuring & Dunnett, 2014, 2019). There is evidence to suggest that steady state conditions were recorded for phosphorus (e.g., Mitchell et al., 2017) but contributions from nitrifying activities continue to add nitrogen to the plant and substrate stocks of old GRs such that they never achieved steady state conditions (e.g., Mitchell et al., 2021).

4. Implications for GR design and management

As substrates are the main source of nutrients lost from GRs, most research focused on improving their design to minimize the initial poor water quality observed in young GRs. Design modifications often include amending substrates with materials such as biochar, crushed brick, alum, seaweed and compost (e.g., Beck et al., 2011, Malcolm et al., 2014, Kuoppamäki and Lehvävirta, 2016, Zhang et al., 2019). Vijayaraghavan et al. (2019) provides a recent account of the

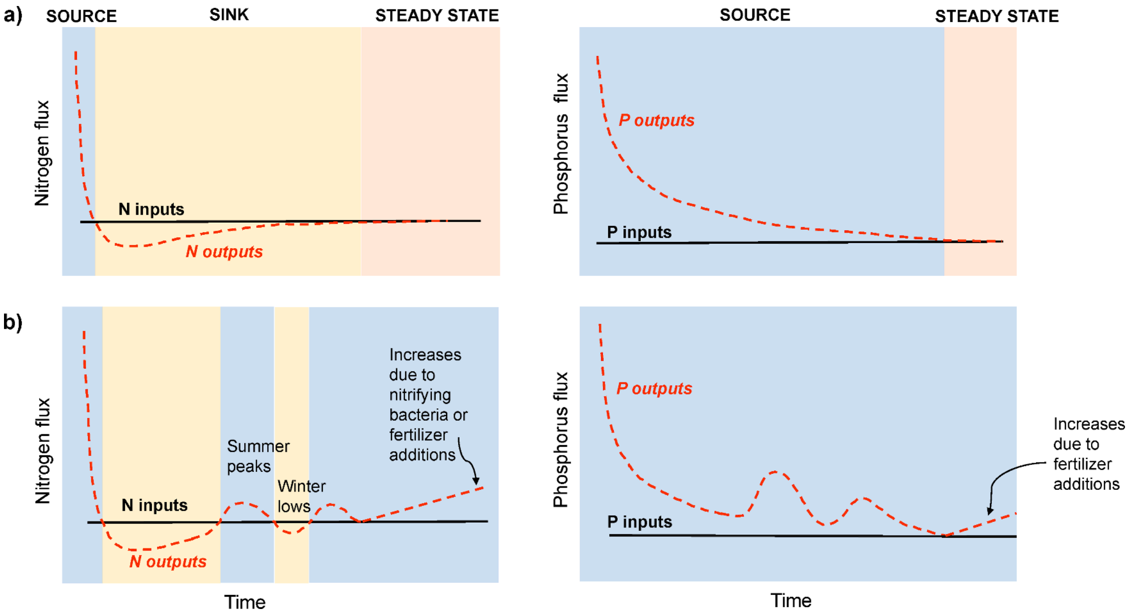

Fig. 9. Temporal variability in nitrogen and phosphorus flux in GR runoff for a) original conceptualization of Buffam and Mitchell (2015), b) updated conceptualization that includes short-term increases in nutrient losses due to seasonal fluctuations such as summer peaks and winter lows (e.g., Buffam et al., 2016). Long-term increases in nutrient fluxes are due to fertilizer additions or from living organisms that promote nitrification. Graph not drawn to scale.

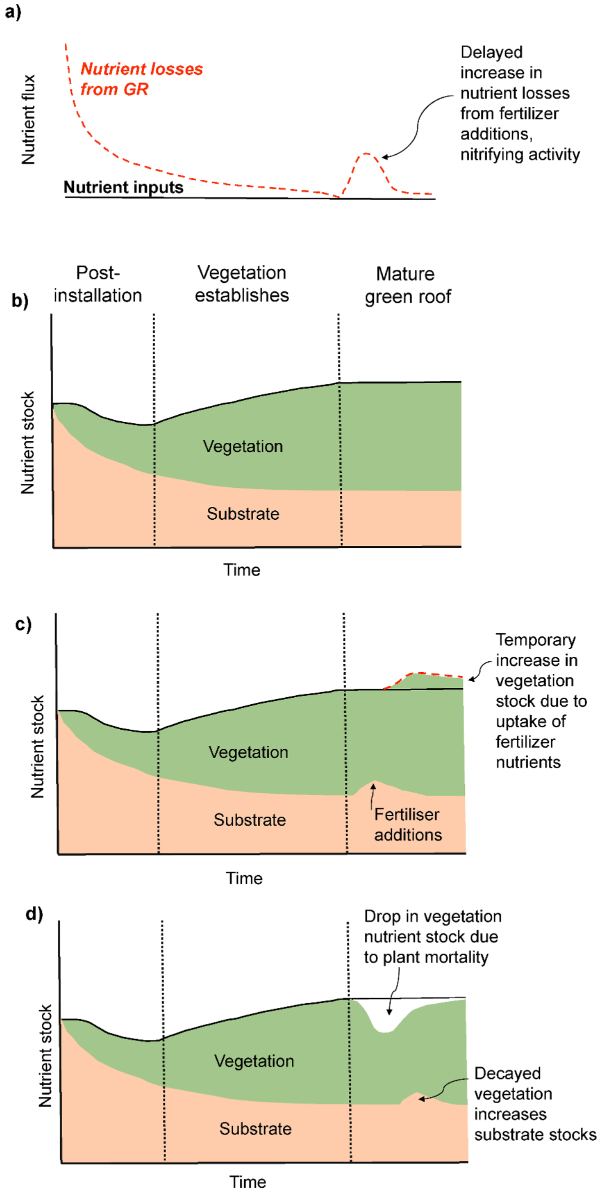

Fig. 10. Seasonal influences and fertiliser additions cause temporary spikes in GR runoff quality (outputs) with the level of variability decreasing as the GRs age (e.g., Buffam et al., 2016, Mitchell et al., 2017). The GR lifespan is divided into the initial post-installation phase, a period when the vegetation establishes itself and actively participates in nutrient retention, a mature stage when the GR substrate and vegetation are established. Graph not drawn to scale.

characteristics of materials added to GR substrates to improve pollutant retention. Design modifications to GRs also include the innovative design of a dual substrate system where nutrients not captured by one substrate is captured by an adjacent substrate below (e.g., Wang et al., 2017b). This design not only improved nitrogen and phosphorus retention, it was also effective for other pollutants such as organics and heavy metals. Nitrogen and phosphorus were released when big rainfall events occurred. In such situations, a larger-scale integrated design approach that includes a treatment train system of blue-green infrastructure to capture nutrient rich runoff from GRs for reuse may reduce the risk of downstream pollution (e.g., Teemusk & Mander, 2011, MacAvoy et al., 2016). An important consideration is that other blue-green infrastructure such as bioretention basins, rain gardens and swales may also release nutrients (e.g., Barrett, 2005, Winston et al., 2011, Mangangka et al., 2015, McPhillips et al., 2018). To examine the impacts of a treatment train system on runoff quality, modelling efforts can help determine the optimal type, number, size, and arrangement of BGIs (Carter and Jackson, 2007, Zhang and Chui, 2018).

Apart from design modifications and improvements, policy changes and development of planning and governance frameworks, support design efforts to improve GR runoff quality. These include policies around testing substrates before their deployment in urban environments, developing guidelines for GR management and lists of substrate materials and plant types suitable for different climate zone and regulation of their use may reduce the associated water pollution risk from GR runoff (Emilsson et al., 2007, Jennett & Zhang, 2018). At present, the FLL guidelines, which recommend that extensive GRs require 5g N/yr/m^2 (Emilsson et al., 2007), is the most established guideline used for GR design. While the FLL guidelines were designed for German green roofs, they have found widespread use in Europe, the UK and in North America even though local conditions may differ from German conditions. There are now other guidelines for GRs that reflect more nation-specific needs such as the GRO Green Roof Code (UK-specific), the American Society for Testing and Materials (ASTM) standards for GR growing media and the AS3319-2003 standards for Australia as well as those developed by the National Parks Board to suit the warm and wet tropical conditions of Singapore (https://www.nparks.gov.sg/skyrisegreenery/news-and-resources/guidelines, Kazemi & Mohorko, 2017).

Careful selection of plants and choice of establishment methods not only determines vegetation survival but also affects colonization dynamics of both plant and the community of living organisms (Emilsson, 2008, Thuring & Dunnett, 2014, Hoch et al., 2019). The general guide for GR plant selection is to choose plants from a wide taxonomic group, including a mixture of plant growth forms and native species, to ensure that there is vegetation cover for different climatic conditions that occur on a seasonal and long-term basis. A combination of succulents and other vegetation types facilitates better plant establishment as succulents provide good ground cover and also improves the substrate ecosystem (Emilsson & Rolf, 2005, Emilsson, 2008, John et al., 2017, Kazemi & Mohorko, 2017, Thuring & Dunnett, 2019, Mitchell et al., 2021). Farrell et al., (2022) suggest a framework that uses plant traits and their natural distribution to guide plant selection. Using vegetation already established on the substrate during installation ensures a higher chance of their survival, especially since it is likely the substrate also has a healthy soil microbial community (Emilsson and Rolf, 2005, Mitchell et al., 2017, 2021, Rumble et al. 2018).

Increasing shade promotes vegetation and microbiome resilience by reducing ambient air and substrate temperatures since there is some evidence that vegetation may be more sensitive to temperature changes than to water availability (e.g., Savi et al., 2016, Fowder et al., 2021). In the same token, the microbial community can be managed so that it is both diverse and suited to local conditions. This may include inoculating substrates with microorganisms (e.g., arbuscular mycorrhizal fungi) for improved nutrient retention and increased plant diversity (John et al., 2017, Rumble et al., 2018, Xie et al., 2018, Hoch et al., 2019). Planting nitrogen-fixing vegetation may ensure a sustainable long-term nutrient supply (Johnson et al., 2016), since they have been found to supplement nitrogen in excess of plant needs for older GRs (e.g., Mitchell et al., 2021). However, there is a danger that the N-fixers supply nitrogen in excess of vegetation needs. If this occurs, nitrification inhibitors may be useful (McCarty, 1999 cited in Mitchell et al., 2018). Regular testing of the N levels in the substrate as well as the microbial population at different stages of the GR lifespan is necessary because this allows managers to adapt management activities to changing conditions at different stages over time (Barr et al., 2017).

Because fertilizer additions have such an impact on GR runoff quality in terms of the magnitude and duration of impact (e.g., Emilsson et al., 2007, Malcom et al., 2015, Whittinghill et al., 2015. Kuoppämaki et al., 2021), management decisions around their applications have to be flexible to the changing conditions of the GRs at different stages of their development. Rowe et al. (2006) found that only a minimum amount of fertilizer (50g/m^2) was needed to sustain plant health and that the plants (*Sedum spp.* and non-succulent natives of midwestern US prairie) were more sensitive to water availability than fertility. Decisions around fertilizer concentrations depend largely on the objectives of each GR. If GRs are built for the purpose of greening urban areas with minimal water quality impacts, then fertilizer concentrations and frequency may be adjusted to maintain minimum vegetation cover. However, GRs are often designed for aesthetic purposes and such systems often require large fertilizer additions to maintain lush vegetation but have higher water demands, making them sensitive to heatwaves and droughts (Rowe et al., 2006, Emilsson et al., 2007). Lush vegetation are also a source of organic matter when they die (Emilsson, 2008, Getter et al., 2009). If lush vegetation is desired, the use of controlled-release fertilizer, especially when applied as a top-coat, may reduce losses in runoff although further research into its efficacy and duration of impact is needed (e.g., Emilsson et al., 2007), especially when evolving substrate and vegetation species composition change the balance between nutrient supply and demand over time. Other management activities of concern include vegetation trimming and the removal of excess organic matter, especially from surrounding vegetation, to reduce additional nutrient inputs from the decomposition of plant organic matter. These issues should be carefully considered so that fertilization practices are suited to the respective needs of different GRs, at different stages of their development. Finally, the design of substrates, selection of appropriate vegetation and fertilizer management strategies must suit local conditions and be flexible enough to adapt to changing nutrient levels in runoff as GRs mature.

5. Recommendations for future research

Current understanding of GR contributions to urban water quality has improved due to recent monitoring efforts that not only sample GR runoff but also include sampling of the substrate, vegetation and living organisms. Although these studies increased the knowledge base around the characteristics of GR components at different stages of their development (e.g., Mitchell et al., 2017, 2021, Jauni et al., 2020), there are knowledge gaps about how the GR components interact with each other, the factors that control their interactions and how these change over time.

Substrate: This is the most studied component of GR systems. Existing research have so far characterized the changes in important substrate characteristics (depth, textural properties, water holding capacity, organic matter, pH), most limited to the first 5 to 7 years of the GR lifespan (refer to Table 3). However, there are still gaps in our knowledge around the changing nature of nutrient stocks and nutrient fractions and the mechanisms controlling these changes over time and how they affect the community of plants and other living organisms. For example, the community of living organisms change accordingly to pH conditions, which is known to occur as substrates age (e.g., Thuring & Dunnett, 2014, Table 3). Addressing how changing substrate conditions affect the plant and community of living organisms is an important area of research to obtain a better understanding of the interactions between these components and how they affect nutrient levels in runoff. This can be achieved by sampling substrates and testing their physiochemical characteristics and preferably nutrient content, an approach that more recent studies have started adopting (e.g., Mitchell et al., 2017, 2021), but repeating these measurements over a longer period.

While the negative impacts of fertilizer additions are now known (e.g., Emilsson et al., 2007, Malcolm et al., 2014, Whittinghill et al., 2015, 2016), there is limited information about the effect of fertilizer additions on nutrient stock levels and their fractions in the substrate as well as the magnitude and duration of impact for GRs of different ages. Emilsson et al. (2007)'s study forms the basis for further research on the impacts of fertilizer additions (e.g., fertilizer type, concentration, frequency of application) on plant productivity and nutrient stocks within the GR components. Apart from measuring substrate nitrogen and phosphorus forms, information about substrate N:P ratios are useful in identifying the limiting nutrient, to target ferilizer applications (Mitchell et al., 2017). Characterizing the changing nature of nutrient stocks in substrates (or the main components in substrates) over time provides an estimate of their longevity so that practitioners have some indication of when they need to be replaced to sustain vegetation productivity.

Vegetation: Current knowledge around the evolution of GR vegetation indicates that the original planted vegetation evolves due to colonisation by other plants and community of living organisms and develop into unique ecosystems that can be quite different from the planted vegetation (e.g., Thuring & Dunnett, 2014, 2019, Grullón-Penkova et al., 2020). However, there is still inadequate knowledge around the trajectory of vegetation changes and nutrient levels in runoff due to the lack of continuous monitoring. It is often assumed that the GR plant community will arrive at a state of dynamic equilibrium, even though short-term changes in vegetation composition have occurred due to seasonal variations in temperature and water availability (e.g., Emilsson, 2008, Mitchell et al., 2021) (Fig. 10). As plant uptake appears to be more effective in removing N (e.g., Malcolm et al., 2014, Todorov et al., 2018, Mitchell et al., 2018, 2021, Akther et al., 2021), changes to the vegetation composition and structure will likely have a greater impact on nitrogen, especially if colonising species also include N-fixing plants and living organisms (e.g., *Nitrospira, rhizobiales*), offsetting any benefits gained from plant uptake (e.g., Mitchell et al., 2018, 2021). There is a need to continue documenting the plant community and structure, particularly to study the dynamics of plant colonisation as well as the impact of seasonal variation in temperature and/or rainfall and fertilizer application practices at different stages of their life (e.g., Mitchell et al., 2017). Studies should also focus on how important factors such as substrate depth, substrate physiochemical properties (e.g., pH, organic matter, nutrient levels), soil moisture and plant establishment methods control the diversity of the plant community and the role they play in nutrient release from GRs at different stages of development (e.g., Monterusso et al., 2005, Rowe et al., 2006, Dunnett et al., 2008, Emilsson, 2008, Getter and Rowe, 2009).

With reference to plant selection and the type of establishment methods used, studies have shown that a diverse community of plants including natives provides a higher chance of vegetation survival especially for extreme events and also improve biodiversity in urban areas (e.g., Nagase & Dunnett, 2010, Johnson et al., 2016, Fowdar et al., 2021, Calheiros & Pereira, 2023). More research is needed around vegetation characteristics (e.g., water holding capacity, drought tolerance to heat etc) and response to drought and temperature stress, the physiological traits that aid survival and recovery for extreme events and climate change (e.g., Vanuytrecht et al., 2014, Savi et al., 2016, Du et al., 2019, Fowdar et al., 2021). More attention should be given to plant establishment methods to see if using established vegetation consistently reduces the poor water quality observed for GRs in the initial stages post-installation (e.g., Emilsson et al., 2005, Emilsson., 2008). Measurements of nutrient content in plant biomass will improve understanding around nutrient storage in plants and how they change over time giving practitioners an indication of plant nutrient needs to guide fertilizer applications (e.g., Emilsson, 2008, Jauni et al., 2020, Barra & Johan, 2021, Mitchell et al., 2021).

Looking beyond the individual GR systems, studies have highlighted the important role urban ecology have on GRs with nutrient inputs from leaf fall of neighboring vegetation (e.g., Buffam et al., 2016, Mitchell et al., 2017) and colonization of plants and microbes via birds and other wildlife (e.g., Rowe et al., 2006, Nagase & Dunnett, 2010, Catalano et al., 2016). Future research directions may consider the role urban ecology has on the GR nutrient budget through experiments to measure leaf fall from neighbouring vegetation or documenting urban wildlife activity via cameras as an indirect way of accounting for external nutrient inputs to GRs (e.g., O'Brien & Kinnaird, 2008).

Living organisms: While there is an encouraging growing body of work examining soil organisms (e.g., Schrader & Böning, 2006, Rumble and

Gange, 2013; Rumble et al., 2018, Jauni et al., 2020, Kuoppamäki et al., 2021), this is still the least studied component of GR systems. There is scope for more research examining the sequential changes in their population dynamics (due to colonization) and their role in regulating nutrient stores and transformations that occur in the substrate and vegetation components of GRs. This is particularly true for nitrogen where nitrifying plants and living organisms supplement nitrogen to old GRs (e.g., Mitchell et al., 2018, 2021). Importantly, there is a need to also investigate how changing substrate (e.g., depth, pH, water content) and plant characteristics affect the microbial community and vice versa, as GRs age to understand the role these organisms play in nutrient retention/release, the optimal environmental conditions for their survival and how their roles change over time (e.g., Mitchell et al., 2021).

5.1. A focus on holistic and long-term studies

Answers to the issues raised in the previous section can be achieved through a focus on holistic monitoring that includes sampling runoff, vegetation, substrate and the community of living organisms for GRs of different ages (e.g., Emilsson et al., 2007, Mitchell et al., 2018, 2021, Jauni et al., 2020, Barra & Johan, 2021, Kuoppamäki et al., 2021). Studies spanning a few years may be useful in identifying fluctuating patterns in runoff quality, but they do not capture long-term trends in GR components as they develop over time. What is needed are long-term monitoring studies to capture the magnitude and duration of water quality impacts from seasonal changes and disturbances (e.g., extreme events, fertilizer applications) especially for old GRs where such information is lacking. Comparative studies of GRs of different ages provide some answers to address these knowledge gaps but these studies are limited to young and old GRs that are just past 10 years of age (e.g., Malcolm et al., 2014, Mitchell et al., 2017, Okita et al., 2018, Todorov et al., 2018, Akther et al., 2020, 2021). Some cities have old GRs that are approaching 50 years of age or more. Extending these comparative studies to include older GRs ($>$ 20 years or more) helps extend the timeline of changes in runoff quality and GR components over a longer period.

Laboratory experiments under controlled conditions provide a complement to field monitoring activities which are often short-term in their monitoring and sampling activities. Snapshot monitoring at different stages of a GR or comparisons between different GRs do not provide a continuous timeline of changes in GR components and runoff quality which can be simulated under controlled laboratory conditions through ageing experiments (e.g., Lim et al., 2015, Bouzouidja et al., 2018b, Akther et al., 2021). The combination of field, laboratory and modelling experiments provide a holistic and long-term study of GR changes over time. Some of the benefits of a holistic approach that allows practitioners to answer important questions around whether GRs achieve equilibrium conditions, if the amount and periods of high nutrient release change, and if the impact and recovery of GRs from extreme events change as they age.

6. Conclusions

This review has shown that our understanding of GR systems is limited to the first 10 years of their lifespan, mainly for a limited geographical region that includes European countries and the USA. There is enough evidence that highlights the dynamic nature of GRs, with high levels of nutrients observed in the runoff in the first 1 to 2 years after their installation (NO_3: 0.08-100 mg/L, PO_4: 0.01-13 mg/L). Substrate composition and fertilizer use control nutrient release from young GRs but as they age, vegetation and associated microorganisms become important determinants on nutrient dynamics. Runoff quality improves over time and there is evidence to show that GRs achieve equilibrium conditions for P but not for N (GRs over 10 years old: NO_3: 0.05-7 mg/L, PO_4: 0.01-1.2 mg/L). Elevated N and P concentrations recorded for old GRs are often associated with fertilizer applications, presence of unhealthy vegetation and nitrifying plants and living organisms. Long term changes in runoff quality are interrupted by short-term changes associated with seasonal changes in temperature and fertilizer applications. Of the two nutrients reviewed, nitrogen is more variable and short-lived in terms of its concentration and mass flux behavior than phosphorus due to its higher mobility whereas phosphorus release is tied to changing substrate properties.

Amongst the GR components, the knowledge base for the substrate is most extensive. More efforts should be placed on sampling the community of living organisms to better understand their roles in nutrient transformation and retention over time. A holistic approach that includes sampling all components of the GR over a longer-term period provides a clearer understanding of how the GR components evolve individually and interactively with each other over time. There is an urgent need to pursue this path given the rapid proliferation of GR systems in cities across the globe, particularly with the rise of rooftop agricultural activities and pressures from extreme events and climate change. Improved GR designs and their subsequent management will ensure a more sustainable urban environment for future generations.

CRediT authorship contribution statement

H.S. Lim: Conceptualization, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data used (Figure 3) appeared in the supplementary of Todorov et al. (2018). I drew graphical plots from the data in the paper and credited the data source.

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Supplementary materials

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