Received: 1 February 2023 | Revised: 25 August 2023 | Accepted: 1 September 2023

DOI: 10.1002/ppp3.10444

OPINION

Plants People Planet PPP Open Access

Environmental horticulture for domestic and community gardens—An integrated and applied research approach

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Funding information

Allensmore Nurseries; Department for Environment, Food and Rural Affairs, UK Government, Grant/Award Number: C15718; FarPlants Group; Frank P. Matthews Nursery; Hillier's Nurseries; Hills Plants; Johnsons of Whixley; Lovania Nurseries; VitaCress; Volmary; Royal Commission for the Exhibition of 1851; Oak Foundation; Fargro

Societal Impact Statement

Daunting global challenges of climate change and biodiversity loss may seem overwhelming. However, gardeners have a secret weapon—gardens, balconies, indoor planting, yards and allotments are mini-ecosystems that offer opportunities to counter perceptions of helplessness, inadequacy and resultant inaction by using those spaces to 'Do what we can, with what we have, where we are'. Minimising gardening 'footprints' to mitigate harmful impacts, whilst maximising gardening 'handprints' to enhance benefits, is readily achievable. With this in mind, the Royal Horticultural Society is leading research into environmental horticulture for gardens, and benefits for individual wellbeing.

Summary

This article presents an integrated and applied research approach to the unique and multi-disciplinary area of science referred to here as environmental horticulture. It does this by: (a) providing an institutional perspective (The Royal Horticultural Society) on a research approach for this particular area, emphasising why domestic and community gardens are important in the context of global environmental threats; (b) presenting four primary research focus areas and project examples; and (c) highlighting interdisciplinary linkages, future research needs, public engagement/knowledge sharing opportunities, and 'Green Skills' development in the area of environmental horticulture. Research focus areas discussed are: (1) responding to the changing climate (adaptation, mitigation and resilience solutions in gardens); (2) 'plants for purpose' (harnessing the potential of horticultural plant diversity, and gardening, to help regulate environmental conditions); (3) sustainability and climate risk reduction through effective and efficient resource management (reduction, reuse, recycling and repurposing); and (4) gardening and cultivated plant choice for human health and wellbeing. We argue that a key research priority is improving our understanding of the linkages and interactions between soil, water, plants, weather and people. These crucial linkages affect above and below ground processes, for both outdoor and indoor plants. They impact the effectiveness with which water and nutrient cycling takes place, the extent to which ecosystem services may be delivered, and the resultant capacity of gardens and gardening to provide environmental and human health benefits.

KEYWORDS
ecosystem services, human wellbeing, Royal Horticultural Society, soil health, sustainability

1 | INTRODUCTION

The world is facing numerous, urgent and diverse challenges. Extreme weather, biodiversity loss and rising competition for natural resources all feature amongst the top 10 global risks over the next 10-years, with the primary threat identified as failure to mitigate climate change (WEF, 2023—World Economic Forum—Global Risks Perception Survey 2023). Environmental challenges threaten the long-term viability of the horticulture industry directly (Webster et al., 2017). Climate model projections for the UK indicate a move towards hotter, drier summers and warmer, wetter winters (Met Office, 2021), with climate extremes and challenges of excessive or insufficient water becoming more prevalent (Lane & Kay, 2021). Furthermore, over 50% of the global population are now living in urban areas, with the estimate for the UK being almost 90% (World Bank, 2022). Ongoing urbanisation, and its associated environmental and social pressures, compounds environmental challenges (Ali et al., 2019; Artmann, 2014; Dasgupta, 2021; Turner et al., 2004). Global action is needed on many levels, but what actions can individuals take in their own gardens and green spaces, to make a difference? We suggest counteracting perceptions of helplessness, inadequacy and resultant inaction (Sharman & Perkins, 2017; Stevenson & Peterson, 2016), with a mindset to 'Do what you can, with what you've got, where you are'—inspirational words attributed to Squire Bill Widener of Widener's Valley, Virginia (Roosevelt, 1913).

In the UK, the value of the horticulture industry in 2017 was estimated at £24 billion, supporting nearly 570,000 jobs (Oxford Economics, 2018), with the capability of growing to support Gross Domestic Product (GDP) contributions worth £41.8 billion by 2030 (Oxford Economics & Foresight Factory, 2021). A mechanism that has been identified towards realising this potential growth is the Environmental Horticulture Green Growth Plan (EHG, 2023). In line with this and as part of the wider UK horticulture industry, domestic and community gardens and gardening are a significant resource in terms of urban land cover and population access to green space. Up to 30% of UK towns and cities comprise domestic garden space (Cameron et al., 2012; Gaston et al., 2005; ONS, 2019), estimated to cover 521,872 ha in total (ONS, 2019). Including domestic outdoor spaces outside urban areas brings this area up to 728,891 ha for Great Britain (ONS, 2020a). This represents approximately 3.5% of the land area of Great Britain, but constitutes a land-use type that 87.5% of UK residents have access to (ONS, 2020b), with significant potential to deliver wellbeing benefits to people (Chalmin-Pui, Griffiths, et al., 2021; Chalmin-Pui, Roe, et al., 2021; de Bell et al., 2020) and the environment (Owen, 2010). Interest in, and understanding of, how composition, management and use of urban green spaces influences the environment and people, has grown in recent decades (Edmondson et al., 2014; Graca et al., 2022; Lindén et al., 2020; Reyes-Riveros et al., 2021). For example, gardens capture and store carbon from the atmosphere (Davies et al., 2011; Hand et al., 2019), provide summertime cooling (Grilo et al., 2020; Zölch et al., 2019), support biodiversity through pollination and habitat provision (Baldock et al., 2015; Salisbury et al., 2017), facilitate Sustainable Drainage Solutions (SuDS) to reduce localised flood risks (Kelly, 2014; Sjöman et al., 2015), and help mitigate noise and improve air quality through pollutant capture (Hewitt et al., 2020; Van Renterghem et al., 2015). Gardeners' planting choices have progressed from purely aesthetic considerations, to site-species compatibility and increasingly towards plant selection for specific structural and functional benefits (Hall & Dickson, 2011). Evidence of the impact of cultivated green spaces on urban residents' wellbeing is also growing (Chalmin-Pui, Roe, et al., 2021). Gardening approaches that support these ambitions are gaining prominence as a result (Cameron, 2023; Griffiths et al., 2020). We refer to these initiatives as environmental horticulture in gardens, broadly defined as 'supporting sustainability, environmental and human health and wellbeing through how we manage plants, water and soil in a gardening context'.

Despite increasing acceptance and understanding by the public, industry and policymakers alike, far greater levels of uptake and behaviour change are required to realise environmental horticulture benefits. Furthermore, greater understanding of the complex interactions between various components of garden 'systems' (e.g., water and nutrient cycling, ecosystem functioning) is needed, to encourage overlap between research disciplines and greater appreciation that they are intrinsically linked and impact each other. This article presents an integrated and applied research approach to the unique and multi-disciplinary area of science referred to here as environmental horticulture. It does this by: (a) providing an institutional perspective (The Royal Horticultural Society) on a research approach for this particular area, emphasising why domestic and community gardens are important in the context of global environmental threats; (b) presenting four primary research focus areas and project examples; and (c) highlighting interdisciplinary linkages, future research needs, public engagement/knowledge sharing opportunities and 'Green Skills' development in the area of environmental horticulture.

2 | INSTITUTIONAL CONTEXT AND RESEARCH APPROACH

The Royal Horticultural Society (RHS) is a longstanding (since 1804), respected and leading gardening charity with 1000+ staff, 1300+ volunteers and over 630,000 members at the time of writing. It provides membership, inspirational public gardens (five across England) and flower shows (including the flagship RHS Chelsea Flower Show, with its 100 + year history), scientific research, RHS education and community programmes, and garden centres, through to freely accessible RHS advisory web pages, which receive approximately 30 million visits annually.

The environmental horticulture Team sits within the RHS Science and Collections Division, based at RHS Hilltop: the Home of Gardening Science (Figure 1), within RHS Wisley Gardens, Surrey, UK. The team uses an applied research approach to address challenges driven by the climate and biodiversity crises, which are impacting gardening, cultivated landscapes and the ornamental horticulture sector, with the goal of providing evidence for practical gardening interventions to enhance sustainability, environmental health and human wellbeing.

This research is by nature highly interdisciplinary, merging aspects of plant physiology, soil science, hydrology/water management, ecology, social science and environmental psychology. Strategic objectives include improving understanding of how gardens can be managed to build resilience to climate change (adaptation), how gardeners and the horticulture industry can mitigate harm by optimising resource use (minimising environmental 'footprints'), and how they can enhance benefits (by maximising 'handprints') (Biemer et al., 2013). With the large number of gardeners in the UK, and the size of the horticulture industry within which they operate, the potential cumulative impact of implementing a more environmentally sustainable approach is considerable (EHG, 2023; RHS, 2021b). As people are more likely to nurture what they love, encouraging a passion for environmentally considerate gardening is critical. We aim to do this by promoting the fact that, with the right practices, gardens can have tangible and positive benefits for plants, people and planet. The primary research focus areas of the RHS Environmental Horticulture team are: (1) responding to the changing climate (adaptation, mitigation and resilience solutions in gardens); (2) 'plants for purpose' (harnessing the potential of horticultural plant diversity, and gardening, to help regulate environmental conditions); (3) sustainability and climate risk reduction through effective and efficient resource management (reduction, re-use, recycling and repurposing); and (4) gardening and cultivated plant choice for human health and wellbeing (Figure 2). These research themes are explored through examples of completed, ongoing and proposed future work in the following sections.

FIGURE 1 Royal Horticultural Society (RHS) hilltop: the home of gardening science. The UK's first horticultural scientific centre of excellence dedicated to domestic and community gardening, located in the RHS's Wisley garden, which is also open to the public. © RHS, image credit: RHS/Oliver Dixon.

3 | RESEARCH FOCUS AREA 1: RESPONDING TO THE CHANGING CLIMATE

Previous RHS responses to climate change focussed on *adaptation* (Bisgrove & Hadley, 2002; Webster et al., 2017), advocating the avoidance of potentially unsuccessful plantings and practices given the climatic changes already underway. However, the urgency of climate and biodiversity challenges now calls for horticultural *mitigation* as well. Accordingly, the RHS aims to help gardeners enjoy gardening whilst keeping their 'footprints' small and maximising their climate positive 'handprints'. Suggested approaches as to how gardeners might pro-actively adapt to and mitigate climate change are: (a) directly, by reducing the magnitude of climate change (e.g., through increased carbon capture and storage in their gardens and limiting emissions of greenhouse gases associated with garden-related management activities, landscaping and purchasing); (b) indirectly, by contributing to landscape-scale resilience (e.g., improved hydrological functioning and ecosystem services); and (c) by displacing household consumption-associated emissions. This can occur when the production of fruit, vegetables, cut flowers, seeds, plants or compost and so on from the garden displaces the consumption of products with a higher negative climate impact produced elsewhere.

Improving the health of soil can enhance the efficiency of all three above approaches. This stands to reason, as the term 'soil health' has been described as *the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals and humans* (Lehmann et al., 2020). Accordingly, it follows that the use of environmentally costly soil amendments, with a significant embodied 'fossil-carbon' cost (from extraction, manufacture or transport) have potential to undermine these benefits. Fortunately, more sustainable improvement of soil health can be achieved using resources generated in gardens. Mulching with home-grown biomass, for example, supports biodiversity, reduces soil evaporation, regulates soil temperature and can have a fossil carbon footprint close to zero (Stavi, 2020). By harnessing the wealth of ecosystem services driven by plant structure and function (Salmond et al., 2014), as well as those enhanced through good soil health and biodiversity (Wagg et al., 2014), gardeners can create 'positive feedback loops'. Fundamental to this

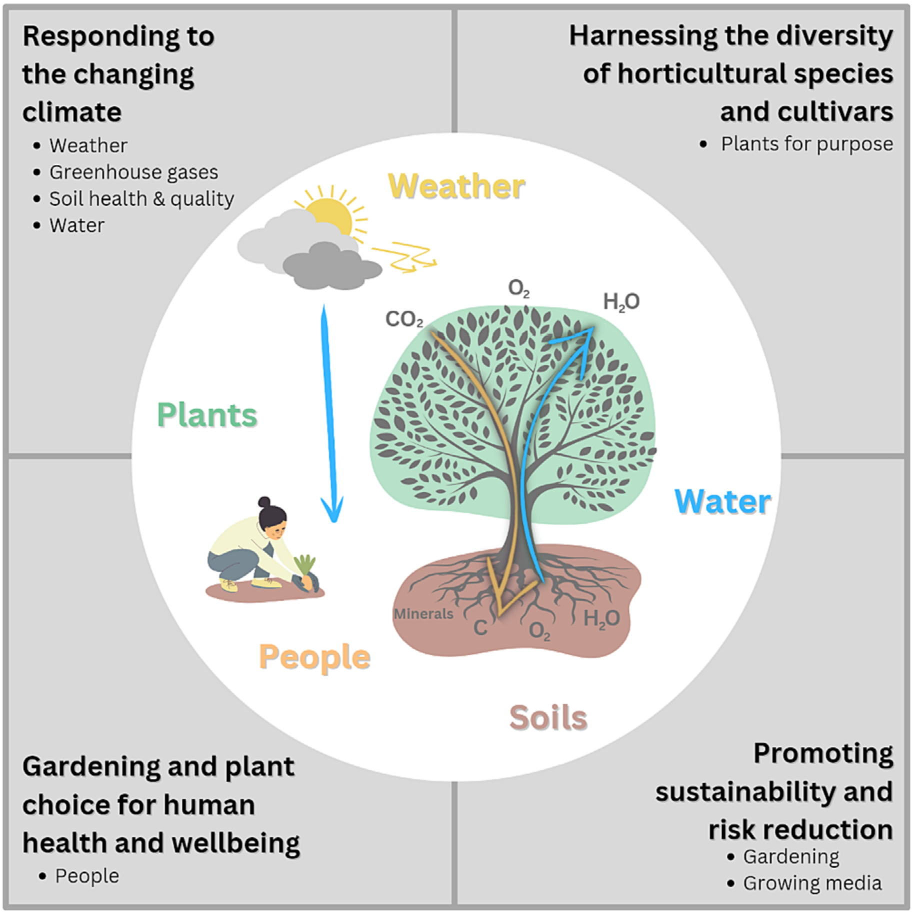

FIGURE 2 Framework illustrating the primary focus areas of the environmental horticulture research approach, within the Royal Horticultural Society (RHS). The four primary research focus areas (corner stones) all interact with the cross-cutting components associated with gardens and gardening, depicted in the centre, recognising the importance of an interdisciplinary and interconnected focus, for practical application. © RHS, image credit: RHS/Mark Gush and Lauriane Chalmin-Pui.

concept is that both soil health and soil biodiversity depend on sustained inputs of plant carbon, either via plant-litter or via exudates in the plant rhizosphere (Vezzani et al., 2018).

3.1 | Research areas

3.1.1 | Weather

With projections of future UK climate tending towards warmer and more extreme conditions coupled with greater climate uncertainty, the availability of long-term, accurate and representative weather data for research purposes is critical. As key drivers of natural processes associated with environmental horticulture, weather data sets should ideally comprise a full suite of weather variables (including rainfall, solar radiation, temperature, humidity and wind speed/direction). Prevailing weather directly influences physiological processes associated with gardening (e.g., photosynthesis, stomatal control, evapotranspiration and phenology). The RHS has extensive local weather records available for some of its gardens (e.g., RHS Garden Wisley weather data from 1904 to present), and this data is being used to interpret research trial results (e.g., the extent to which particular ecosystem services are delivered), and also to identify longer term climatic changes and occurrences of extreme events. The data are being used to assess the potential or anticipated impacts on horticultural practices (e.g., the need to plant for resilience to extreme weather conditions) and on the resultant functioning of gardens and cultivated green spaces. The data are also being used to calculate daily reference evapotranspiration (ET_o) and crop coefficient values according to the FAO-56 Penman-Monteith modelling approach (Allen et al., 1998), for RHS research sites. This has application in predicting water demands of various plant species, cultivars and planting combinations, facilitating improved understanding of water balances, better water management, and potential for SuDS in gardens.

3.1.2 | Greenhouse gases

Elimination of peat as a horticultural growing medium (Kitir et al., 2018), use of peat-free alternatives (Barrett et al., 2016) and restoration of damaged peat-bogs (Waddington et al., 2009) all help safeguard the vast carbon stocks associated with peat. Through a 5-year post-doctoral fellowship, the RHS is supporting the transition to peat-free UK horticulture, and mitigating against CO_2 releases associated with peat use. Home composting supports this, with RHS estimates suggesting that home composting can save fossil fuel emissions from green-waste kerbside collection and subsequent processing of up to 1 kg fossil-derived CO_2 per 10 kg compost produced (RHS, 2021). Compost addition to garden soils supplies nutrients enhancing plant growth and improves soil health (Duddigan et al., 2022), with the added advantage that every 1% increase in soil organic carbon (to 30 cm depth) stores approximately 5 L more plant-available water per square metre (Minasny & McBratney, 2017). Home-grown soft fruits can also displace a horticultural carbon footprint of around 2 kg CO_2 per kg berries produced (Poore & Nemecek, 2018). Besides reducing the amount of fossil-carbon embodied in gardening practices and products, reducing emissions of the highly active greenhouse gas nitrous oxide (N_2O) can contribute to short-term mitigation of climate change. Ways to reduce N_2O emissions from gardens include (i) ensuring a well-drained soil structure, (ii) less frequent irrigation, and most importantly of all, (iii) avoiding excessive use of nitrogen rich fertilisers, which can magnify N_2O emissions by over 500% (Yu et al., 2023).

3.1.3 | Soil health and quality

The physical stability of soil aggregates is frequently used to represent soil quality and soil health because it is so influential for greenhouse gas dynamics, plant health and environmental credentials (Rieke et al., 2022). Both fungal hyphae and bacterial cells living in the soil form patchily distributed biofilms (Cai et al., 2019). The cells in a biofilm produce bonding agents, which help to impart a functional soil microarchitecture (Costa et al., 2018). These bonding agents, termed Extracellular Polymeric Substances (EPS), can be quantified independently of cellular biomass by extraction (Redmile-Gordon et al., 2014). Increases in EPS have been found to be dependent on exudates of root-carbon (Redmile-Gordon et al., 2020), which in combination with fungal hyphae lead to soil structural improvements and improved flows of water and nutrients (Figure 3). This conceptual diagram illustrates how microbial EPS production is facilitated by root exudates (left of root), whilst aggregates disintegrate without EPS (right). Figure 4 shows a quantitative example of the relationship between EPS and aggregate stability in an agricultural setting. More studies elucidating microbial generation of soil health are clearly required in the context of gardens. Amongst the diverse components of EPS (including polysaccharides, proteins and uronic acids) the proteinaceous EPS are the most active in stabilising soil structure (Olagoke et al., 2022). Microbial production of stable extracellular carbon has also been found to be influenced by the chemical composition of plant-root exudates (Wang et al., 2022).

3.1.4 | Water

Increasingly constrained water resources are of particular concern to horticulture and gardening, where water is a critical element (Knox et al., 2020). A 3-year Knowledge Transfer Partnership (KTP) between the RHS, Cranfield University and Innovate UK investigated the risks associated with the dependence of ornamental horticulture on water,

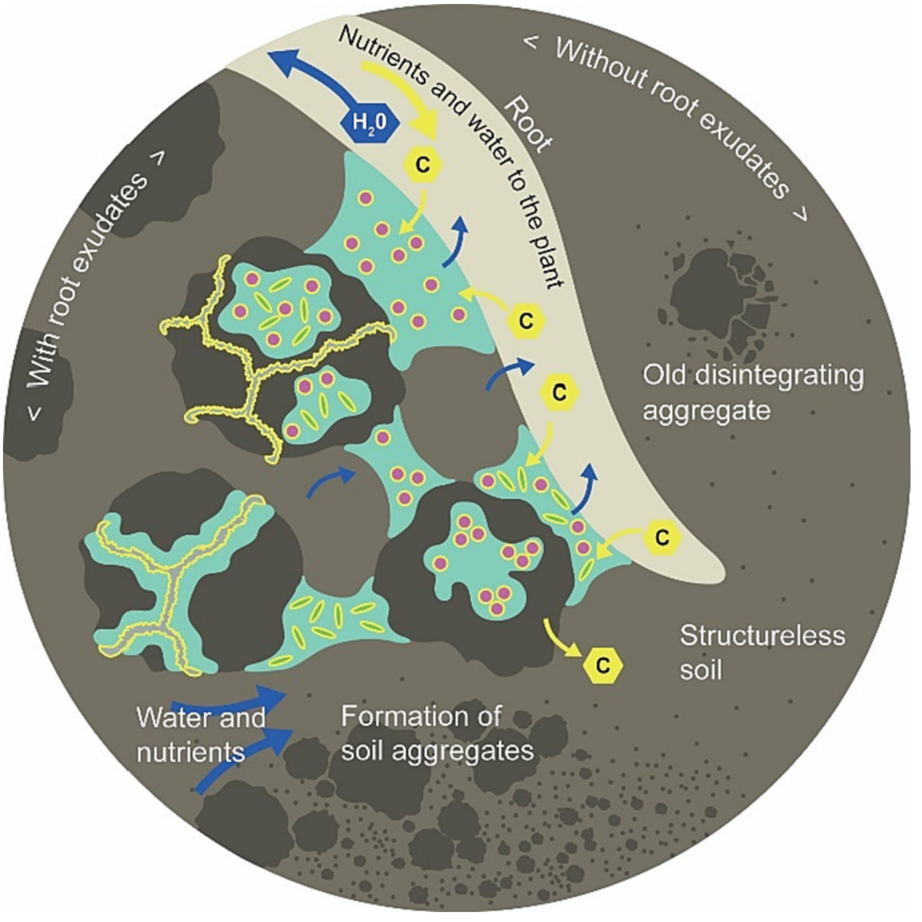

FIGURE 3 Diagram illustrating the symbiotic relationship between plant roots, soil microbes and the production of extracellular polymeric substances (EPS) as bonding agents for improved soil structure. EPS are bonding agents that enable soil microbes to generate and modify soil-architecture. Plant roots provide carbon, enabling microbial production of EPS, whilst soil and EPS provide water and nutrients to plants in a positive feedback loop. © RHS, image credit: RHS/Marc Redmile-Gordon and Rachel Burgess.

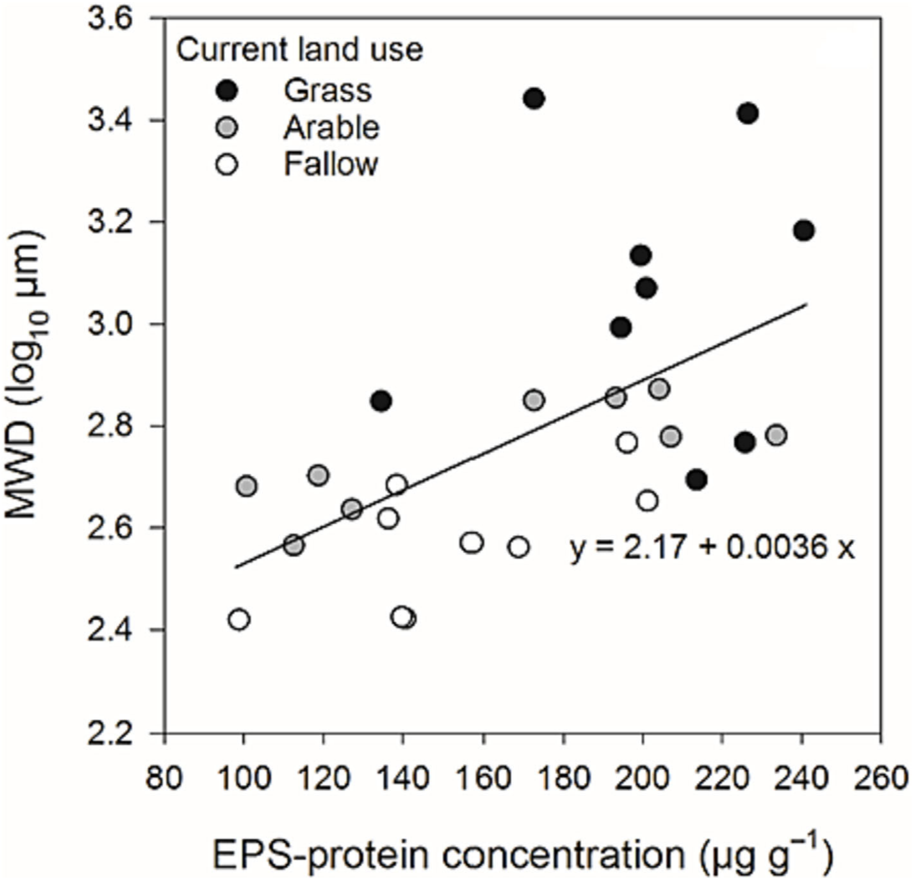

FIGURE 4 Extracellular polymeric substances (EPS) per gramme of soil, as related to a physical indicator of soil structural stability ('Mean Weight Diameter' [MWD]), after Redmile-Gordon et al. (2020).

whilst promoting the role of water in sustainable gardening, and in building resilience to increased climatic variability and extremes (Gush et al., 2023). Findings were distilled into four key actions: (i) maximise the collection, storage and use of rainwater; (ii) minimise lateral runoff and maximise infiltration; (iii) maintain soil health to balance water retention and drainage; and (iv) select appropriate plant taxa according to site conditions. The project developed the www.Mains2Rains.uk website to help drive behavioural change in water management within gardens, by inviting pledges from gardeners on water-saving actions to be taken, and encouraging them to switch from mains/public water use to harvested rainwater use wherever possible. At the time of writing (September 2023), 3377 water saving pledges had been made, with a potential saving of 40.65 million litres of mains/public water—equivalent to the 1 day average per capita water consumption (145 L per person per day [CCW, 2023]) of nearly 280,000 people. The project also developed strategically and operationally important outputs for the RHS, including a water policy, a water roadmap for their flagship garden Wisley, and contributions towards their Sustainability Strategy (RHS, 2021b). RHS gardening advice webpages on water were updated, and relevant information incorporated into the curriculum of RHS horticultural qualifications. The project culminated in a show garden at the 2021 RHS Chelsea Flower Show (Figure 5), which attracted considerable public interest.

RHS research towards improved understanding of garden water dynamics is ongoing, with the objectives of increasing resilience to extreme weather conditions such as droughts and floods (Lewis et al., 2019), better understanding plant water uptake (Rees et al., 2023), assessment of the broader hydrological services of garden plants (Gush, 2021), garden water balance studies and maximising water use efficiencies within gardens.

4 | RESEARCH FOCUS AREA 2: PLANTS FOR PURPOSE

In order to support gardeners to choose the right plants for the right places and purposes, it is necessary to better understand the extent to which particular plants provide particular ecosystem service benefits. For over a decade, RHS research has explored plant characteristics linked to regulating ecosystem services such as pollination (Salisbury et al., 2017; Tew et al., 2022), ambient cooling (Blanuša et al., 2013), building insulation (Monteiro et al., 2017; Thomsit-Ireland et al., 2020), improved soil water storage capacity (Blanuša & Hadley, 2019), reduction of rainfall runoff (Kemp et al., 2019) and trapping of airborne particulate matter (PM) (Blanuša et al., 2015, 2020). This research showed that differences in the delivery of such services can be readily measured at individual plant scale (Cameron & Blanuša, 2016; Monteiro et al., 2016) or small plot scale (Blanuša et al., 2019; Monteiro et al., 2017; Thomsit-Ireland et al., 2020). In a small garden, choosing a tree with a denser canopy or larger inherent evapotranspiration rate will reduce ambient and surface temperature more effectively than a sparser, less water-

FIGURE 5 Display at the Royal Horticultural Society (RHS) Chelsea flower show 2021: 'Water the way nature intended—Switch from Mains2Rains', exhibiting practical garden water management interventions, infographics and advice (RHS, 2021a). © RHS, image credit: RHS/Neil Hepworth.

demanding one (Rahman et al., 2015, 2023). However, at street scale, some of this individual taxa-dependent cooling effect will be masked by diurnal or seasonal variability, weather conditions, complex air circulation, street design, and/or height of buildings (Blanuša et al., 2013; Lindén et al., 2016; Vaz Monteiro et al., 2017), and the main cooling benefits may relate to the more general balance between 'green' versus 'grey' surfaces. As gardens are known to act as corridors and stepping stones for wildlife, their potential contribution to localised environmental benefits is recognised, irrespective of individual garden size (Cameron et al., 2012; Owen, 2010).

4.1 | Research areas

With an estimated 400,000 different species and varieties/cultivars of plants in cultivation in the UK, and actively being collected by the RHS for its herbarium (RHS, 2021), identifying plant taxa that possess characteristics (structural and functional traits), which optimise delivery of environmental services for domestic and community gardens, is a research priority for the RHS. Plants for purpose research now focuses chiefly on using small garden trees and urban hedges as case studies in the search for structural and functional characteristics that are beneficial in delivering ecosystem services. The longer term research objective is to be able to use the knowledge gained on effective traits of the varieties being monitored, to identify a wider range of plant taxa that have higher likelihood of being able to deliver *multiple* ecosystem services in domestic and community gardens. The range of potential services is extensive (Figure 6) but current RHS research efforts are exploring plants' specific capacity for thermal regulation, water runoff/flood risk reduction, effectiveness as green screens against airborne PM and noise, ability to capture and store carbon, and potential for supporting pollinators and biodiversity.

4.1.1 | Plant structural and functional traits

Plants directly influence the microclimate of their surroundings through thermal regulation, flood, runoff and soil erosion mitigation, and air- and noise pollution reduction. These *regulating* services are particularly applicable in an urban context, which is dominated by grey infrastructure and its associated challenges such as the heat island effect, impermeable surfaces, and air and noise pollution (Baró et al., 2014; Cimburova & Pont, 2021). Functional and structural plant traits that have been associated with greater capacity of a plant to deliver environmental benefits include: greater transpiration rates (Rana & Ferrara, 2019), larger and denser canopies (Baptista et al., 2018) and presence of leaf hairs and scales (Barwise & Kumar, 2020; Blanuša et al., 2020; Monteiro et al., 2016; Monteiro et al., 2017). Greater evapotranspiration increases a plant's capacity for removing water from the substrate, subsequently increasing the substrate's capacity for water absorption, thereby mitigating localised flood risk. Furthermore, high evapotranspiration, in combination with some tolerance to heat and drought whilst maintaining capacity to provide shade, increases a plant's capacity to cool the surrounding air and thereby reduce excessive urban heating (Doick et al., 2014). Plants with denser foliage can limit soil erosion by reducing the speed and size of raindrops and thus the intensity and volume of rainwater reaching the ground (Carlyle-Moses et al., 2018; Llorens et al., 2007). Larger plant leaf area and presence of trichomes (leaf hairs) facilitates the extent to which PM may be (temporarily) deposited (Blanuša et al., 2015, 2019). However, the preferred traits of plants chosen for a setting will depend on the preferred service to be delivered.

We are currently investigating how smaller trees for a domestic garden setting can provide the most effective ecosystem services relative to their size (Larsen et al., in press). Ten different garden tree taxa have been monitored over a 2-year period to quantify each taxon's water uptake/flood mitigation capacity, thermal regulation potential and

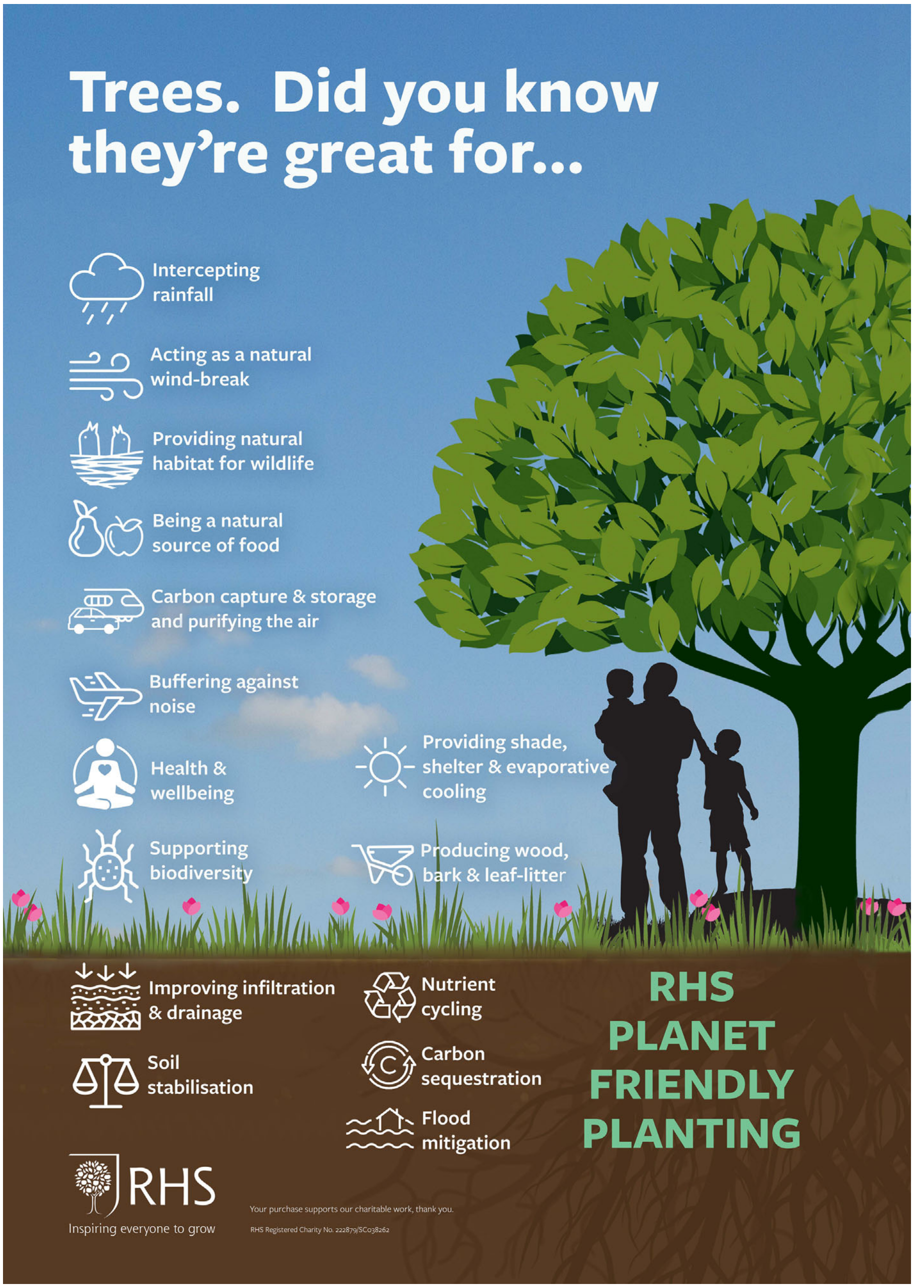

FIGURE 6 Royal Horticultural Society (RHS) poster illustrating the environmental, health and wellbeing benefits of trees, and promoting tree planting as a contribution towards planet-friendly gardening (https://www.rhs.org.uk/gardening-for-the-environment/planet-friendly-gardening-tips). © RHS.

carbon sequestration rate. The ongoing research is assessing these services for different taxa and under different environmental conditions, looking at continuous measurements of total transpiration together with meteorological parameters. This will provide gardeners with information regarding ecosystem services provided by specific trees and could add an additional selection criteria, or even motivation to plant a tree.

5 | RESEARCH FOCUS AREA 3: SUSTAINABILITY AND CLIMATE RISK REDUCTION

Gardens offer key points of contact and influence between humans and nature, presenting an opportunity for practical and conceptual engagement with several critical planetary boundaries (Rockström et al., 2009) in microcosm at the domestic scale (Ives et al., 2018; Steffen et al., 2015). Aiming for sustainable resource management in gardens reduces environmental harm and reduces gardens' vulnerability to risks (Deksissa et al., 2021). By reducing, re-using and recycling resources, and avoiding or minimising the use of damaging products and/or practices such as peat, synthetic fertilisers and pesticides, gardeners can reduce negative contributions to climate, chemical and plastic pollution (Kawecki et al., 2021; Massa et al., 2018; Meftaul et al., 2020). Meanwhile, increasing positive impacts on the environment by providing food and habitat resources for garden wildlife and biodiversity enables gardeners to begin to address ecological breakdown and the extinction crisis, with collective efforts across urban landscapes delivering important contributions (Goddard et al., 2010).

The decisions we make about what to plant and how to manage our gardens not only determine our gardens' resilience to risk, but affect our own environmental risk exposure too. Within the built environment, gardens and green infrastructure (such as hedges, trees, rain gardens, green walls and green roofs) enhance human comfort by reducing flood risk, limiting urban heat island effects and reducing airborne particulate pollution (Abhijith et al., 2017; Edmondson et al., 2016; Prudencio & Null, 2018). If used to grow food, gardens can also increase food security and help buffer against the risk of food price volatility resulting from global crises (Armanda et al., 2019). Sustainable management principles that limit use of fossil fuel-powered garden machinery also reduce vulnerability to fuel shortages and price shocks in the context of the transition to a carbon-free economy (van der Ploeg & Rezai, 2020). Additionally, gardens reduce risks to mental health by alleviating stress and increasing wellbeing, as illustrated very clearly by a raft of research studies that took place during the Covid-19 pandemic (Corley et al., 2021; Egerer et al., 2022; Marques et al., 2021).

5.1 | Research areas

RHS research is aiming to encourage sustainable resource use in gardens for environmental benefit by means of several projects. These include several postdoctoral fellowships and PhD studies.

5.1.1 | Impact and adoption of gardening activities

One RHS fellowship is assessing the sustainability of gardening by quantifying the footprints and handprints of typical gardening activities and identifying factors that contribute to the adoption of sustainable horticulture by domestic gardeners in the UK (behaviour change). The development of a gardening calculator will permit domestic gardeners to assess the positive and negative environmental impacts of their gardening, and permit the RHS to investigate how best to frame and communicate quantified environmental impacts information to support the transition to sustainable horticulture. Some key uncertainties require further research, for example, how different planting and management strategies impact soil carbon sequestration. Nevertheless, based on existing research, we can be confident that gardeners can reduce their carbon footprint by following some key recommendations. These include avoiding the use of peat, producing their own compost at home from kitchen and garden waste, and switching from fossil fuels to green electric power as soon as possible. Encouraging gardeners to implement actions that directly support biodiversity and encourage the presence of garden wildlife is an important response to the biodiversity crisis that importantly helps build connection to nature, which in turn can lead to further pro-environmental behaviours.

5.1.2 | Growing media

A further RHS fellowship is assessing ways to assist growers/nurseries/gardeners in the transition to peat-free horticulture. The project is supported by the UK Government Department of Environment, Food and Rural Affairs (DEFRA) and a consortium of nurseries that collectively produce over 143 million plants annually. The recently initiated project is collaborating across the horticulture industry supply chain to understand key challenges in its transition to peat-free growing, to organise scientific trials, and disseminate resulting knowledge. In support of accelerating the transition to peat-free UK horticulture, the project is characterising the physical, chemical and biological properties of peat-free growing media, investigating its feasibility for plugs and propagation, and using peat-free media to propagate and grow on challenging plant species such as carnivorous plants (which naturally occur in peat-bogs) and Ericaceous species (which demand an acidic medium).

6 | RESEARCH FOCUS AREA 4: GARDENING AND PLANT CHOICE FOR HUMAN HEALTH AND WELLBEING

The fourth research focus area centres around mitigating the decline of mental, physical and social health accelerated by urban densification and the loss of green space and domestic gardens (World Health Organization, 2016). The body of evidence for the positive effects of gardening on mental, physical and social health is ever-expanding (Buck, 2016; Chalmin-Pui, Roe, et al., 2021; Howarth et al., 2020; Murroni et al., 2021; Soga et al., 2017; Thompson, 2018). Environmental horticulture provides a sustainable approach to making healthy (green) places for resilient populations and aims to optimise garden design, processes and gardening activities for wellbeing across socio-demographic groups. Scientific knowledge can be integrated into the community-led creation of locally-relevant wellbeing gardens, removing barriers to participation and access, and building capacity across the health and landscape industries via social prescribing of gardening, for example. Settings of particular importance include care homes, schools, hospitals, community centres, prisons and workplaces.

Gardening together helps build socially and environmentally sustainable communities (Suh et al., 2021) bridging traditional social divides (Cockburn et al., 2020). Gardening can also broach the concept of urban commons—including seed-libraries, and the sharing of produce, information, water and other resources (Garcia-Llorente et al., 2016), and contributes to maintaining a sense of belonging, self-identity and self-expression (Chalmin-Pui, Griffiths, et al., 2021).

6.1 | Research areas

6.1.1 | Human health and social care

A collaborative RHS postdoctoral fellowship with the University of Sheffield is focused on demonstrating how gardens, garden features and gardening activities can be used in health and social care as early interventions, to support recovery and cope with symptoms. Research priorities include emotional responses to garden-based scents, shapes and colours (Neale et al., 2021) and garden design recommendations (Harries et al., 2023). The experience of pleasant emotions and the regulation of unpleasant emotions, as triggered by visual or olfactory stimuli in the garden, can contribute to foundations of resilience, joy, hope and wellbeing. The recovery from acute stressors is also being tested using psychological and physiological outcome measures to better understand the stress-reducing effects of plant exposure.

7 | INTERDISCIPLINARY FOCUS AND APPLICATION

The concept of sustainability in horticulture and gardening recognises the deep interconnectedness of earth's ecosystems through time and space from the micro to the macro-scale (Cook et al., 2012). Viewed as socio-ecological systems, gardens are sites of horticultural management that provide an interface between people and the natural cycling of water and nutrients by plants, fungi, bacteria and archaea (Egerer et al., 2020). Gardens are also places that can promote physical, mental and social health, through opportunities for connection with ourselves and others (Hanson et al., 2021). Given that activities and processes associated with gardens and gardening do not operate in isolation, we argue that a key research priority is improving our scientific understanding of the linkages and interactions between substrates, water, plants, ambient growing conditions, weather and interventions by gardeners (Figure 2). The concept of the Soil-Plant-Atmosphere continuum is well-established (Kramer & Kozlowski, 1979), primarily in terms of understanding water relations of plants, and more recently interdisciplinarity in research has been shown to facilitate the provision of unique approaches to, and solutions for, complex societal problems, and be more likely to generate results that achieve greater societal visibility (i.e., that attract the attention of non-academic audiences) and are more socially relevant (D'Este & Robinson-García, 2023). An example of this is the challenge posed by a transition to peat-free horticulture, where elements of plant physiology, meteorological drivers, plant water relations, soil biogeochemistry, economics and social science (behavioural change) all need to be taken into consideration simultaneously. In this case, positive change is only possible when all of these elements are satisfactorily addressed in an integrated way, because disregarding just one element could undermine success in reaching the goal of a peat-free horticultural industry. An alternative scenario, where an integrated approach is preferable but not mandatory for success, is the transition to more sustainable gardening practices. Whilst this is likely to also involve consideration of a wide range of inter-linked disciplines such as carbon and water footprints, waste management, pest and disease control, and biodiversity changes, positive change on just one or more of these elements could be considered successful progress (small wins), without necessarily achieving all desired outcomes simultaneously, and provided progress continued moving in the right direction. Integrating understandings of key flows within environmental systems is key for sustainable development, as is enhancing access to scientific ecological knowledge amongst practitioners at the landscape design stage (Baleta et al., 2019; Hall & Knuth, 2020; Nassauer & Opdam, 2008). Dissemination of evidence-based outputs from interdisciplinary research, by means of a public and membership-oriented institution such as the RHS, facilitates the practical applicability of research outcomes.

8 | PUBLIC ENGAGEMENT

Public engagement is a core consideration for RHS science, with research outcomes and subsequent communications oriented to RHS members and the gardening public. Whilst engaging in the production of traditional scientific outputs (such as peer-reviewed papers, informal articles, conference presentations, research-based teaching and supervision), RHS science activities also support other outcomes linked to the charitable aims of the RHS, including advancing the science, art and practice of horticulture for the benefit of future generations and the environment, and transforming communities through gardening.

RHS research findings are integrated into publicly accessible horticultural advice by the RHS Horticultural Information and Advisory service, which provides RHS gardening advice, web page development, and editorial and social media content. RHS shows, campaigns, press releases and media outputs communicate research findings to the wider public with a focus on promoting evidence-based, environmentally responsible and sustainable gardening advice. The Environmental Horticulture team also collaborates closely with the Education & Learning and Communities teams (providing input to school visits, the Campaign for School Gardening, Britain in Bloom, Healing Gardens, and other ad hoc programmes). Our team also collaborates with industry and works with government to inform and influence policy. For the general public, research scientists make frequent contributions to Hilltop Live, a programme of talks freely accessible to members of the public at RHS Hilltop: Home of Gardening Science. This facility also houses a large auditorium where the RHS hosted an international Health and Horticulture Conference in March 2022, bringing together horticulturists, planners, designers, healthcare professionals and policymakers from across the world. Our aim was to promote specific actions that support health and to encourage social care professionals and the government to increase the use of horticulturally-based health interventions. Scientific meetings on a range of horticultural topics regularly take place at this facility and are planned for the future.

9 | CONCLUSIONS AND VISION FOR FUTURE WORK

An increasing global focus on sustainability, driven by the United Nations (UN) Sustainable Development Goals (SDGs) (UN, 2015) and the IPCC Climate Change Sixth Assessment Report (AR6) (IPCC, 2021), are strong catalysts for the development of adaptation and mitigation actions for gardeners. Looking to the future, three critical elements of an environmental horticulture research programme are noted: (1) identifying and resourcing future research needs; (2) improving knowledge/results dissemination; and (3) developing 'Green Skills' capacity in horticultural and environmental science. In order for the research approach presented here to have impact at scale, it simultaneously requires implementation of best practice by gardeners, as well as expansion of evidence-based knowledge on specific topics through relevant research (Table 1). The extent and diversity of environmental horticulture research that is required is well beyond the capacity of the RHS alone to address and necessitates a collaborative approach across multiple institutions with specialist expertise. Progression of this research portfolio is facilitated through collaborative projects with academic and industry partners, joint PhD studies and post-graduate Fellowships. This research needs to be garden-centric in order to resonate with, and be more likely to be adopted by, gardeners. The uniqueness of the gardening context as a land-use of national significance (alongside agriculture and forestry, for example) provides justification for a garden-specific research focus. For example, scale is an important consideration, with the need for greater understanding of the cumulative impact of multiple small areas (islands and corridors) as opposed to larger landscapes. With regard to the high degree of urbanisation in the UK, the important role of gardens in an urban context is another research gap, with topics such as the ecological impacts of artificial (plastic) lawns needing further research, as well as urban gardens ability to address heat islands, biodiversity loss, pollution and storm water management in an urban context. Finally, there are the extensive research possibilities opened up by the substantial diversity of plants (400,000+) available to gardeners, primarily in terms of their potential for delivery of biodiversity support, ecosystem services and climate resilience.

Topics for future research within domestic and community gardens include water balance studies; quantifying use of mains/public water for gardening activities and how much this can be reduced by the adoption of rain water harvesting and use; water use efficiency considerations through appropriate gardening practices and plant selection; assessment of carbon and nitrogen balances (above- and below-ground); lawn management supporting sustainability/biodiversity (e.g., species mixes, mowing regimes, water and nutrient management and practices that improve infiltration and drainage capacity); quantification of energy use within gardens and how this may be reduced by the adoption of alternative energy sources and management practices. Soil health and soil quality research needs include (1) developing understanding and advice around soil structural improvements, (2) investigating how different plant-cultivars and soil management practices affect soil ecosystem services, and (3) understanding how EPS, soil structure, soil carbon storage and exchanges of greenhouse gases are affected by different approaches to gardening. Understanding the nature, diversity and characteristic features of peat-alternatives/peat-free growing media requires research in order to optimise irrigation, nutrition and plant management practices, as well as to come up with new growing protocols for challenging plant groups. The sustainability credentials of built-environment features and the plant taxa selected for these, such as use of green roofs, green walls and facades to reduce energy use in buildings, and use of land drains and rain gardens for attenuation of rainfall, deserve closer attention. These are by definition 'high-risk' items with environmental credentials that may be more questionable (typically containing substantial levels of embodied energy in features such as foundations, fixings and materials), but they are also potentially 'high gain', with capacity for substantial benefits from an ecosystem services perspective (such as flood alleviation, PM capture, thermal regulation), so it is the *net balance* effect of these structures (e.g., their Life Cycle Assessment [LCA] outcomes) on overall sustainability that is key. From a human health and wellbeing perspective, greater understanding of the biological mechanisms (e.g., microbiota, volatile organic compounds, physiology, neurology) underlying causal relationships between nature exposure and mental health as well as immune system function is required.

The impact of this research agenda relies on effective knowledge dissemination. As is typical from an academic perspective, there is potential for substantial impact and behavioural change through scientific outputs (peer-reviewed papers, informal articles, presentations and community science), post-graduate student supervision (research, papers, theses, presentations) and engaging with the general public or specific community groups. In addition to this, the RHS is fortunate to have the ear of the gardening public, and positioned with unique opportunities for communicating with and engaging them on research being undertaken and knowledge being generated. Potential knowledge dissemination channels include RHS garden-based information and interpretation; campaigns, press releases and media outputs; information & advice (RHS web pages, editorial, social media); horticultural industry collaboration & networks; RHS shows, gardens and landscape design influences; government/policy influence (e.g., DEFRA); and provision of education and training material to gardeners, horticultural apprentices, industry stakeholders and botanical educators. This combination of unique RHS positioning, combined with more typical sector/academic collaborations, provides great opportunity for impact.

Enthusing and educating younger generations, policy makers and the general public on the importance and relevance of environmental horticulture research is key to maintaining and growing a pipeline of 'Green Skills' resources in this field, who are equipped to produce outcomes with long term positive impact for gardeners, the horticultural community and wider society. For example, programmes like the currently-ongoing National Education Nature Park (https://nbn.org.uk/news/national-education-nature-park/ funded by the UK Department for Education) provide a way to embed the study of plants' environmental value into the national educational curriculum. This should help to avoid just the reliance on individual teachers' enthusiasm and interest, but increase the likelihood of the next generation not only appreciating the value but also understanding the how/why of plants' positive impact. Additionally, programmes like RHS's Campaign for School Gardening (https://schoolgardening.rhs.org.uk/home), which

TABLE 1 Best practice examples/calls to action, for gardeners and researchers, to facilitate an evidence-based approach to environmental horticulture.

Research focus area	Key findings[a]	Best practice/calls to action for gardeners	Calls to action for researchers
1) Responding to the changing climate.	• Projections of future UK climate tending towards warmer and more extreme conditions, with greater climate uncertainty. • Increasing stress on water resources. • Plant diversity and vegetative cover improves the resilience of gardens and their habitability. • Good soil health (to maintain ecosystem services) is dependent on sustained inputs of carbon, via plant-litter, exudates in the plant rhizosphere, or climate-positive soil amendments which foster 'positive feedback loops'	• Increase carbon capture and storage in gardens (plants/soil). • Contribute towards landscape-scale resilience (e.g., hydrological functioning and ecosystem services). • Displace household consumption-associated emissions with home-produce. • Improve soil health (e.g., mulching) • Practice planet-friendly gardening (https://www.rhs.org.uk/gardening-for-the-environment/planet-friendly-gardening-tips). • Apply Mains2Rains techniques (www.mains2rains.uk).	Studies on: • Water balances in horticultural settings. • Carbon and nitrogen fluxes (above and below ground) in gardens. • Soil health and soil quality. • Facilitating the transition to peat-free horticulture. • Sustainability credentials (embodied energy vs potential ecosystem benefits) of built garden infrastructure. • Potential plant species for future climates. • Managing lawns for climate resilience and ecosystem services delivery (above and below ground).
2) Plants for purpose.	• Horticultural plant diversity can be used to deliver ecosystem services and regulate environmental conditions. • Plant choice and vegetative cover impact delivery of ecosystem services.	• Optimise gardening 'handprint'; • Garden with ecosystem services in mind ('right plant, right place, right purpose').	• Understanding the potential of genetic diversity in cultivated plants for the delivery of ecosystem services. • Identification and assessment of plants' structural and functional traits, which can be linked to the delivery of a broad range of ecosystem services.
3) Sustainability and risk reduction.	• Correlations between sustainable gardening practices (limiting emissions & enhancing carbon sequestration) and biodiversity support. • Sustainable horticulture delivers immediate as well as longer term benefits for both human and environmental health.	• RHS Sustainability Strategy (RHS, 2021b); • Reduce consumption levels, re-use, recycle and repurpose where possible. • Optimise gardening as a way to connect socially and with nature.	• Understanding drivers of and barriers to different pro-environmental gardening behaviours. • Behaviour change towards sustainability amongst domestic gardeners and horticultural professionals; • Energy use within gardens. • Circular plastics and waste (e.g., artificial lawns).
4) Gardening and plant choice for human health and wellbeing.	• Gardens and gardening can be used and optimised as places and tools for health promotion in general and clinical populations.	• Create and maintain gardens that are safely accessible, legible and with spatial organisation that adequately reflects emotional needs, fosters serenity, and incorporates diverse multisensory planting and culturally relevant features. • Partner with the health and social care sectors to provide opportunities for service delivery in garden spaces.	• Causal links between garden exposure or gardening with various medical outcomes; • Biological mechanisms (e.g. microbiota, volatile organic compounds, physiology, neurology) underlying causal relationships between nature exposure and mental health as well as immune system function; • Tailoring garden design and process to the diversity of emotional needs across society; • Analysing strategic implementation of green social prescribing and nature based solutions in health and social care sectors.

[a]Refer to relevant section of the manuscript for more detail and references.

involves over 30,000 members including over 14,000 schools in the UK, also play a crucial role in enthusing the youngest and 'planting the seed' for the life-long appreciation of plants (RHS, 2023), encouraging professional career choices in this field in the decades to come.

Environmental horticulture is an accessible and increasingly important approach available to gardeners, for adaptation to, and mitigation of, climate and biodiversity crises on a national scale, and provision of environmental and human health benefits, so continued investment in the science, art and practice of this discipline is vital.

AUTHOR CONTRIBUTIONS

Mark B. Gush formulated the original concept and structure presented in this opinion piece. Mark B. Gush, Tijana Blanuša, Lauriane S. Chalmin-Pui, Alistair Griffiths, Elisabeth K. Larsen, Raghavendra Prasad, Marc Redmile-Gordon and Chloe Sutcliffe subsequently collaborated in roughly equal proportion to contribute to and refine the structure and content of the manuscript.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to Frank P. Matthews Nursery, Allensmore Nurseries, Hillier's Nurseries, Hills Plants, VitaCress, Volmary, Farplants Group, Johnsons of Whixley and Lovania Nurseries, as well as DEFRA, Fargro, the Royal Commission for the Exhibition of 1851 and the Oak Foundation, who are facilitating some of the research described here, through funding or in-kind support.

CONFLICT OF INTEREST STATEMENT

No conflicts of interest are declared by any of the authors.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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How to cite this article: Gush, M. B., Blanuša, T., Chalmin-Pui, L. S., Griffiths, A., Larsen, E. K., Prasad, R., Redmile-Gordon, M., & Sutcliffe, C. (2023). Environmental horticulture for domestic and community gardens—An integrated and applied research approach. *Plants, People, Planet*, 1–17. https://doi.org/10.1002/ppp3.10444