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TOPICAL REVIEW

Merits, limits and preposition of coupling modelling tools for blue-green elements to enhance the design of future climate-resilient cities

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Supplementary material for this article is available online

Abstract

This paper presents a comprehensive survey of the process-based models currently available for blue-green infrastructure for the assessment of cooling potential, stormwater and pollution control, carbon sequestration, and water provision. The assessment of the modelling tools for blue-green elements (BGEs) documents that currently there is no process-based model for the simultaneous evaluation and optimisation of multiple ecosystem services of BGEs. To evaluate coupling options, this study conducted a meta-analysis on model interoperability by assessing the model scales, drivers, overlaps, gaps, and interfaces of these models for BGEs. Model meta-analysis points out the conceptual and constructual constraints preventing easy model coupling, and thus, an integrated assessment of ecosystem services. Constraints arise due to very different disciplinary approaches from different scientific communities involved in model development, differences in the simulation of transformation and transport processes at urban interfaces relevant for BGEs, and fundamental divergences in spatial and temporal scales and time steps of existing models for single ecosystem services. In particular, the lack of vegetation models tailored for BGEs hinders current model developments towards developing a process-based tool for multiple ecosystem services, which would be able to handle nonstationary climate conditions, including feedback assessments of drought and heatwave impacts on the functioning of BGEs.

1. Introduction

The growing environmental pressure from increased urbanisation and climate change has intensified the interest in blue-green infrastructure to ensure sustainable liveability for humans and ecosystems in cities. Urban blue-green infrastructure is considered a critical structural facility for nature-based solutions that have the potential to increase urban resilience by providing multiple ecosystem services (Xue *et al* 2024). Blue-green infrastructure is used here as an umbrella term for various concepts of green infrastructure, sponge city approaches, and a wide range of stormwater management terminologies (Fletcher *et al* 2014). Blue-green infrastructure incorporates green spaces and water elements that are designed as intervention actions that utilise natural or mimic natural processes to address urban problems (Pinto *et al* 2023). Individual blue-green elements (BGEs) were identified as urban grasslands, bioretention cells (such as rain gardens and swales), green roofs, living walls and facades, urban trees, wetlands, permeable pavements, and cisterns for rainwater harvesting. Blue-green infrastructure has been shown to provide adaptive responses and multiple ecosystem services to acute climate disturbances, such as heavy rainfall, floods, and heat waves, as well as long-term stresses, such as increased CO_2 levels, air and water pollution, and deterioration of biodiversity (Almaaitah *et al* 2021). Ecosystem functions include cooling via evaporation and evapotranspiration, water and pollutant storage, peak attenuation and retention during heavy rainstorms, and vegetation growth in order to reduce CO_2 emissions (Voskamp and Van de Ven 2015).

Maintaining the vegetation health of various BGEs plays a key role in enabling their functioning (Probst *et al* 2022). However, their functioning is affected by continuing climate warming, which further increases summer heat and drought periods. At the same time, rainfall events intensify in terms of their magnitude and frequency (Kendon *et al* 2014, Westra *et al* 2014). In particular, under rapidly changing and nonstationary boundary conditions, it is essential to guide the future development and expansion of cities by working towards a climate-resilient design.

For this purpose, modelling and mapping tools can be used to design, optimise, and prioritise blue-green infrastructures (Hou *et al* 2023, Dong *et al* 2024). Modelling tools can play an invaluable role to maximise efforts of urban planners and decision-makers to adapt their cities to the increasingly detrimental effects of climate change, to prevent disfunctioning under non-stationary conditions or avoid mutual cancellation of different types of blue-green infrastructure. A drawback of past modelling approaches for BGEs is their focus on a single benefit, which is often stormwater management (Meerow 2019). In the recent past, a wealth of GIS-based spatial planning tools have been developed in order to facilitate the integration of different ecosystem services into the city-wide planning of blue-green infrastructure, including multi-criteria analyses (see van Oijstaeijen 2020; Meerow and Newell 2017, Lourdes *et al* 2022). Lourdes *et al* (2022) in their study employed the InVEST model to map six different ecosystem services in Kuala Lumpur, Malaysia: heat mitigation, runoff and sediment retention, urban recreation, and agricultural production. Meerow and Newell (2017), Wang *et al* (2021), and van Oorschot *et al* (2021) developed spatial planning tools to capture the multi-functionality of heat mitigation, runoff retention, air quality, and habitats for cities in the US, China, and the Netherlands, respectively. All three studies showed the importance of a spatially explicit overlay to identify suitable locations for interventions and enable hot and cold spot analysis by referring to areas with high and low amounts of ecosystem services. With the imminent advent of urban digital twins (Ketzler *et al* 2020, Weil *et al* 2023), one might expect the first applications to inform real-time decision-making regarding the ecosystem services of BGEs. Some digital twins exist that look at multiple ecosystem services within cities, such as the twin by Gonzalez-Caceres *et al* (2024) simultaneously assessing wind comfort, energy demand, and noise, or the study by Therias and Rafiee (2023) to deal with typhoons in Japan, tracking extreme rain, flooding, shelter availability, and traffic behaviour across entire city districts. However, to the best of our knowledge, no digital twins are currently available that deal specifically with the assessment of blue-green infrastructure.

Current planning tools for BGEs exhibit some inherent limitations regarding the description of the ecosystem functions of BGEs. GIS-based spatial planning tools mostly use simple overlays of spatial data to describe rather than simulate the functioning of BGEs. For examples, areas prone to flooding are associated with highly sealed areas or heat stress is derived from remotely sensed land surface temperatures (Meerow 2019, Wang *et al* 2021). Normally, they do not comprise process-based models that describe the interactions of BGEs with their surroundings or their dynamics under nonstationary climate conditions. There are a range of well-tested process-based modelling tools for BGEs that calculate relevant fluxes and storage, but mostly for single ecosystem functions (Vico *et al* 2014, Lisenbee *et al* 2021, Fowdar *et al* 2022, Zezzo *et al* 2023). Models have been developed separately for different disciplines, including microclimatology, soil physics, ecology, and urban drainage engineering. No modelling framework exists for the multiple ecosystem benefits of the BGEs. However, to render the multiple effects and feedback of BGEs, we clearly need a process-based approach to evaluate individual hazards, such as extreme rainstorms and heat waves, and long-term behaviour, such as vegetation health under drought conditions, to ensure the full functioning of BGEs. It remains unclear what kind of modelling framework is needed to quantify the dynamics of multiple ecosystem functions and, for this purpose, the relevant key fluxes, storages, and their interactions. Can we couple existing process-based models for BGEs designed for single benefits, or do we need a process-based model that can do it all, and how should it look? In summary, a modelling framework that considers the inherent biogeophysical feedback of BGEs and their surroundings under nonstationary climate conditions is required.

A key aim of this study was to contribute to the integration of process-based modelling of multiple functions of blue-green elements to enhance future urban planning and design processes under non-stationary climates and changing boundary conditions. To achieve this aim, this study sets out to (i) compile a survey of process-based modelling tools, their process descriptions, and setups for a whole range of different ecosystem benefits; (ii) carry out a meta-analysis on model interoperability by assessing model scales, drivers, overlaps, gaps, and interfaces of these models for BGEs; and (iii) assess the opportunities and limitations of the current tools to reproduce multiple, possibly interconnected, ecosystem functions in unison, including a proposition of model coupling for the simultaneous evaluation of multiple ecosystem functions.

2. Methods

2.1. Multidisciplinary survey of process-based models for BGEs

In recent years, multiple models were developed to evaluate benefits and ecosystem functions of BGEs (Vico *et al* 2014, Lisenbee *et al* 2021, Fowdar *et al* 2022, Vieira Zezzo *et al* 2023), which could be, as depicted in figure 1, roughly grouped into five major purposes to simulate: (1) stormwater control, (2) pollution control, (3) heat mitigation & cooling potential, (4) (plant) water provision and (5) carbon sequestration. Other benefits of BGEs, such as mitigation of air and noise pollution, biodiversity, and groundwater recharge, were not considered in this assessment.

A survey of the current model types and process descriptions for BGEs is presented here by a mixed group of scientists from the disciplines of hydrology, urban drainage engineering, soil science, climatology and urban ecosystem science. The group has experience in modelling a wide range of different BGEs with specific proficiency in the urban drainage model SWMM (Rossman and Simon 2022), the microclimatology model PALM (Maronga *et al* 2020), the soil-hydraulic model HYDRUS-1D (Reck 2021), the water provision and water stress model for urban trees like URbanTRee or Street Tree ET models (Tams *et al* 2023, Kluge and Kirmaier 2024) and the carbon sequestration model Anthro-BGC (Ma *et al* 2011).

Using the expert knowledge of this multidisciplinary modelling team, we have collated in section 3 for each modelling purpose a short mini review that summarises: (i) the purpose of the modelling tools, that is, which individual ecosystem benefits are the core results of these tools, (ii) one to two commonly used packages and software, (iii) typical spatial and temporal scales (including model time steps), (iv) key processes that are being modelled, (v) required input parameters and model drivers, resulting outputs (fluxes or pools, as visualised in figure 2) and (vi) the types of BGEs they can be used for. The fields of application and the most commonly used model software are referenced with contemporary studies and the key processes, input and output information derived from the method sections' of these studies. Typical spatial and temporal scales of model applications are derived from an internal workshop of the authors' team. Owing to space limitations, existing review studies are quoted wherever possible rather than carrying out lengthy reviews for each model type.

A comprehensive list of the quoted models, including their specific ecosystem benefit types, descriptions, and references, is provided in the Supplementary Materials for further reference.

2.2. Approach for meta-analysis on model interoperability, scales, urban interfaces and coupling options

With a few exceptions, most existing process-based modelling tools concentrate only on the simulation of one ecosystem benefit (figure 1) of BGEs rather than multiple benefits, which hinders the prioritisation, optimisation, and trade-off assessment of multiple ecosystem services provided by BGEs, especially under nonstationary climate conditions.

To move towards model integration for a process-based evaluation of multiple benefits, five model type surveys were used to evaluate interoperability and model coupling options following the methodology of Harvey *et al* (2019) and employ the five-level coupling hierarchy for environmental models compiled by Brandmeyer and Karimi (2000). For this purpose, it is necessary to evaluate how well temporal and spatial scales match; compare model drivers; identify critical interfaces of BGEs using the concept of urban interfaces by Gessner *et al* (2014); and identify overlaps, singularity gaps, and resulting limitations due to boundary conditions or simplified process descriptions.

3. Survey of process-based modelling tools for BGEs

Benefit 1: stormwater control modelling

BGE modelling tools for stormwater control are used for the assessment of BGEs impacts on the urban runoff regime, including (i) stormwater runoff reduction potential, particularly towards decreasing frequent sewer overflow events, (ii) quantification of BGEs' retention effects, (iii) optimisation of BGEs performance with regard to different BGE numbers and spatial layout, and (iv) the assessment of design factors influencing the effectiveness of BGEs in stormwater control (Liu *et al* 2022a). Modelling stormwater control by BGEs is simulated mainly as subfeatures in conventional urban drainage models (e.g. SWMM, MUSIC, MOUSE/MIKE URBAN) or catchment hydrology models (HEC-HMS, SWAT), and less commonly as individual model elements using soil-hydraulic models (e.g. HYDRUS-1D, RECARGA, DRAINMOD-Urban,); reviews of these models is available in Lisenbee *et al* (2021) or Jayasooriya and Ng (2014).

Scales: the models can simulate multiple types of BGEs except facades, urban trees, and wetlands. The BGE is simulated either explicitly as a single unit (more common in soil-hydraulic models, but also possible in classical drainage models such as SWMM) or implicitly with multiple elements of the same or different types as an integrative part of a sub-catchment (mostly urban drainage models). Accordingly, large variations in model domains exists ranging from a few square meters for individual BGE

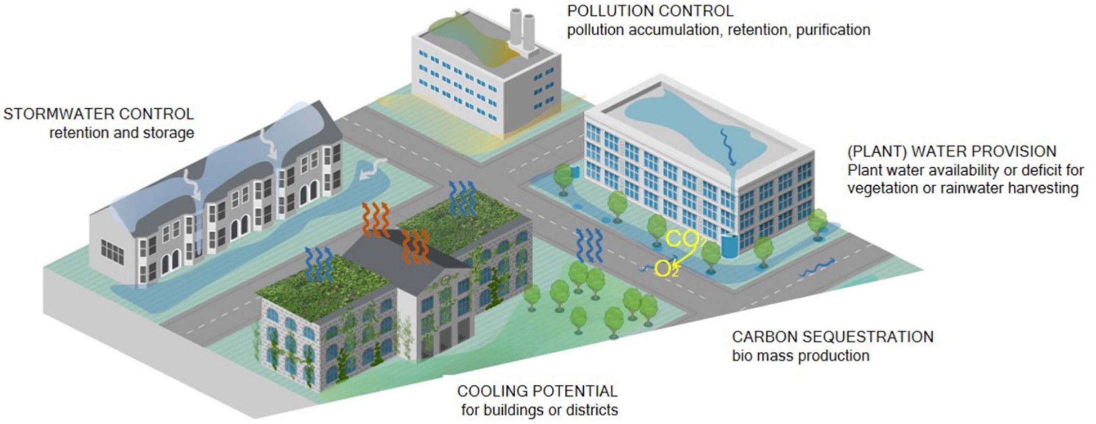

Figure 1. Blue-green elements and their five key benefits to make cities more climate-resilient: stormwater control, pollution control, plant water provision, heat mitigation and carbon sequestration.

evaluations, such as bioretention cells (e.g. using the HYDRUS-1D model as done in Meng *et al* 2014 or Li *et al* 2018, 2020) up to several hectares for new estates or re-developments, or entire cities equipped with multiple BGEs of the same or different types (see Li *et al* 2017, Jefferson *et al* 2021 for reviews of catchment-scale impact modelling studies of BGEs). Simulations were run for individual or designed storms of up to several hours or several years or decades in order to assess the long-term dynamics or impacts of climate and land-use changes. Flow processes during the storm are normally calculated with 1–15 min time steps, and less often larger, adaptive time steps of days to weeks are used for interstorm periods (e.g. for SWWM, Recarga, MUSIC as summarised in Li *et al* 2016, Lisenbee *et al* 2021 or Imteaz *et al* 2013).

Processes: numerical process descriptions relevant to BGEs depend on the model type. Urban drainage and hydrological models use various simplified rainfall–runoff models (e.g. SCS Curve number or unit hydrograph), flow routing towards BGEs (dynamic or kinematic wave or Muskingum Cunge approach), surface infiltration, infiltration between layers of BGEs, soil water retention using bucket models or Green–Ampt versions, and bucket model quantifications for overflow, ponding depth, and exfiltration. For the less common soil-hydraulic models, inflow is not calculated but has to be user-supplied, while infiltration and soil moisture dynamics are considerably better represented using the Richards' equation, tile drain boundary conditions, and modified Van Genuchten for seepage, and aerodynamic models for evapotranspiration considering plant water uptake and root depth.

Model input and output: input data include multiple catchment and drainage properties and land cover information for the rainfall–runoff sub-models, geometry and design of the BGEs, rainfall data, and other climate data if routines for the calculation of evapotranspiration are included, and more or less extensive characteristics of the soil-hydraulic properties of the BGEs. The main outputs comprised water inflow, surface, and drain outflows as time series if they were modelled explicitly, and as lumped sum values over the entire simulation period if modelled implicitly. Depending on the model type, information on the soil moisture content, infiltration rates, and groundwater recharge was simulated (Lisenbee *et al* 2021).

Benefit 2: pollution control modelling

Modelling of BGEs for pollution control is carried out to (1) assess the potential or efficiency of BGEs in runoff contaminant removal through various complex processes such as sedimentation, infiltration, filtration, adsorption, and biodegradation; (2) evaluate the design requirements to achieve the desired contaminant removal; and (3) understand contaminant transport and retention within the BGEs (see reviews e.g. in Jeon *et al* 2021, Kaykhosravi *et al* 2018, Quinn and Dussaillant-Jones 2014a, 2014b).

Two categories exist for pollution control modelling. Firstly, pollution control of BGEs is simulated as an additional feature of urban drainage modelling for entire catchments (Elliott and Trowsdale 2007) using e.g. the SWMM (Rossman and Huber 2016, Baek *et al* 2020) or MUSIC model (Fowdar *et al* 2022) or various catchment models (HSPF, HEC-HMS). Secondly, pollution control modelling may also be carried out using soil-hydraulic models such as HYDRUS-1D (Yu *et al* 2023) or the GIFMod (Massoudieh *et al* 2017), where the BGEs are modelled as individual elements with a much larger focus on vertical transport processes within the BGEs.

Scales: pollution control can be modelled for any type of BGE except for green facades and urban trees. The spatial scale of pollution control models varies from individual BGEs of a few meters, for example the HYDRUS-1D modelling study by Gong *et al* (2023), to multiple BGEs in sub-catchment to catchment or city scales, for example, the SWMM application by Bai *et al* (2018). Most models can be run for individual rain events and design storms or for continuous simulations of days, years or decades. Although the possible temporal resolution varies from seconds to days, models are often simulated with time steps of 1 min to 1 h (Baffaut *et al* 2015).

Processes: pollution models driven by urban drainage models, such as SWMM or MUSIC, use build-up and wash-off functions or event mean concentrations for modelling pollution transport from surrounding surfaces to determine pollutant load entering a BGE (Rossman and Huber 2016, Fowdar *et al* 2022). They use simplified empirical methods such as removal fractions and first-order decay to simulate water quality improvement processes happening within a BGE.

Soil-hydraulic models such as GIFMod and HYDRUS-1D are considerably more process-based as the Yuse Richards' equation for determining infiltration processes and include reaction kinetics and adsorption processes, which makes them more suitable for detailed simulations of pollutant fate and transformation within BGE systems (Massoudieh *et al* 2017). As a result, they are better suited for site-scale analyses and research applications where understanding the complex interactions between pollutants, media, and biogeochemical processes within BGEs is essential. Soil-hydraulic models do not simulate water and pollutant inflow into BGEs from surrounding areas; this information has to be supplied externally by urban drainage models (Gong *et al* 2023).

Input and output: input data include meteorological, hydrological, pollutant type, and model-specific data such as soil and surface properties. Pollutant accumulation models require initial pollutant build-up, street-cleaning intervals, build-up and wash-off model parameters, and cleaning efficiencies. The soil-hydraulic models need more detailed input data such as geometry of the BGE, soil hydraulic properties, adsorption parameters of the contaminants and initial pollution concentrations. The majority of these models simulate a time series of pollutant concentrations in the effluent from the BGEs and the total pollutant load for the duration of the simulation. Models such as the MUSIC model provide the contaminant removal efficiencies for the design parameters given for the BGEs (Liu *et al* 2022b). If modelled explicitly, models such as GIFMod can simulate the time series of water quality cycling through different segments of a single BGE (Massoudieh *et al* 2017).

Benefit 3: heat mitigation and cooling modelling

Energy models are used to estimate the heat mitigation and cooling potentials of BGEs by quantifying their thermophysiological effects on both humans and surrounding environments (Fröhlich and Matzarakis 2020, Vieira Zezzo *et al* 2023). They are implemented as either building energy models or urban microscale climate models. Building energy models are used to quantify an individual building's energy performance and evaluate retrofitting measures such as green facades or green roofs (see Hoffmann 2024 for a full review). BGEs implemented directly on the building surface can be modelled as single vegetation layers (green façades) or in combination with a substrate layer (green roofs and living walls). The heat mitigation and energy performance of these systems can be calculated in sub-modules of building energy models (e.g. 'Green Wall and Roof Systems' in the model ENVI-Met, 'EcoRoof' submodule within EnergyPlus, Sailor 2008) or as stand-alone models (Stec *et al* 2005, Kontoleon and Emorfopoulou, 2010, Šuklje *et al* 2016).

Urban microscale radiation models are used to simulate heat mitigation and cooling potentials of BGEs for multiple building blocks, entire settlements or even cities. They consider atmospheric processes, allowing for the calculation of the full energy balance of all surface and vegetation elements of the model domain. Thus, the effects of individual BGEs on air temperature, humidity, wind speed, and radiative fluxes can be assessed. Prominent model tools include ENVI-met (Liu *et al* 2021, Peng *et al* 2020), SOLWEIG (Lindberg *et al* 2008), RayMan (Matzarakis *et al* 2007) and the PALM model (Resler *et al* 2017, 2021, Maronga *et al* 2020). The climate models usually differentiate between unresolved vegetation elements on soil or on urban surfaces (green roofs, green walls and façades), and resolved three-dimensional vegetation elements such as trees or high-rise shrubs (Resler *et al* 2017, Salim *et al* 2018, Krč *et al* 2021). The main purpose of the vegetation module employed to reproduce BGEs in an urban microscale climate model was to calculate the shading effects and energy fluxes of vegetation. The latent heat flux due to transpiration typically depends on static vegetation parameters (e.g. leaf area index, leaf area density, and stomatal resistance) and dynamic meteorological conditions (e.g. soil water, incoming radiation, and air humidity) (Bruse and Fleer 1998, Maronga *et al* 2020). Sensible heat flux can be parameterised explicitly or determined as the outcome of the energy balance equation.

Scales: the model domains of building energy models vary between single-wall units (Stec *et al* 2005, Kontoleon and Eumorfopoulou 2010, Šuklje *et al* 2016) and individual buildings (Carlos 2015, Djedjig *et al* 2015, Dahanayake and Chow 2017, EnergyPlus 2023). Simulation periods can extend from several days to multiple years (TRNSYS 2019, EnergyPlus 2023).

Urban microscale radiation models can simulate domains as small as a single unit, such as street trees and their surroundings, up to entire cities (Maronga *et al* 2020). The main limiting factor for the domain size and resolution is the high computational demand, particularly for climate models. This demand often restricts the simulation period to only one or a few days. Microscale urban radiation models calculate instantaneous values based on input values and urban geometry, without time development. The model time steps of microscale urban climate models are typically of the order of seconds, thus allowing for high-frequency output without temporal limitations.

Processes: the models calculate radiation exchange between surfaces using geometric factors and simulate heat transfer between the atmosphere, built environment, and BGEs. For this purpose, heat balance is calculated at distinct nodes within the model domain, ranging from 1D (e.g. Stec *et al* 2005, Sailor 2008, Šuklje *et al* 2016) to 3D models (ENVI-Met). Depending on the location of the node, appropriate heat transfer laws, such as Fourier's law of heat conduction or Newton's law of cooling, are applied. These laws are combined into a system of differential equations solved using the finite-difference method (Quezada-García *et al* 2020). Radiation is the main source of heat gain for vegetation because plant metabolism is typically neglected. Plant heat loss occurs primarily through radiation, evapotranspiration, and convection (Monteith and Unsworth 2013).

Input and output: the input data comprises a detailed description of the urban surface, including the positions of buildings and vegetation elements, their size, surface properties, and description of the surface materials. The level of detail of these parameters varies depending on the model used. Building energy and radiation models require meteorological forcing data, whereas urban climate models require dynamic meteorological initial and boundary conditions, such as air temperature, wind speed, and air constituents), from the surface to a height of a several kilometres. Because of the comprehensive calculation of atmospheric conditions within the urban domain, these models can generate a wide range of climatic output variables. Bio-meteorological indices, derived from near-surface air temperature, wind speed and relative humidity, are used as indicators of human heat stress. The primary outputs of building energy models provide the temperatures of walls and vegetation surfaces, indoor and outdoor environments, and the corresponding heat fluxes (Šuklje *et al* 2016, EnergyPlus 2023, ENVI-Met 2023).

Benefit 4: (plant) water provision modelling

Modelling tools for water provision are models that simulate plant-available water of urban green used in BGEs (trees, shrubs, and grass), or models that simulate rainwater harvesting with water stored in cisterns and used for irrigation of BGEs. Water provision modelling is employed to identify water stress periods for vegetation, estimate irrigation demand, analyse the influence of urban site characteristics (e.g. shading and sealing), and optimise water use and vegetation health. Ecohydrological models, such as urban street trees (Vico *et al* 2014, Tams *et al* 2023, Rosenberger *et al* 2024) for green roofs (Stovin *et al* 2013, Jahanfar *et al* 2018) or facade greening and green walls (Segovia-Cardozo *et al* 2019, Bakhshoodeh *et al* 2022) calculate water availability, water deficit, and irrigation demand as functions of evapotranspiration and soil moisture content. Qin *et al* (2016) employed the HYDRUS-1D model to evaluate the water stress on green roofs under different irrigation scenarios. Hörnschemeyer *et al* (2021) developed an extension (UrbanEVA) of the SWMM drainage model to include evapotranspiration processes in the calculation of multiple BGEs. However, the latter cannot be used to determine the irrigation demand.

Water provision via rainwater harvesting is modelled using hydrological storage models based on annual or monthly precipitation amounts (see review by Basinger *et al* 2010) or continuous rainfall–runoff modelling using behavioural models with hourly to daily time steps (Fewkes and Butler 2000). A few coupled harvest-irrigation model frameworks exist, such as those described in the study by Prenner *et al* (2021), who modelled rainwater harvesting for vertical greenery to evaluate system reliability and optimised irrigation schemes, and the studies by Stratigea and Makropoulos (2015), Almeida *et al* (2021), and Xie *et al* (2023) for green roofs. None of the models dealing with water provision for BGEs are able to generate information on vegetation health or supply vegetation mortality metrics. Often, information on water availability is only included in modelling tools to evaluate the efficiency of a BGE to deliver other control functions, such as their efficiency for cooling or stormwater retention.

Scales: most current modelling tools for water provision consider single BGEs, such as a specific green roof, a single street tree, or individual rain barrels. For rainwater-harvesting models, only a few tools can calculate the entire network of elements in rainwater-harvesting systems (Xu *et al* 2022). The calculation time step in the aforementioned models is hourly to daily, with simulations running either over a single vegetation season or for long-term evaluations over several decades.

Processes: most plant water provision models originate from crop models with a simplified bucket model (except the HYDRUS-1D model, which use more detailed, soil-hydraulic sub-models) to calculate soil moisture storage in the upper soil zone and both potential and actual evapotranspiration based

Table 1. Model type and relevant blue-green elements (marked with an x, if most models can simulate them, with an x in brackets if this holds true only for a few, more specific models).

Model type	Grassland as infiltration area	Bioretention cells (rain gardens, infiltration trench, vegetative swales)	Green roofs	Living walls & facades	Urban trees	Urban wetlands	Permeable pavements	Cisterns
Stormwater control	x	x	x	(x)		x	x	x
Pollution control	x	x	x			x	x	
(Plant) water provision		(x)	x		x			(x)
Cooling potential			x	x	(x)			
Carbon sequestration	x	x	x	x	x	x		

on the Penman–Monteith equation (e.g. as described in Tams *et al* 2023). Water deficit phases for vegetation are then derived if either the soil moisture level or actual evapotranspiration drops below a critical level (Tams *et al* 2024, Wessolek and Kluge 2021).

In contrast, rainwater harvesting models are essentially rainfall–runoff models for single or multiple storage units that consider overflow events (Fewkes and Butler 2000); deficit phases are easily identified when the storage volume is reduced to zero.

Input and output: the key drivers of water provision models are precipitation and climate variables for the calculation of evapotranspiration (at least the temperature series, ideally the radiation, wind, and humidity series). For plant water models, more detailed information on vegetation, the upper soil zone, local site conditions, and catchment area is required. The key output information is the duration of the water deficit phases, the required amount of irrigation, and ideally information on vegetation health and drought-related mortality, although the latter has not yet been implemented in current models.

Benefit 5: carbon sequestration and biomass production modelling

BGEs for carbon sequestration and biomass production are used to assess the effects of BGEs on the carbon cycle, offsetting urban carbon emissions from burning fossil fuels for energy production, and therefore mitigating climate change. Carbon sequestration by BGEs can be simulated using stand-alone models simulating development of individual trees and its benefits for carbon sequestration (i-Tree tool, USDA Forest Service 2024, Nowak *et al* 2018) or vertical greening (Marchi *et al* 2015). Generic biogeochemical process models simulate carbon cycle of different vegetation types such as the BIOME-BGC model (Milesi *et al* 2005) and the Anthro-BGC model (Ma *et al* 2011). Remote-sensing-driven carbon models for urban forests and grasslands are exemplified by Urban-VPRM models (Winbourne *et al* 2022) or specialised modules built into coupled land–atmosphere models, such as WRF (Beck *et al* 2011, Chen *et al* 2020, Zhao 2022).

Scales: the models can simulate most BGEs. The BGE is explicitly simulated either as a single unit, such as an urban park (using the big leaf concept), or as a collection of individual elements, such as trees in urban forests. The model domains range from a few square meters for vertical greenery models and high-resolution land atmosphere models to several kilometres for remote sensing-based models. Most models are scalable, and their scale depends on the availability of input data at a certain spatial resolution. The typical temporal scale ranges from 1 d to 1 year.

Model input and output: input data included land cover information and climate data, such as temperature, precipitation, solar radiation, atmospheric concentrations of CO_2, atmospheric N deposition, vegetation type parameterisation, vegetation indices, and soil properties. The key model outputs include carbon emissions, carbon uptake, carbon storage, biomass, and evapotranspiration.

The BGEs that could be simulated for all of the five model types are summarised in table 1.

4. Meta-analysis of scales, interfaces, gaps, overlaps, and singularities of models for BGEs

A prerequisite for model coupling is the appropriate assessment of model interoperability (Brandmeyer and Karimi 2000, Harvey *et al* 2019). The following sections evaluate the extent to which the spatial and temporal scales of different BGE model types, as derived in section 3, correspond, and what kind of processes describing the functioning of the BGEs across different model types interface, interact or feedback.

4.1. Scales of models

Disparate temporal and spatial modelling scales become apparent for the various model types, as

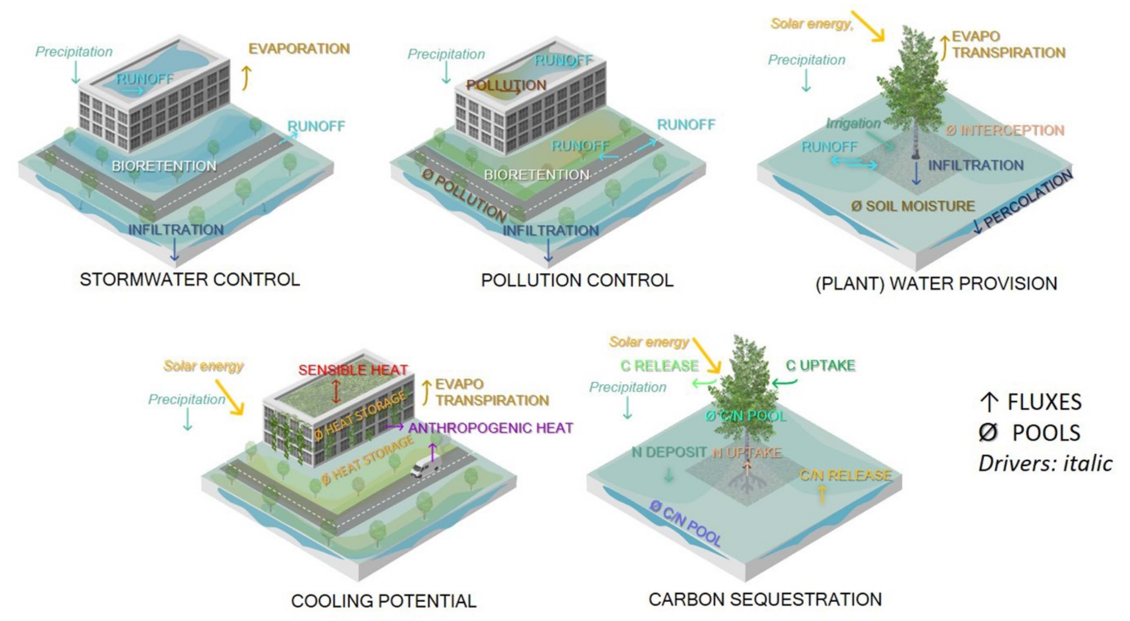

Figure 2. Key drivers and output variables of the different modelling tools focusing on major fluxes (↑) and pools (Ø) of blue-green elements. Main drivers are given in italic.

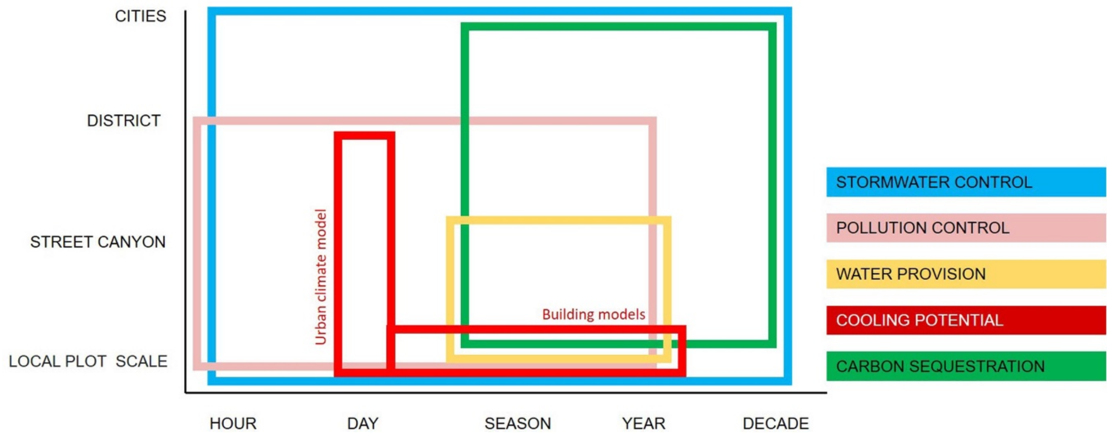

Figure 3. Typical spatial and temporal scales of the five modelling types for blue-green elements dealing with stormwater control, pollution control, water provision, cooling potential (horizontal square: for individual buildings, vertical square: for building blocks or large) and carbon sequestration.

depicted in figure 3. At the same time, not all model types cover all types of BGEs (table 1). Stormwater control models cover the largest scale ranges, including model studies from street canyons to city scales for individual sub-hourly events, as well as long-term assessments of the functionality and layout options of BGEs across cities (Lisenbee *et al* 2021). Pollution control models, often driven by stormwater control models, have a similarly large range of spatial scales; however, the assessment of BGEs is somewhat restricted to the district/neighbourhood scale and has rarely been carried out for more than a few years, mainly because of the lack of long-term validation data (Bauffaut *et al* 2015). Carbon sequestration and water provision models do not run below the seasonal scale. Cooling models stand out regarding their temporal scale; urban microscale radiation models are usually run only for a few days because of their immense computational demand. Only building energy models, designed for individual buildings with mostly a single BGE, such as green façade models, can be run for longer timescales (Djedjig *et al* 2015, Yuan and Rim 2018).

The discrepancies between the modelling scales are further highlighted by the different, hardly even overlapping, modelling time steps (figure 4), which are typically used to run the various model types.

To allow for numerical stability and convergence, the cooling models normally require time steps of 1 s and the stormwater and pollution control models of 1 min. The latter may run with larger time steps, such as hourly time steps, but a coarser time

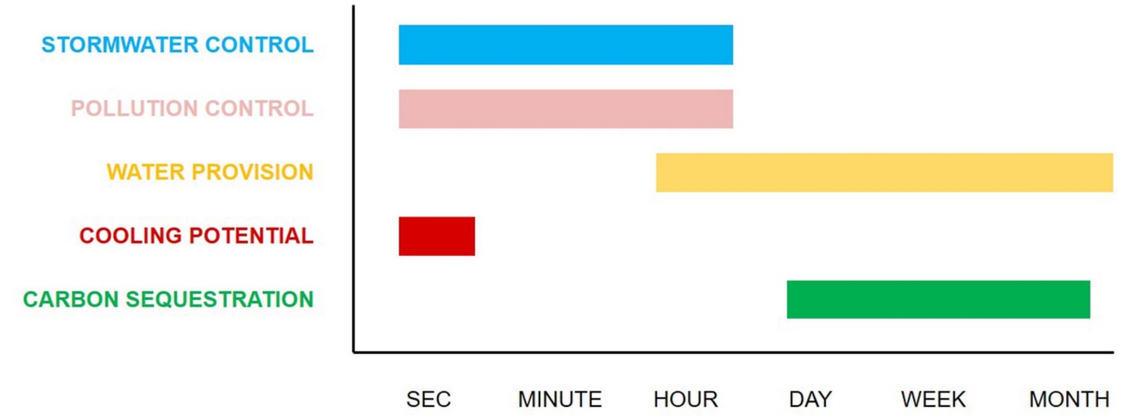

Figure 4. Range of calculation time steps of the five modelling types of blue-green elements dealing with stormwater control, pollution control, water provision, cooling potential and carbon sequestration.

step may not adequately reflect convective rainfall intensities. Water provision and carbon sequestration model time steps vary between hours and days; for some cruder water provision models in the form of rainwater harvesting storage, monthly time steps are used (Alrayess *et al* 2017).

For model coupling, differences in scales and calculation time steps must be resolved; otherwise, the models cannot be meaningfully coupled (Brandmeyer and Karimi 2000). A coupled model needs to be able to reproduce quick processes, such as rainfall runoff during rainstorm events or extreme heating during a heat period, as well as processes that occur on much larger time scales, such as vegetation growth, the development of a drought, or long-term transfer of pollution into deeper soil layers.

Looking at the various models described in section 3, we can see that even though models may share information or even entire sub-models, such as the usage of the Penman–Monteith equation for the calculation of evapotranspiration, they calculate related processes on completely different time scales. For example, evapotranspiration is calculated continuously for entire vegetation periods, considering the changing soil moisture dynamics using water provision models (Tams *et al* 2023, Kluge and Kirmaier 2024, Rosenberger *et al* 2024). In contrast, the cooling models run only for approximately a day (red upright square in figure 3) and use some initial values for soil moisture, which may not always reflect the real moisture levels. If the cooling model runs commence, for example, during actual drought conditions, an initial moisture value which was set significantly higher in comparison to real conditions, may result in the simulation of large cooling effects of BGEs in the model due to enhanced transpiration. However, in reality, the BGEs may not provide any cooling, hence misfunction, owing to water stress.

4.2. Inter-comparison of model drivers, interfaces, and gaps in process descriptions of the functioning of BGEs

Model drivers

A main driver for nearly all of the BGE models (figure 2) is precipitation, although it drives different internal model processes. For the stormwater and pollution control models, precipitation is the driver for the calculation of the (mostly) horizontal water transfer; for the plant water provision and carbon sequestration models, it is the source of water supply, that is, mainly in the vertical downwards direction. For the heat mitigation models, precipitation provides water for evapotranspiration and hence the basis for the calculation of cooling potential. Radiation is another main driver, but only for three of the five model types, and it is used in the Penman–Monteith and energy-balance calculations to calculate the cooling potential and evapotranspiration rates in the plant water provision and carbon sequestration models.

Modelling across urban interfaces

Quantification of the ecosystem functions of urban BGEs is essentially the simulation of transformation and transport processes of water, matter, gas, or energy within the individual BGE itself and with its surrounding compartments, atmosphere, urban surface, and upper soil layer (Gessner *et al* 2014), resulting in the exchange of mass, momentum, and heat. The major modelled fluxes relevant to BGEs are runoff, infiltration, contaminants, C uptake and release, and heat; the major pools include soil moisture, accumulated pollutants, and C and N pools, as depicted in figure 2 in their relevant compartments. Following a system's perspective, as elaborated in Gualtieri and Mihailovic (2013), we can delineate six urban flux interfaces relevant for BGEs (as derived from the model surveys in section 3 and the summaries of key processes and units in figure 2) which are modelled with boundary zones between the atmosphere, urban surface, vegetation and soil layer involving gas-liquid–solid phase transitions (with associated model types in brackets):

1. *Interface: atmosphere (water)—urban surface* between rainfall separation and soil moisture dynamics (stormwater control, water provision and cooling models),
2. *Interface: atmosphere (energy)—urban surface* between the evapotranspiration and soil moisture availability via heat transfer (water provision and cooling models),
3. *Interface: atmosphere (water, matter)—urban surface (water, matter)*, between rainfall separation and horizontal/vertical nutrient and pollution transfer (pollution control models),
4. *Interface: vegetation and atmosphere/urban surface (water, energy)*, between vegetation health and vertical water fluxes (with feedback mechanisms: vegetation health influences evapotranspiration, soil moisture influences vegetation health, and vegetation health influences soil moisture through root growth) (currently not properly addressed by any model),
5. *Interface: vegetation—urban surface (matter)*, between vegetation health and nutrient and pollution impacts (currently not properly addressed by any model),
6. *Interface: vegetation—atmosphere (CO_2)*, between vegetation health and carbon sequestration (carbon sequestration model).

Overlaps, singularities and gaps of current BGE models Distinct overlaps can be identified in the functioning of current BGE models, in which several types quantify the same ecosystem functions or simulate the same processes; however, some models perform this considerably more accurately than others. For example, rainfall separation is implemented in all models, but the degree of detail on how to reproduce interception, runoff, and infiltration is very different with regard to the process description and boundary conditions. There is a clear focus on the high-resolution reproduction of horizontal water transfer for urban drainage and pollution control models, whereas long-term soil moisture dynamics within BGEs do not play a role (except in specific soil-hydraulic models such as HYDRUS-1D, Simunek *et al* 1998). In contrast, the other model types focus mainly on vertical water transfer processes with a much more elaborate reproduction of soil–water in the upper soil layer (as part of the water provision models), even to the point that runoff is neglected entirely (e.g. in the PALM model, Maronga *et al* 2020).

Similarly, the water provision and cooling model types calculate evapotranspiration using the Penman–Monteith equation or derivatives, but incorporate very different boundary conditions, including a full cycle of infiltration and soil moisture dynamics over the entire vegetation period. In contrast, cooling models, which are often run only for a short period of one or a few days, often lack appropriate initial moisture conditions, potentially distorting the simulated transpiration rates under water stress.

A few singularities exist regarding the BGE model's process descriptions: only the cooling model simulates thermal states relevant to the attribute cooling potential, only the pollution models can simulate vertical and/or horizontal matter transfer, and only the sequestration models reproduce CO2 fluxes.

One clear methodological gap in the current model descriptions of the ecosystem functioning of BGEs is the lack or oversimplification of vegetation dynamics, which affects potential feedback with processes across all recorded urban interfaces and may result in severe limitations and uncertainties in model applicability (Li *et al* 2017, Lisenbee *et al* 2021). In fact, all the reviewed models, except the carbon sequestration models, contain surprisingly little information on vegetation dynamics. This is even though vegetative effects, such as above-and below-ground growth, phenological stage, vegetation health, and mortality, directly affect the critical parameters required in the interception, infiltration, runoff, evapotranspiration, and soil moisture equations on a continuum of temporal scales. These processes, in turn, affect vegetation development because of the tight coupling of soil–water–plant feedback. The effects of redistributed nutrients (e.g. through organic litter or dry deposition) or toxins from heavily contaminated urban surfaces on vegetation health have also been neglected in most BGE model descriptions.

In summary, in their current state, individual models for BGEs can quantify one, but not multiple ecosystem services. At the same time, several model types are marked by critical limitations in their general functioning including insufficient descriptions at the models' system boundaries or at relevant BGEs interfaces, often resulting in setting initial conditions inadequately and missing process descriptions, namely, omitting vegetation dynamics of the BGEs as an important regulative ecosystem function.

5. Proposition of a model-coupling framework for simultaneous evaluation of multiple ecosystem functions of BGEs

5.1. What should a coupled model framework for the multiple ecosystem functions of BGEs be able to do?

Considering the potential for interoperability and the limitations of current BGE quantification tools, we see the capacity for a step change in the setup of process-based BGE modelling. Previously, process-based models for BGEs were developed to address narrowly defined ecosystem functions and services. For a more holistic assessment, no tool currently exists that can compare or optimise a whole range of BGEs' ecosystem functions and services using dynamic process-based tools. There are few exceptions of larger model packages such as the i-Tree software (USDA Forest Service 2024, Nowak *et al* 2018) that comprises different modules to describe alterations of urban environments by trees through shading, air pollution removal, carbon sequestration and irrigation requirements, however solely for urban trees and not for any other BGEs. Going a step further, Xue *et al* (2024) combined three modelling tools, SWMM, Gabi, and i-Tree, to assess different urban resilience scenarios of green infrastructure when considering short-term hazards such as flooding and chronic pressures. For this purpose, Xue *et al* employed the drainage model SWMM to quantify urban stormwater under extreme rainfall, the i-Tree model to calculate particular matter absorption and carbon emission reductions, and required irrigation water, and the ecosystem accounting model Gabi to evaluate environmental effects. In this comprehensive study, they ran three modelling tools in parallel; however, they did not include direct feedback of BGEs in their modelling and did not assess long-term simulations or the effects of changing boundary conditions. To evaluate the full functioning of BGEs under different climate and boundary conditions, a new model framework that goes beyond the capabilities of existing spatial planning tools is necessary. Such tools should have the ability to (i) prioritise BGE measures, their locations, and their spatial layouts for new or existing city districts, (ii) compare and optimise different BGE effects, (iii) carry out risk assessment of mitigating the effects of natural hazards in built environments (heat, drought, stormwater, pollution) with and without BGE measures, and (iv) perform efficiency evaluation by assessing the benefit and failure periods of BGEs, also with regard to vegetation health, that is, BGEs detrimentally affected by drought or pollution. Simple and easy-to-understand metrics that jointly assess the multi-functionality of BGEs are required to summarise their complex biogeophysical dynamics, such as

- for cooling potential: heat stress reduction and number of heat waves per year,
- for stormwater control: the stormwater reduction amount and remaining days of flooding per year
- for pollution control: the pollutant reduction amount per year,
- for carbon sequestration: the carbon sequestration amount per year,
- for vegetation status: the days with poor plant health and degree of plant mortality per year,
- for water status: the irrigation demand per season and duration of deficit periods.

Similar metrics were used in the multi-functionality studies by Lourdes *et al* (2022), Dong and Yang (2023), and Hou *et al* (2023); however, they were mostly employed under static conditions. A process-based approach would allow this metric evaluation of timeframes to study the effects and mitigation of short-term hazards, long-term chronic stress, and interannual variabilities. Thus, the performance of BGE combinations should be simulated over a time span of at least 10 years and compared to a default scenario without BGEs to include not only 'normal' climate conditions but also years characterised by extremely or extensively hot or dry but also by wet or flashy periods in different combinations.

5.2. Conceptual approach for BGE model coupling

The meta-analysis in section 4 clearly indicates that it is not feasible to simply run the existing types of BGE models in parallel because of differences specifically in temporal scales (figure 3, some model types run only for some days, others for decades), potentially incoherent initial conditions of the model runs, and missing information on vegetation health. This approach is likely to yield flawed results. Owing to the inherent complexity of current model implementations (i.e. many lines of existing source code), it appears equally unrealistic to work towards one large BGE model that can do this all. Model coupling appears to be the way forward to preserve investments in existing software and computational implementations. From the many ways to couple environmental models (Brandmeyer and Karimi 2000, Yalew *et al* 2018), one can select along a progression from simple one-way data transfer to loose, shared, joined, and integrated coupling approaches, taking into account the increasing level and type of interactions regarding functions and databases, end-user friendliness, and aspects such as proprietary issues and source adaptability. For the proposed BGE modelling, the selection of the coupling mode was guided by three premises. First, coupling should improve inadequate process descriptions of individual models (i.e. usage of runoff generated from stormwater models for soil-hydraulic pollution control models and water provision models). Second, the initial moisture conditions should be enhanced in the cooling control model. Third, critical vegetation interactions and feedback (parameter interactions as a function of vegetation health for all model types, plant health as a function of water availability, and nutrient and toxin inputs) are required for long-term simulations of BGE performance.

Two potential coupling modes are depicted in figure 5: a simpler one-way data transfer (solid arrows only) and an integrated model coupling after Brandmeyer and Karimi (2000), shown with solid *and* dashed arrows considering the crucial vegetation feedback of the BGEs.

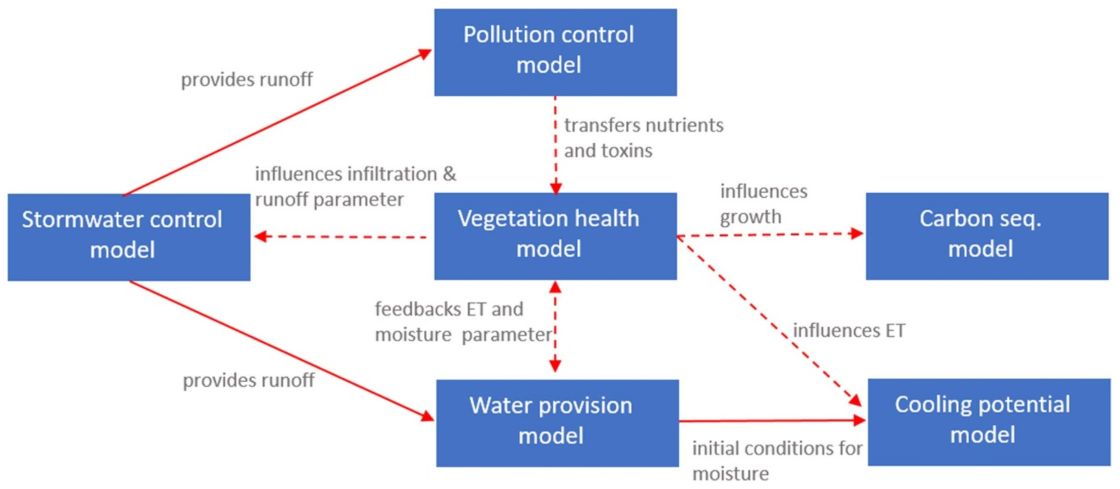

Figure 5. Model coupling for the simultaneous assessment of multiple BGEs linking stormwater and pollution control, cooling control, carbon sequestration, water provision and vegetation health models: one-way data transfer coupling (solid-line arrows) or integrated coupling including a vegetation health unit (solid-line and dashed-line arrows).

One-way data transfer coupling represents the most basic level of coupling and is also the most easily implemented, in which a modeller interfaces with each model and manually transfers data within existing model tools. In doing so, the models remain completely separate; however, the output produced by one model becomes the input for the others. The suggested one-way data transfer coupling (solid arrows, figure 5) comprises a stormwater model that provides runoff from a long-term series of individual rainstorm events as a driver into the soil-hydraulic pollution control model and inputs runoff into a continuous water provision model, which in turn provides the initial conditions for soil moisture to the cooling control models, which are run for individual heatwave periods only. One-way data-transfer coupling can be performed manually and does not require source code changes.

Integrated model coupling is considerably more complex because existing models would share a major component in the form of an integrated interface that steers real dynamic feedback between existing models (Brandmeyer and Karimi 2000). For BGE, an essential steering component could be a separate vegetation health model (figure 5, solid and dashed arrows), which does not yet exist as a standalone version for various types of BGEs. The vegetation health model for the BGEs obtains information on plant-available water from a water-provision model and transfer of nutrients and toxins from a pollution model, and would in turn influence the infiltration and runoff parameters of the stormwater control model and influence growth and evapotranspiration rates in the carbon sequestration and cooling control models. Such a new vegetation health model would incorporate different statuses of vegetation health, including the mortality and reestablishment of the vegetative parts of the BGEs.

Alternatively, routines that describe vegetation health as a function of water and nutrient availability and toxin load may be integrated into existing models. For example, existing sub-models of the evapotranspiration rates of BGEs in urban drainage models, as implemented in the SWMM-UrbanEVA extension by Hörnschemeyer *et al* (2021), could be extended to reproduce long-term trajectories of BGEs health. However, a stand-alone model for vegetation health may be preferable in regard to the coordination of multiple interconnections (figure 5) that occur at different temporal scales with other model types.

The run sequence for integrated coupling in figure 6 shows how temporal coupling can be incorporated on a continuous time scale with changing time steps and cross-model exchange of variables and parameters during storm and heat events (defined by certain thresholds) and inter-storm times. Figure 6 depicts six model types, including a vegetation health model, and how the exchange of parameter specifications, fluxes, and boundary conditions (red arrows) are distributed during and after rainstorm events, before heat waves, and at specific times when major changes in vegetation health are detected (green arrow). The presented design allows us to define different coupling intervals among the model times, including small (fast) and large (slow) time steps (grey narrow and wide ellipses), thus ensuring the correct reproduction of fast processes during storms (e.g. runoff and pollution transfer) and slower processes between storms (e.g. vegetation dynamics) (Beven 2012). During a storm event, stormwater and pollution control models are run at higher temporal resolution (e.g. minutes), whereby the infiltration and runoff output from the drainage models are directly supplied to the pollution model. At the end of the rainstorm, runoff and matter flux variables are supplied to the water provision and vegetation health

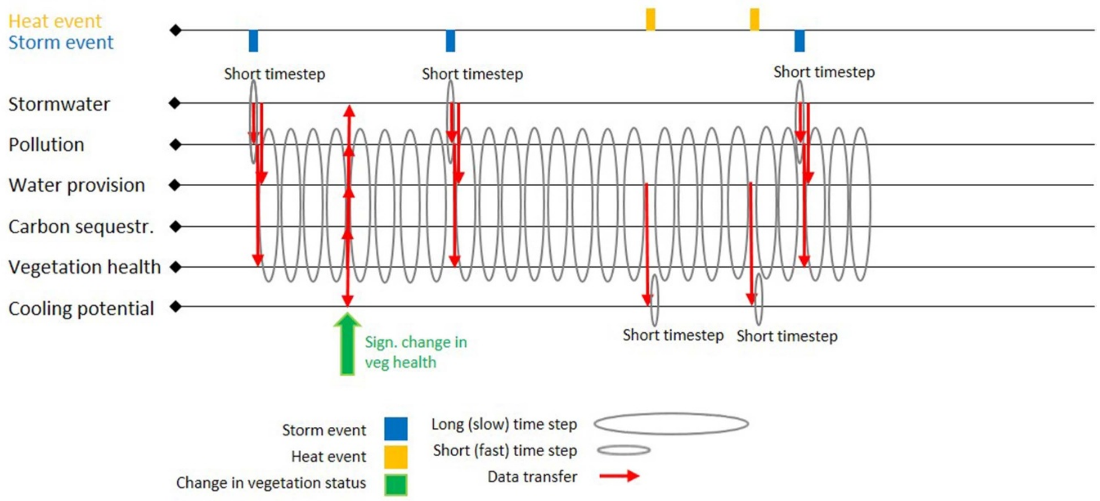

Figure 6. Run sequences of the integrated model coupling for the BGEs showing the key drivers (rainstorm event and heat events) and model interconnections (transfer of fluxes from one model to another changing their initial conditions or parameters or adding additional fluxes). Green arrow shows a significant change in vegetation health affecting parameters of all other model types. Narrow ellipses represent short (fast), wider ellipse long (slow) calculation time steps.

models, respectively. At larger time steps (hours or days), the water-provision model quantifies water availability. In the case of extended water stress or pollution loads, the vegetation health model informs the other models to change the vegetation-related parameters (infiltration, runoff, and ETO parameters). When information of cooling potentials is required, for example, during specific heat events, the cooling model is turned on (again with very fast calculation time steps of seconds), obtaining initial conditions and current vegetation status from the water provision and vegetation health models, respectively.

5.3. Way forward

We wrote such a long article on a modelling framework, yet we do not present a fully coupled model version—ideally tested and validated for several BGEs–as substantial groundwork is required to achieve this goal. In addition to the development of a vegetation health model for BGEs and advanced computational efforts to connect existing models across platforms and programming languages, one major hurdle is the absence of parameterisation and validation data for a coupled model system. Although plenty of separate datasets are available for individual model types (e.g. Lisenbee *et al* (2021) and Pons *et al* (2023) with a comprehensive overview of testing studies), to the best of our knowledge, no field site exists that simultaneously collects parameterisation data for all discussed model types and, more importantly, validation data for the resulting multiple metrics as stated in section 5.1, yet alone for different types of BGEs or in the long term. Finally, the biggest hurdle may be the implementation of a user-friendly tool that can be used by non-scientists. This study involved specialist BGE modellers from five disciplines, and handling an integrated model is already a complex task for a multi-disciplinary group of scientists. How an easy-to-use and computationally stable interface can be created for urban planners outside academia who are supposed to advice decision-makers on BGE implementation at the city scale remains an open question.

6. Conclusion

To work towards future climate-resilient cities, a tool that fosters optimisation and multi-criteria analysis for the ecosystem services of BGEs is needed. This survey of BGE modelling tools documents that no process-based model currently exists for the simultaneous evaluation of multiple ecosystem services of BGEs. Model meta-analysis points out the conceptual and construct constraints preventing easy model coupling, and thus, an integrated assessment of ecosystem services. Constraints are given through very different disciplinary approaches from different science communities involved in model development, resulting in differences in the simulation of transformation and transport processes at urban interfaces relevant for BGEs and fundamental divergences in spatial and temporal scales and time steps of existing models for single ecosystem services. Surprisingly, little is known about urban ecohydrological interactions of BGE models. The lack of adequate vegetation models for BGEs has been identified as a critical gap in essentially all existing model implementations.

Existing models for single ecosystem services cannot be easily harmonised to achieve a multi-criteria analysis. Two model coupling options were evaluated: a simpler one-way data transfer, and a more complex integrated modelling coupling that included a new steering unit to model vegetation dynamics. This vegetation model unit is required for the simulation of vegetation health, disturbance, mortality, and interference, which affect the critical parameters and processes of all linked models of stormwater and pollution control, water provision, cooling potential, and carbon sequestration. A dynamic vegetation unit could then reproduce the detrimental impacts of climatic extremes such as droughts and heat waves on the functioning of the BGEs themselves. The implementation of such integrated model coupling is considered a mammoth task and is further impeded by the current lack of parameterisation and validation data from study sites considering the ecosystem services of multiple BGEs. Nevertheless, there is an urgent need for functioning tools that support city planners and decision makers in their task to make cities more climate-resilient. They should not be guided in their decisions by faulty tools, as this may result in implementing BGEs across cities and then they do not provide the expected benefits, e.g. due to droughts, wrong locations or cancelations of one ecosystem benefit over another (e.g. increased infiltration of pollutants resulting in groundwater pollution). A significant advantage of a process-based, coupled tool is that it should also work under non-stationary climate conditions, i.e. it help to deal with novel climate conditions, which had not occurred previously. Further development of such a tool into digital twins will open more options for real-time natural hazard warning and management; however, there remains a long way to go to achieve this goal.

Data availability statement

No new data were created or analysed in this study.

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Conflict of interest

The authors have no conflict of interest.

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