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ARTICLE

Climate-controlled conservation: Remaking 'the botanical metropolis of the world'

Jonathan Rutherford[1] | Simon Marvin[2]

[1]LATTS (Laboratoire Techniques, Territoires et Sociétés), UMR 8134—Ecole Des Ponts ParisTech, CNRS, Université Gustave Eiffel, Marne la Vallée, France

[2]Urban Institute, University of Sheffield, Sheffield, UK

Correspondence
Jonathan Rutherford, LATTS (Laboratoire Techniques, Territoires et Sociétés), UMR 8134—Ecole Des Ponts ParisTech, CNRS, Université Gustave Eiffel, 6 Avenue Blaise Pascal, 77455 Marne la Vallée, France.
Email: jonathan.rutherford@enpc.fr

Abstract

This paper examines the understudied relationship between nature conservation and climate control in botanic gardens. Drawing on research conducted at Kew Gardens in West London, we analyse how the relations between climate control, techniques that allow the creation of particular microclimatic conditions in volumetric enclosures, and ex-situ—out of nature—botanical management have changed over time. The paper shows how climate-controlled conservation works through three spatial-technological modes—acclimatisation, climate simulation, and climate security—that reconfigure in-situ and ex-situ relations. These modes increasingly transcend local environmental conditions, creating the possibility of conservation without natural climate. The paper extends existing geographies of climate control by focusing on the role of technology in permitting plant life to be moved between different geographical contexts, in enabling ex-situ and in-situ natures to become increasingly entwined, and in constructing enclosed conditions decoupled from local climate. Secure climate-controlled conservation now strategically transforms ex-situ botanic gardens into the actual sites, and in some cases the last remaining sites, of these natures.

KEYWORDS

artificial environments, botanic garden, climate control, Kew Gardens, nature conservation, plants

1 | INTRODUCTION

Kew Gardens in West London was described in the House of Lords in 1917 as 'the botanical metropolis of the world' (Lord Bryce, cited in Desmond, 1995, p. 312). In the twenty-first century, this evocative description arguably holds even more intensely, as over 70% of the world's recognised plant families—from tropical, temperate, arid, boreal, and alpine environments—are represented in its living collections and seedbanks (Kew Gardens, 2019). With increasing threats to natural environments (in-situ) worldwide and decreasing levels of biodiversity in many places, out of habitat (ex-situ) conservation spaces such as Kew have become crucial to safeguarding the existence and reproduction of many plant species (IUCN, 2017; Mounce et al., 2017; Neves, 2019; Oldfield, 2010).[1]

Geographers have been instrumental in studying the spatial shifts in management of nonhuman life and in biodiversity practice. The traditional dichotomy between in-situ and ex-situ in nature conservation policy and practice has been significantly challenged to the extent that it is no longer possible to maintain a simplified bifurcated view of 'nature' and 'captivity' (Braverman, 2014; Hinchliffe, 2007). The challenge to this dualism is part of the wider relational critique of the artificial nature/society divide (see Anderson, 1995; Latour, 2004). Rather than continue the distinction between in-situ and ex-situ contexts, this work shows it is more relevant to think of the many human-shaped situs of conservation activity. What now constitutes 'nature' and 'conservation' is constructed within, and not outside of, social relations and human action, but at the same time is not reducible to these (Hinchliffe, 2008; White et al., 2016). This work bridging the nature–society divide has, however, rarely focused explicitly on the role of technology and infrastructure in enabling the spatial movement and immobilisation of species across in-situ and ex-situ contexts. This is in spite of the increasing need, over time, to develop technologically mediated environmental conditions supporting nature conservation at sites such as botanic gardens that lie beyond traditional habitats.

While the conservation priorities of Kew Gardens have evolved since its formation, an underexplored dimension of its role as a 'botanical metropolis', in constituting a key site of globally important plant ecologies, is the development and application of climate control capacities. Climate control refers to the systems, techniques, and practices that allow the creation and management of particular microclimatic conditions that are distinctive from the external climate conditions in the immediate local setting. Over time, evolving, quite distinctive technological modes of climate control have enabled different degrees of ex-situ plant display/propagation, from rudimentary hothouses to hi-tech plant chambers. This historically constituted, nested set of artificial environments has rarely been studied in depth, with the notable exception of specialist histories of glasshouses, conservatories, and laboratories (see Grant, 2013; Hix, 1996; Munns, 2017; Woods & Warren, 1988). Yet, without climate control, it would have been impossible to assemble plants from various parts of the globe that have in-situ climates that are fundamentally different to that of West London, and to keep them alive in enclosed ex-situ artificial environments. Climate control is thus the key socio-technical-ecological system for creating the conditions for ex-situ conservation of living plants in any botanic garden.

The aim of this paper is to examine the shifting relationships between nature conservation and climate control in botanic gardens as a way of analysing the role of technology in forging socionatural relations that are the basis of conservation practices (cf. Braverman, 2014; Lorimer, 2015). We analyse how the relations between climate control and ex-situ—out of nature—botanical management have changed over time, with a specific focus on the increasing strategic capacity of climate control practices to ensure the survival of threatened plant species. The focus on technologically mediated 'conservation without nature' (Braverman, 2014) is designed to extend existing work on climate and environmental control centred on the spatial expansion of air-conditioned human life and settlement possibilities to/in areas with turbulent outdoor climates (e.g., Cooper, 1998; Hitchings, 2010; Shove, 2003). As climate control is increasingly used to secure more-than-human environments through circulation and stabilisation of human and nonhuman modes of life, there is a need for relational geographies that analyse how conditions of existence and performance of life are modulated and enhanced to overcome local environmental limits. The paper thus explores the emerging strategic significance of climate-controlled conservation as a distinctive way of analysing the material, socio-technical processes through which ex-situ and in-situ are becoming increasingly entwined and conditions for life decoupled from local climate.

The paper is structured in six further sections. Section 2 interrogates existing geographical research on climate control and how this can be advanced to frame our analysis of the socio-technologies of more-than-human life support in botanic conservation. Sections 3–6 use this framing to explore, through a focus on Kew Gardens, three distinctive modes of climate control in botanic practice over time, how these shape particular configurations of in-situ/ex-situ relations, and the challenges and issues raised. The final section analyses the main features of strategic conservation mediated through climate control capacities and outlines key implications for further geographical research.

2 | GEOGRAPHIES OF CLIMATE CONTROL: DECOUPLING ENVIRONMENTAL CONDITIONS FOR LIFE FROM PLACE

Geography and affiliated disciplines have had longstanding interest in understanding changing forms of climate and environmental management and control (e.g., Bryant & Wilson, 1998; Lippert et al., 2015). Indeed, environmental control has been at the heart of agricultural and botanical practice for centuries, as humans have sought ever more precise and efficient use of the elements—light, heat, air, water, earth—to bypass climatic and seasonal constraints of their immediate environments to coax plants and crops to grow far from their natural milieu. But this broad-based concern has evolved in a rather piecemeal manner with regard to understanding how artificially engineered indoor environments have become increasingly important to a host of human- and nonhuman-centred activities and functions (Gissen, 2014; Marvin & Rutherford, 2018). Analysis of this existing work highlights two main reasons why geographers have engaged with processes and practices of climate control.

First, climate control processes and practices are inherently geographical and recast in important new relational ways some of the most fundamental concepts of geographical thinking, notably environment, nature, local context/place, etc. Climate control draws attention to an increasing, techno-mediated spatial capacity to decouple humans and nonhumans and their climatic experiences and practices from immediate local environments (e.g., Squire et al., 2022). Historical geographers have drawn attention to the different understandings of climate that complexified the role of climate control in imperial projects (e.g., Endfield & Randalls, 2014; Mahony, 2016). Once indissociable (for some) from stable, regular local outdoor physical conditions, 'climate' has been destabilised as a category (Hulme, 2016; Mahony & Randalls, 2020), and untethered, unbundled, and rebundled as a set of intersecting parameters that can now be assembled and managed to (it is claimed) optimise conditions within particular bounded spaces or enclosures (Gissen, 2006).

Much existing work has focused in particular on the production and experience of air-conditioned environments as a form of 'thermal modernity' for managing human comfort and productivity historically and in climate-changed urban areas (Chang & Winter, 2015; also Hitchings & Lee, 2008). Air-conditioning configures a 'standardised, homogenous "comfort zone"' in which the interplay of bodies, buildings, environments, and cultural norms produces ostensibly similar dispositions (Healy, 2008, p. 312). It furnishes a techno-mediated capacity to create liveable indoor bubbles within otherwise hostile immediate environments. A multitude of research in different contexts has shown this capacity to be subject to both varied cultural dynamics (Hitchings, 2010) and how residents constantly adjust and rework the conditioned environment according to their own needs and sensitivities (e.g., Hitchings, 2020; Sahakian, 2014). It has also been shown how practices of keeping cool or warm evolve as people move between contexts (Strengers & Maller, 2017; also Fuller & Bulkeley, 2013).

But, of course, climate control is not evenly deployed and used/experienced, and so geographers have been, second, highly attentive to its socio-spatially unequal features, rollout, and consequences at different scales. Bouzarovski and Robinson (2022) focus, for example, on how air, energy, and human activity intersect within the domestic sphere to recast understandings of energy vulnerability and deprivation, thereby reinforcing the notion of indoor spaces as markers of shifting and uneven human–environment relations (Biehler & Simon, 2011). There is an emerging focus on uneven accessibility to cooled space or 'heat refuges' in urban areas, in the context of rising extreme outdoor temperatures (Fraser et al., 2017). This is part of wider work on 'urban thermal metabolism' (Caprotti & Romanowicz, 2013) highlighting the role of individual buildings as key nodes of exchange and circulation of climate elements across larger spatial scales. In this vein, Winter (2013) suggests that resource-intensive air-conditioning systems in buildings are discursively and materially positioned as pivotal to modern urban life across Asia, bound up in a sprawling 'indoor capitalism' that is inequitably accessible to urban residents.

Controlled environments are drawn here into wider geographies of urban development and (techno)politics, thereby deepening understandings of their purpose, make-up, and spatial diffusion. Gissen's (2014) exploration of the 'atmospherically engineered' indoor environments of New York is emblematic here, as climate-controlled stable atmospheres are linked to the city's contested wider restructuring in a time of crisis (see also Lockhart & Marvin, 2020). Human comfort here merges with logics of symbolic power and productivity, as we increasingly see artificial environments in the plant-filled atria of office towers as global firms seek to demonstrate their capacity to manage, master, and bypass 'nature'. On a different scale, McNeill's (2022) recent study of Singapore's Gardens by the Bay connects control of 'nature' to a long-held technopolitical state project of 'botanic urbanism' that expands our view of Singapore as the quintessential 'air-conditioned nation' into the domain of biodiversity management. Broader geo-histories of climate control and 'manufactured weather' have also highlighted the situated social, cultural, and political economic mediations and uneven outcomes of efforts at knowing, predicting, and controlling environmental conditions (Cooper, 1998; Fleming, 2010; Harper, 2017) and of new understandings of the atmospheric conditions that shape urban life (Janković, 2013; Whitehead, 2011).

Geographies of climate control have then been fundamental in developing an understanding of the reshaping of the spatial conditions, means, and uneven outcomes for the maintenance and reproduction of human life in increasingly turbulent and uncertain climatic contexts. This work has in particular foregrounded the delinking of conditions for inhabitation and settlement from local place and climate, as technology can be used to transform an ostensibly hostile environment into a hospitable one. Extending productively this existing work means, notably, broadening relational geographies of the circulation and immobilisation of life in and beyond 'nature', and examining how the differential capacities and practices of climate control are used to support and secure more-than-human environments. This contributes, overall, to demonstrating the layering and accretion of climate control technologies and capacities in particular places, and the sheer diversity of domains of life now mediated by climate control, through which whole conditions of existence and life support are disconnected from local geographies and environments.

3 | CLIMATE CONTROL, CONSERVATION, AND KEW GARDENS

The constant evolution of technologically mediated capacities to shape and enable particular socio-spatial configurations of life calls for a *geohistorical* analysis of climate control dynamics over time. The above work has shown how ever more sophisticated air-conditioning systems in particular have extended possibilities of urban existence and sustained, albeit unevenly, the diversity of human bodily experiences and sensitivities in environments of high or irregular temperature. Plant and animal life too has been spatially reconfigured over time through the evolution of climate control systems, and a move to understanding the contradictions and biopolitics of conservation logics and practices (see Biermann & Anderson, 2017; Büscher & Fletcher, 2020; Searle, 2022). The growing role of digital technology in conservation has been highlighted as an important element in changing how 'nature' is monitored and managed (see Adams, 2019; Millner, 2020). These shifts contribute to the possibility of what Braverman calls 'conservation without nature' (Braverman, 2014, p. 48). The complex interconnections between species and sites of conservation must be understood as 'the messy overlap of natures that consist of complex human-nonhuman networks and assemblages in various stages of becoming' (Braverman, 2014, p. 55; see also Lorimer, 2015; Whatmore & Thorne, 1998).

In botanic conservation practice too, there is no longer a clear distinction made between populations in the wild, in reserves, or in captivity (Heywood, 2017; Marris, 2011; Neves, 2019). The priority is now recognised to be, in some cases, species survival irrespective of in-situ or ex-situ location. The 'One Plan' approach, a framework developed by the International Union for Conservation of Nature, proposes integrated planning that aims for 'the development of management strategies and conservation actions by all responsible parties for all populations of a species, *whether inside or outside their natural range*' (IUCN CPSG website(n.d.), added emphasis; see also IUCN's Species Strategic Plan: IUCN, 2017). The UN-led Global Strategy for Plant Conservation (GSPC) also aims for coordination and 'linkages' across in-situ and ex-situ conservation strategies (UN, 2011). As one major botanist pointed out more than a decade ago: 'Storage of as much wild plant diversity as possible in ex-situ collections is an immediate imperative. We cannot give up on the wild – but do we know what or where the wild might be?' (quoted in Oldfield, 2010, p. 21). These most recent tendencies envision botanic garden structures, reserves, and seedbanks as important repositories for threatened plants, indeed as 'the world's greatest resource for the cultivation and conservation of individual plant species' (Wyse Jackson & Sutherland, 2000, p. 24; see also Heywood, 1990; Maunder, 1994). The world's 3000 or so botanic gardens are diverse, albeit heavily concentrated in urban areas of the temperate North (Golding et al., 2010; Mounce et al., 2017), with significant shifts over time in their purpose (Heywood, 2017). A common feature, however, has been to concentrate and steadily improve the technologically mediated conditions for their practice and goal of displaying and conserving plants 'out of context'. Thus, the role of climate control technologies in enabling the circulation, stabilisation, and securing of plant life in artificial environments often well beyond 'natural' in-situ climate conditions is essential, but has been far less explored. This is in spite of increasing recognition that existential threats to biodiversity mean that all life now depends to some extent on technological capacities to extend and redistribute spatially the basic 'natural' conditions for plant life (see Adams, 2017).

The paper therefore develops a geohistorical approach to study the progressive converging of conservation and climate control in botanic gardens. Specifically, we ask how has climate-controlled conservation been socio-technically achieved at different times, through what kinds of geographical relations, and to enable what forms of conservation outcomes? We focus on the dynamic and changing role of climate control capacities in enabling the collection and circulation of botanical resources and their stabilisation in techno-mediated enclosed environments of Kew Gardens. This allows us to study a nested landscape of controlled environments, ranging from the nineteenth to twenty-first centuries, where the ongoing refinement and development of climate control capacities seeks to address the limitations of previous systems in relation to shifting conservation rationales. In order to study climate control practices over time in relation to evolving conservation logics and wider geographical relations between in-situ and ex-situ, the paper adopts a geohistorically sensitive methodology. Four main methods were used to combine historical research for information not available from contemporary sources and visits and interviews to understand more recent, as yet undocumented, developments. First, we drew on the substantial secondary literature about Kew's historical development and contemporary strategies to situate our study and extract the limited information present in these works about its climate-controlled enclosures.

Second, we carried out research in the National Archives and Kew Library to study the historical reports and primary documents about the development of Kew's glasshouses, focusing especially on periods of refurbishment that provided an important window on to issues involved in changing climatic and technological capabilities. Third, we undertook site visits to both public glasshouses and private climate-controlled zones accompanied by Kew staff. These visits enabled us to see the structures, layout, and work that goes on to create and maintain the environments. We questioned staff about the underlying rationales of their work, and how they deal with technical and botanical issues. Fourth, we conducted eight in-depth semi-structured interviews of varying length with Kew's technical staff, representatives of the private company managing the climate control systems, and botanic and conservation specialists in and around the gardens. The interviews provided deeper exploration of issues raised in the site visits and probed the nature of the technical and/or conservation expertise of interviewees. Interviews were explicitly oriented towards both fact-finding, because of the lack of information elsewhere about the socio-technical systems of climate control, and analytically drawing out reflections from experts on their own work and our evolving typology of modes of climate control.

This comprehensive geohistorical approach enables us to trace and reconstruct through time the evolving role of climate control and its intertwining with Kew's plant collection and conservation mandate. This approach structures the subsequent analysis in three sections focused on the distinctive modes of climate control present in Kew's activities. We characterise these modes as acclimatisation, climate simulation, and climate security, respectively, to capture succinctly the main drivers, climate capacities and practices, and wider geographical significance of each mode. We recognise that there is considerable overlap between modes—indeed, while showing the distinctive features of each, we emphasise the gradual build-up, layering, and accretion of climate-controlled conservation systems, techniques, and practices at Kew over time. This is pertinent as the Victorian acclimatisation glasshouses have been renovated many times and still stand side-by-side with later, more modern enclosures. We suggest then that these modes provide an important and powerful analytical framing for tracing the increasingly diverse and complex efforts at actively managing non-human plant life and charting the changing role of climate control and relations between in-situ and ex-situ conservation.

4 | ACCLIMATISATION

During the nineteenth century, botanic gardens like Kew became focused on bringing plant collections from colonial empires to the global city (Brockway, 2002; Johnson, 2011; Miller & Reill, 1996). The expansion of Kew enabled the common citizen who rarely travelled to 'see the world' to view distant ecologies in London, at the centre of the empire. Sir William Thiselton-Dyer (1880, p. 273), the third director of Kew, suggested that the Victorian botanic garden should be where 'a vast assemblage of plants from every accessible part of the earth's surface is systematically cultivated – imitating as far as possible their various physical conditions of growth – for the purpose of showing visitors'. Like his predecessors William and Joseph Hooker, Thiselton-Dyer recognised that this function of display and novelty overlapped with both an economic rationale of plants for commerce, medicine and food, and scientific progress in knowledge and systematic categorisation of plant species (see Brockway, 2002; Endersby, 2008).

Initially, this extractive relationship reproduced the clear dichotomies of the time between wilderness and civilisation, and nature and the city (see Driver & Martins, 2005). New international infrastructure networks, especially shipping and expanding rail systems, allowed the transport of plants across the world. The Wardian case was developed in the mid-nineteenth century as an enclosed glass box, effectively a miniature greenhouse, that protected plants on arduous journeys (Keogh, 2019; Klemun, 2012). This new concern for climate control was representative of 'the Victorians' artificial manipulation of nature' (Darby, quoted in Klemun, 2012, p. 34)—using wood, glass, and steel cases and greenhouses to protect plants against hostile ex-situ climatic conditions in transit and in London.

The practice of acclimatisation, developed in the sciences and promoted by acclimatisation societies in major cities, was used to support the movement of plant species across the globe. Acclimatisation represented imperial intervention in the natural order of the world in close counterpart to political and military intervention in the human order in the colonies (Anderson, 1992; Osborne, 2000). Nineteenth-century acclimatisation was about aiding adaptation of Europeans and their domestic plant species to make them feel more at ease in their adopted surroundings (Osborne, 2000). But it also included a reverse process for species brought back from other climes to European temperate zones for the purpose of imperial economy, science, and public display (Anderson, 1992). In both cases, acclimatisation as a key technique of botanic environmental control worked through a process of transporting and transforming plants, taking them out of their natural habitat and forcing them to physiologically adjust to a new environment. Movements drew on the new scientific focus on the dynamic relations between organisms and their environments and the gradual realisation first of the shaping effects of the latter on hitherto stable species, and then of the prospect that the ties between species and their original habitats/climates might be disbanded. This allowed botanic gardens to become the cogs for a 'planetary botany' (Bonneuil, 1999) based on exchange and acclimatisation of plants, with the creation of more than 80 gardens in British colonies in the nineteenth century. Transfers to and from Kew were made through the technologically enabled capacity of climate control.

4.1 | Acclimatisation structures: Victorian glasshouses

The Palm House and the Temperate House were constructed in the mid-nineteenth century to offer early climate-controlled acclimatisation structures at Kew. These glasshouses were incredible technical achievements for using 'the whole gamut of Victorian engineering' (interview, glasshouse manager, September 2019) with wrought iron and then steel frames, glass panes, boilers, and box ventilation systems. They focused on optimising light and heat to create stable, year-round environments—tropical in the Palm House and cooler in the Temperate House (Diestelkamp, 1982; Minter, 1990; Schoenefeldt, 2011). In this way, the Victorian glasshouse materially demonstrated the 'triumph of science over nature' and became a significant context where 'new environmental technologies could be developed and tested' (Valen, 2016, p. 407).

The Palm House, completed in 1848 for Kew's tropical plant collection, was described as 'an indoor rainforest' (Minter, 1990), where 'the trees thrived, several species flowering for the first time outside the tropics' (Price, 2019, p. 79). It was heated by 12 underground boilers connected to a system of pipes below an iron grating floor 'producing a more efficient circulation of heat' (Desmond, 1995, p. 161). The Temperate House, the largest Victorian glasshouse in the world, was constructed from 1859 and houses more than 10,000 plants of 1500 species (ferns, acacias, camellias, rhododendrons, etc.) from all the major temperate zones of the planet (Kew Gardens, 2019). In contrast to the Palm House, the 'common denominator' of the plants here originally 'was their intolerance of high temperatures, combined with the need for protection from frost' (National Archives CM 1/487). Organising the plants within the structure proved to be a continual issue, as parameters of light and shade, and direct or less direct access to heat, have not always met the exact requirements of each species (interview, glasshouse manager, September 2019). Already in 1860, correspondence between the Kew director and the Office of Works stressed the importance of heating the Octagon sections of the Temperate House to 50°F for 'Winter's use' (National Archives WORK 16/30/2; CM 8/220).

Both glasshouses have been renovated a number of times, notably falling into decline between the 1950s and 1970s when elements of their structures became a hazard for the visiting public. During discussions about the planned renovations, a technical note from October 1970 from the assistant curator summarised a widespread observation that 'the [Temperate] House has several limitations environmentally the low light levels, inadequate ventilation and poorly controlled heating make it difficult to grow a wide range of plants' (National Archives LSS/4000/108/B). In particular, 'increased light transmission so as to permit reasonable plant growth in winter' was viewed as 'the paramount requirement' because the existing glazing was too opaque and subject to dirt accumulation on its surface (National Archives LSS/4000/108/B; CM 8/219/2). The curator at the time ruled out any form of artificial lighting for cost and technical reasons, so new glass became a prime means to manage the internal climate for plant photosynthesis. Furthermore, cast iron heating rods ran around the edge of the buildings, leading to more heat being diffused there and less heat available to beds located in the central parts (National Archives SSG/4000/108/B.PT4). In the case of the Palm House, the 'tropical' indoor climate using the high temperature and humidity necessary for the palm trees and cycads accelerated corrosion of the cast iron columns (National Archives WORK 16/1956). Both glasshouses were threatened at various points with potentially being demolished, until senior Kew curators impressed on 'public works' officials the overarching botanical value of the structures for housing specimens that were 'literally priceless' and 'irreplaceable', and that their loss would be 'a botanical disaster of the first magnitude' (National Archives WORK 16/1956).

The key implication of this historically constituted acclimatisation mode of climate control was the capacity to render 'plants commensurable across contexts' (Neves, 2019, p. 52). Through distinctive light and heat management in glass and iron structures, in-situ plants from distant lands could be gathered together as captive resources in an ex-situ metropolitan centre (Endersby, 2008; Miller & Reill, 1996). This is the original meaning of the 'botanical metropolis of the world', Kew in London as an advanced cultural hub where diverse global ecologies were assembled to be understood and displayed as the fruits of imperial science, reason, and power, and which 'improved' the world (Drayton, 2000). The subsequent re-exporting of some species to other climate zones is part of the same 'economic botany' logic and the clear separation between in-situ and ex-situ—seeds or plants had to pass through Kew for ex-situ growing or further knowledge development before being sent to countries elsewhere, often in Wardian cases (Desmond, 1995, p. 213).

5 | CLIMATE SIMULATION

During the second half of the twentieth century, with the decline of empire, the rationales underpinning activities at Kew shifted from purely 'imperial botany' to the 'expansion of Kew's plant sciences and an increasing involvement in plant conservation' (National Archives CM 1/487). An attempt was made at offering a 'realistic' ex-situ experience and encounter with botanical environments by informing visitors about species as well as the need for in-situ protection of plant habitats in nature. This led to the production of naturalistic settings that sought to recreate tropical climates that people could experience and learn from: 'In the botanical garden, the world shrank' (Klemun, 2012, p. 45; also Luke, 2000). The need for more elaborate enclosures for plant display in realistic settings necessitated improvements in glasshouse structures and more complex climate control technology that could directly replicate the heat and humidity of the tropics (Johnson, 2011, chapter 4; Woods & Warren, 1988). While conventional glasshouses for plant display could make do with the highly variable conditions, whereby 'In ten minutes, light intensity could change by 50 percent, air temperature by 10 percent, and the air itself by 30 percent', the new botanical plant science in the post-war period had developed altogether more precise and controllable conditions for experiments that relied on repetition and reproducibility (Munns, 2017, pp. 7–8). The Caltech phytotron built in 1949 had, for example, more than 50 separate zones to 'create any number of artificial climates' (Kingsland, 2009, pp. 308–309). Although the phytotron was not explicitly designed to replicate natural systems, it did provide the technical capacity and knowledge to produce more precise climate-controlled environments for botanic gardens. These systems thus became interwoven with artificial ecosystem construction to produce more tailored environments for the display of plants, with multiple climates inside the same building. This ex-situ simulation of the in-situ habitats and conditions of plants began to further problematise the dichotomy between natural and captive environments with the recognition that some species could be nurtured quite successfully if local conditions resembled those of their origins (Guerrant et al., 2004). This constituted an inversion of the acclimatisation logic, changing the ambient conditions of the plants rather than relying on plant physiological adaptation to a standardised artificial environment.

5.1 | Reworking the phytotron: Increasing climate precision

At this time, Kew's existing glasshouse structures were renovated and modernised to offer more precise microclimatic recreations of tropical and temperate zones (Minter, 1990). Both the Palm House and Temperate House heating systems were switched from coal to gas, providing improved heat output, while improved glass quality let more light into the buildings (National Archives LSS/4000/108/B). Reverse osmosis units were increasingly used to process London tap water, which is recognised to be 'dreadful for plants', and turn it into soft water and stop high pressure misting systems clogging up (interview, horticulturist, September 2019).

Due to the early 1970s energy crisis, heating and lighting efficiency concerns were taken closely into consideration in the design and construction of new glasshouses. The Princess of Wales Conservatory was built without side walls, with much of the space below ground producing a smaller overall volume 'for rapid temperature adjustment' (interview, engineer, February 2022). Building on phytotronic techniques, it ambitiously offered 10 distinct climate zones—including arid desert, humid tropical, dry tropical, and temperate—within a single building using new computer-controlled environmental systems, including automatic shading (Figure 1). A Guernsey-based company, Climate Controls, was contracted to install the systems to recreate the precise conditions for the varied plants in the Conservatory. The living collections curators of the time stressed that decisions around primary settings and parameters involved their plant specialists with in-situ experience, and could be continually modified:

> The exact temperatures, humidities, light levels and watering regimes maintained have been determined on the basis of the collective experience of many horticulturalists. New information results in constant refinements. The benchmarks for these conditions are derived from field observations of the weather and soil conditions, amongst many other things, experienced by the plants in their native habitats.
>
> (National Archives CM 1/487)

FIGURE 1 Climate simulation in the Princess of Wales Conservatory (*Source*: photos by authors).

Thus, more precise digital control became central to creating these more realistic and multiple environments through early use of automation and climate simulation systems, which also reinforced the justification for ex-situ plant collections:

> Whilst this automation saves energy and accurately maintains the required environment, it also allows the Conservatory staff to concentrate on what they do best – growing plants … removing the onerous tasks of ventilating and damping down…
>
> (National Archives CM 1/487)

The horticulturists can use the control precision to give the plants seasons. For some species, 'It's better getting cooler over winter, it stops them growing. You don't want them growing when there's not enough sunlight, because then they get etiolated and don't move up. And then, some of them need a bit of dormancy to flower' (interview, September 2019). Here, we see the beginnings of distinctive modes of climate variation operated across Kew's glasshouses, with increasingly complex sets of parameters regulated through digital systems in the more recent enclosures, and 'essentially just a temperature thing' for the hardier specimens in the Temperate House (interview, glasshouse manager, September 2019).

The outcomes and implications of this mode of climate control are the beginnings of a more intensified entangling of relations between in-situ and ex-situ environments. Air travel reduced the time it took to transport plants to and from

Kew, and also demanded more space-efficient ways of housing plants in transit in aircraft holds, leading to the replacement of the Wardian case by simple polythene bags and carry-on cases (Keogh, 2019).

Crucially, novel technological advances allowed claims of substitution to be made—that species could be cared for and grown in realistic conditions almost the analogue of their native environments—and at more efficient cost and protective capability, as demonstrated by the Princess of Wales Conservatory. The 'botanical metropolis of the world' here begins to signify a distinctive metropolitan nature, through recreating specific environments from other zones 'in microcosm' from which people could learn and benefit (Minter, 1990). At the same time, however, Kew actors make clear that there have long been significant contributions made by its botanists to in-situ plant species management in a range of locations around the world (see Desmond, 1995, chapters 13 and 19; interview, conservation specialist, February 2022). This in-situ work increasingly began to be oriented by conservation concerns, with participation in international conservation programmes (Desmond, 1995, p. 345),[2] which would go on to shape the importance of climate control for plant growing in new ways in recent years.

6 | CLIMATE SECURITY

Over the last 20 years, Kew's overarching purpose has evolved again and is now closely tied to global conservation objectives, providing 'carefully managed growing spaces for plants from around the world' and curating a 'living reference library' for science and conservation (Price, 2019, p. 10). Kew highlights the fact that it constitutes the largest and most diverse collection of living plants in the world: 'the most biodiverse place on the planet' (interview, glasshouse manager, September 2019). Many of the plants in its glasshouses are on the IUCN Red List for conservation priority.[3] The development of a sister site at Wakehurst in Sussex, housing the Millennium Seed Bank, is an acknowledgment of the need for secure and protected biological repositories as 'an insurance against the risk of extinction in their native habitat' (Price, 2019, p. 104). At the same time, this evolution signifies a recognition of a wider failure to protect and conserve plant species in-situ. The pivotal role that Kew and other botanic gardens and seed banks around the world now play, in offering ex-situ conservation of plant biodiversity that would otherwise be severely threatened or even lost, renders these sites fundamentally strategic to planetary ecological futures.

Critically, the modes of climate control at Kew have had to be reconfigured to meet this fundamental concern for 'species prioritisation' (interview, conservation specialist, February 2022). While microclimatic management in the existing display glasshouses has become more complex over time, it is in the private tropical nursery structure behind the scenes, where Kew's effective conservation and research work goes on, that we can observe the emergence of a new intensified logic of climate control, effectively contributing to plant biodiversity objectives for total population management. Figure 2 shows a whiteboard at the entrance to the tropical nursery, which synthesises the plant collections and why the work at the nursery matters. Originally built in the 1950s, but now relocated and substantially renovated, the 6500 m^2 tropical nursery has no fewer than 21 separate, secure, and fail-safe climate zones monitored 24 hours a day and all year round by specialist computer climate control systems provided by the Guernsey company, Climate Controls. Each zone's microclimate can thus be adjusted and managed according to the precise needs of the 10,000 plant species present (including cacti, succulents, ferns, and other moist tropical or subtropical species, and orchids), some of which no longer exist in the 'wild'. The company provides a service that necessitates three full-time engineers and occasional external specialists. From talking to the engineers, site managers, and plant specialists, it is clear that this 'environmental engineering' (interview, technical engineer, February 2022) in the private nursery is oriented in particular around two aspects that together distinguish this new mode of climate control from the previous ones: (a) intensified digital control of multiple climate variables and (b) permanent maintenance and presence.

6.1 | Digital climates for plants

The expanded, intensified environmental control systems can be configured in different ways in each of the 21 zones, depending on the shifting objectives of the horticultural staff. The engineers create the conditions for propagation of the plants: 'the majority of the time we're assisting plant life ... What we do is basically try to set the systems up for what they need' (interview, technical engineer, February 2022). The conditions the plants need can be a learning process for those looking after them in the nursery: 'many of our target species have not been trialled horticulturally ... so how do you actually maintain these species in ex-situ conditions?' (interview, January 2022). The company Climate Controls developed their digital system for bespoke management and algorithmic integration of 14 environmental variables:

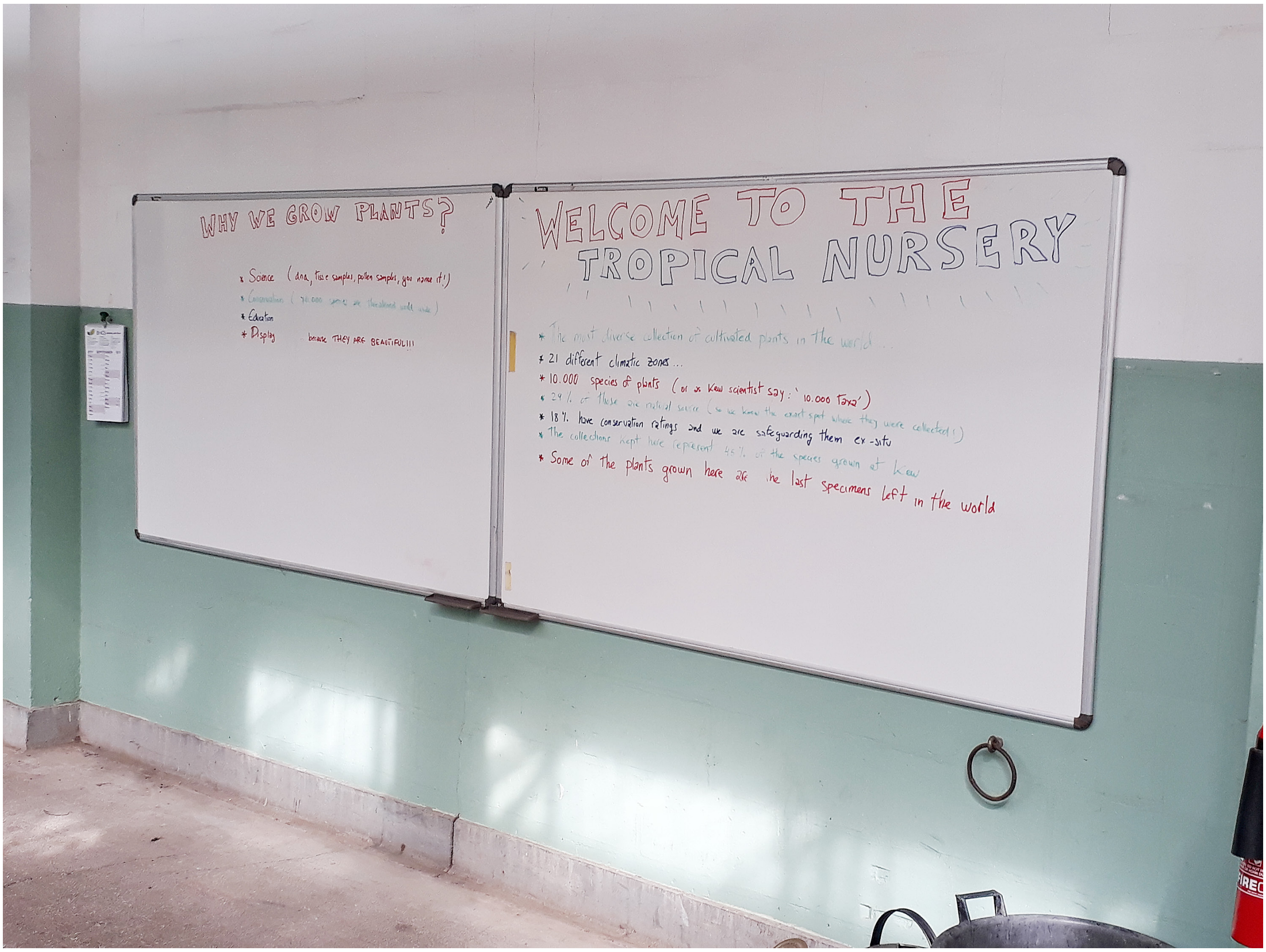

FIGURE 2 The 'welcome' whiteboard in the private tropical nursery (*Source*: photo by authors).

> The desired environment is achieved using a complex set of algorithms rather than a logic-based system. This approach ensures that the target conditions, as set by the user, are more likely to be achieved and more accurately maintained.
>
> (Climate Controls, 2020)

The engineers translate the basic parameters that the horticulturists want for their plants into the precise customised system configuration that changes constantly in order to smooth out and 'temper' any rapid fluctuations in conditions that would 'shock' the plants:

> The end-user will say to use, we want a night temperature of this, we want a day temperature of that, and we will advise them in between ... We do all that. Basically, what they're after, they want to look at the graph, they want to see that nice and smooth curve, and then they want to relay the data levels and see it's working.
>
> (Interview, technical engineer, February 2022)

The plant specialists have faith in their expertise to 'read' the plants and the 'adaptability' of plants in changing ambient conditions (interview, January 2022). The engineers use a combination of algorithms in the digital systems, sensors in the nursery and outside, and constant monitoring of the outdoor and indoor conditions and the relation between the two in order to produce the necessary climate control configuration on a daily basis. This means, for example, 'modulating' the temperature gradually from the typical night-time temperature of 18 degrees when the plants have 'shut down for the night and so they're not under stress', to 'waking the plants up' at 20 degrees at sunrise ('clock time'), and then 'hitting' a 'premium temperature' of perhaps 24 degrees during daytime 'when the radiation level maxes out at 800 or above' (interview, technical

FIGURE 3 Climate security in the private tropical nursery (*Source*: photos by authors).

engineer, February 2022).[4] Obtaining these desired values requires an astronomical clock and latitude inputs, so the system knows when sunrise is precisely at Kew ('in Birmingham there might be five minutes' difference'), and then a host of meteorological data (outside temperature, radiation level, wind speed, rainfall) that affects internal conditions and that are therefore monitored in real-time:

> So, whilst we use this to measure the internal temperature, it's not the inside temperature that dictates how the equipment modulates. What's going on outside determines how the valves operate, how the shading operates, how the heating operates, and all that type of thing. We have to integrate it all.
>
> (Interview, technical engineer, February 2022)

The key thing is for the system to be configured to 'anticipate' the effects of any changes in each variable on the whole microclimate. For example, engineers switch on or increase the power ratio in the heating pipes before the opening of the shading screens to avoid a sudden drop in temperature that would thermally shock the plants: 'they [the plants] need that natural situation' (interview, technical engineer, February 2022). But the engineers/system cannot anticipate all the abrupt changes in outdoor–indoor conditions 'because if it's a cloudy day and the sun suddenly comes out, some of these houses, five, six degrees, it's very, very rapid the temperature'. In this instance, it's about 'stabilising ... it will only try and increase [or decrease] by x amount ... gradually, to compensate' (interview, technical engineer, February 2022). In short, the climate control configuration creates a highly bespoke climate inside (see Figure 3) for sensitive plants that it would not be possible to grow outside in Kew's immediate environment, yet how this artificial climate is created depends on the sometimes rapidly changing weather conditions immediately outside, thereby producing a specific dynamic indoor–outdoor climate hybrid.

6.2 | The permanent maintenance of climate

The engineers have to be present and responsive to deal with any system failure or dysfunction because the consequences for the plants can be catastrophic: 'If the glasshouse fails and it's not controlling the environment, it just changes like that. If the heating suddenly stops ... Likewise, the ventilation, within 15 minutes the temperatures are rocketing. If the shading system fails, within 15 minutes, you scorch your plants' (interview, technical engineer, February 2022). Everything is monitored in the nursery facilities and alarms indicating problems are linked to Kew's own constabulary—effectively, a 'climate police'—who contact the engineers who either go and source the problem on site during the day or if necessary dial into the systems remotely at night. There are three levels of emergency call out: 'immediately, two hours, six hours' (interview, technical engineer, February 2022). The sheer quantity and complexity of the systems mean that glitches are not uncommon:

> Now equipment failure on a site like this where you've got hundreds of motors, hundreds of pumps, hundreds of sensors, you only need 1% failure and you're having a call out every day. It sounds a lot, but when you up the volume of equipment, you will get anything.
>
> (Interview, technical engineer, February 2022)

Back-up generators are present too for electricity supply, providing 'several weeks' of power for all essential equipment.[5] The resource intensity involved in configuring the spaces is high, representing a significant proportion of Kew's energy costs (interview, glasshouse manager, September 2019). Even in a non-emergency situation, the engineers stress the difficulty of maintaining these environments: 'It is very much a hostile environment … if you think the temperatures under the glass, the touch temperature can be 50 degrees, it can be really hostile' (interview, technical engineer, February 2022). The maintenance of these environments is thus always ongoing, and is indeed a part of the daily routines of the engineers who will start their day with visual inspections in all the glasshouses and nursery zones of vents, valves, pumps, motors, etc., all recorded on planned maintenance sheets. Furthermore, the horticultural staff can report something necessitating what the engineers call 'reactive maintenance'. They can also be called out for movement or reconfiguration of technical system components as Kew's horticulturists move plants around, bring new plants in, or decide on new arrangements in a particular zone. In short, climate control here is the result of shifting interactions between engineers, horticulturists, the controlled environment, and the plants themselves. The constant monitoring and regular maintenance interventions of this mode of climate control are a means of dealing with the inherent difficulties of managing interior climates. These spaces are not perfect, optimised environments but compromised precision enclosures—yet the importance of these highly technicised spaces for global plant conservation is revealing of the urgency for renewed biodiversity management strategies: 'the realisation that perhaps things can't always be conserved for the long term where they're growing now' (interview, conservation specialist, December 2021).

In summary, the 21 climate zones, combined with global networks of botanic exchange, constitute an infrastructural nature that exists nowhere else in the world. The nursery managers aim for 'collections diversity', with at least one example of everything at genus level (interview, September 2019). It thus constitutes a unique ark where Kew's horticulturists cultivate and care for species that may be fundamental to future life on earth but may no longer exist in the wild. There are at least two examples of plants—a Rwandan waterlily and the Café Marron plant endemic to Rodrigues Island in the Indian Ocean—that became extinct or near extinct in their original habitats and were revived ex-situ at Kew from propagules by 'replicating' conditions and working out how to make the plants flourish again and capable of being reintroduced in their home environments (interview, conservation specialist, February 2022). This is arguably no longer a question of in-situ—ex-situ relations, but an utterly hybridised conservation environment that seeks to actively and strategically manage and protect species populations through a range of techniques, including a seed repository, growth in digitised precise conditions in Kew's nurseries, exchange with other sites, and reintroduction into managed native environments (interview, conservation specialist, February 2022). Species metapopulations are interconnected across these different sites, creating a hybrid relational space in which in-situ and ex-situ can no longer be meaningfully distinguished. Climate control techniques and practices are a crucial component to allow this 'nature' to be constituted, developed, and circulated. Increasing knowledge of 'exceptional species' that cannot be readily conserved as seed reinforces the importance of the nursery living collections (interview, conservation specialist, February 2022; see Pence et al., 2022). Thus, the development of climate control in glasshouses and nurseries at Kew has fundamentally supported and reinforced the shifting rationales and purposes of its botanic collection and conservation work, and now places Kew at the heart of a planetary infrastructuralised 'botanical metropolis of the world', the continued existence and reproduction of which has existential implications for life itself.

7 | CONCLUSION: STRATEGIC CONSERVATION WITHOUT NATURAL CLIMATE

The Kew case study of one of the most botanically diverse areas of the planet has shown the importance of foregrounding the socio-technical processes and modes of climate control to understand the shifting geographical relations, practices, and implications of plant collection/conservation in ex-situ environments. This geohistorical analysis of climate-controlled conservation has revealed that its modes and significance have evolved over time and increased in strategic importance. Constructing three distinctive modes of climate control across Kew's enclosures—see summary in Table 1—allows us to demonstrate the dynamic and historically constituted importance of climate management technologies for sustaining threatened plants. These modes are not mutually exclusive, with the same species often present in the glasshouses as

TABLE 1 Shifting geographical rationales and technological modes of climate-controlled conservation at Kew.

Modes of climate-controlled conservation	Acclimatisation	Climate simulation	Climate security
	Extractive	Experiential	Secure
Main purpose of climate-controlled enclosures	Plant physiological adaptation	Simulating climate/environments of the plants	Conservation without natural climate—transcending biogeographical limits
Primary elements in climate control	*Rudimentary control* • Glass (light) and temperature management • Little spatial volumetric management	*Advanced control* • Temperature, light, humidity, ventilation through early digital/automation • Spatial volumetric management (10 zones)	*Precision control* • 'Endless parameters', digitised, fail-safe • Bespoke volumetric management (21 zones) • Labour and resource intensive
Relational geographies of conservation	Bringing the world *to* Kew In-situ nature as *resource* for ex-situ sites (dichotomous relation and management)	Experiencing the world *in* Kew Ex-situ *replicates* in-situ (blurring of relation but still dualism)	Saving the world *through* Kew Ex-situ *becomes* in-situ? (hybrid, continuum)
	Shift from climate control as *separate* from nature to climate control as *constitutive* of nature		

well as in the private nursery and as seed in the seed bank—'it's not one or the other' (interview, conservation specialist, December 2021). It has also allowed us to pinpoint the strategic importance of the depth, intensity, and precision of volumetric climate control that is now sought to enable propagation and conservation of often highly threatened species at Kew.

Climate-controlled conservation is here a situated socio-technical process comprising close-hand monitoring and maintenance of ambient conditions. It is striking the amount of work involved in constantly adjusting climate control systems so that routines and cadences of light, temperature, ventilation, humidity, etc., are configured for diurnal rhythms of plant 'comfort'. Overcoming the limits of outdoor climate, this interior climate management takes its lead partially from exterior conditions. This process is more complex, precise, and hands-on than the 'standardised comfort zones' of air-conditioned humans and even the 'stable atmospheres' of other more-than-human interior environments. The need for the engineers to be always present and undertaking constant maintenance underscores the vulnerability of these controlled environments. For all the digital and automated components, threatened plants are clearly fragile, lively, and recalcitrant entities, and demand this sustained engagement and effort to create 'natural situations' for their conservation in a context outside their 'natural' habitats. Of course, climate-controlled conservation is troubling for this dependence on fragile configurations and artificial climate enclosures that represent a 'delocalised' conservation response that does not seek to deal with the underlying systemic processes that led to threatened in-situ ecologies in the first place. Furthermore, through the resource use involved in developing its technological capacities, climate control is contributing to reinforcing those processes.

The contribution of the study is then to establish climate control to be a set of techniques that matters geographically because it has: (i) enabled a displacement of plants from their natural range (taking plants 'out of context'), spatially extending where botanic assets are located and (ii) facilitated the movement and reworking of climates in creating new artificial conditions in which plants can thrive outside of their original environments. Climate-controlled conservation practices therefore involve a quite fundamental transcendence of nature and natural climate, with the development of a spatial and technological capacity to move and maintain biological assets that are fundamental to all life across what would otherwise be quite incommensurate geographical contexts. Basic processes of local climate and botany can be revised or recombined to create enclosed environments in which threatened plants can be propagated. This marks a shift over time from climate control as *separate* from nature—with early glasshouses as simple heated enclosures for plant acclimatisation—to climate control now as actually *constitutive* of nature, in terms of creating the life-supporting environmental conditions for plant growth. Without climate control, it would be impossible for Kew to house, nurture, and grow certain plants—whether a rare hibiscus from Reunion or aloes from South Africa—some of which now only actually exist at Kew. Under acclimatisation and climate simulation modes, plants could be replaced if there were problems or system failures, but the climate security mode signifies that climate control is fundamental to sustaining plant life and any failure could be catastrophic for the species. The significance of climate-controlled conservation, as technologically mediated conservation without natural climate (cf. Braverman, 2014), is that it is now not just a display window on to exotic natures of elsewheres, but that it transforms Kew's nurseries into the actual sites, in some cases the last remaining sites, of these natures. 'The botanical metropolis of the world' now signifies not only a spatial redistribution of plants in cities in the North, but how an urban ex-situ environment has come to replace (or constitute) in-situ nature for a world ravaged by climate and ecosystem transformation.

In a climate-changed world, the capacity to control climate, to sever the connection between local climate and the milieux necessary for the reproduction of life, becomes crucial. This capacity remakes environments that are held to be optimised and secure, in contrast to increasingly imperfect and turbulent local 'natural' climates. Climate control thus fundamentally reconfigures existing spatial patterns and organisations of life. Climate-controlled humans and nonhumans are able to occupy and circulate between places where they would not otherwise survive or thrive if dependent on natural climate, thereby fundamentally remaking global geographies of settlement and movement. In terms of further research, it will be essential, therefore, to continue to investigate how climate control constitutes a set of techniques that allow living beings, whether plants, animals, humans, or microbes, to be disconnected from their natural habitats, through the creation of life-sustaining secure and productive artificial environments within which they can exist and reproduce 'out of context'. Geographers will also need to remain attentive to the uneven spatial distributions, capacities, and outcomes of climate-controlled conservation for global species management. A key question will be whether climate-controlled conservation is about securing an enlarged view of the global commons that encompasses a continuum of spaces and species, or a new intensified imperial mission of gathering and concentrating valued species in the 'botanical metropolises' of the north.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Jonathan Rutherford https://orcid.org/0000-0001-5779-3185
Simon Marvin https://orcid.org/0000-0001-5538-5102

ENDNOTES

[1] In-situ conservation means 'the conservation of ecosystems and natural habitats and the maintenance and recovery of viable populations of species in their natural surroundings and, in the case of domesticated or cultivated species, in the surroundings where they have developed their distinctive properties'. Ex-situ conservation means 'the conservation of components of biological diversity outside their natural habitats' (Source: CBD—Convention on Biological Diversity, Article 2, https://www.cbd.int/convention/).

[2] Kew has been closely involved in both the International Union for Conservation of Nature and Natural Resources (IUCN) set up in the 1950s and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) which came into force in the 1970s.

[3] 'In total, around 872 taxa in the Living Collections are categorised as threatened on the International Union for the Conservation of Nature (IUCN) Red List of Threatened Species (334 Vulnerable, 334 Endangered, 191 Critically Endangered and 13 Extinct in the Wild)' (Kew Gardens, 2019, p. 14).

[4] 800 watts/square metre of solar irradiance.

[5] Recent work on disaster management planning for botanic gardens is more widely indicative of this emerging security rationale (see Gratzfeld et al., 2021).

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