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Microclimates of Urban Reproduction: The Limits of Automating Environmental Control

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Abstract: Enclosed, controlled environments, stretching from sites of luxury consumption to urban food production, are proliferating in cities around the world, utilising increasingly advanced techniques for (re)creating and optimising microclimatic conditions for different purposes. However, the role of automated control systems—to filter, reprocess and reassemble atmospheric and metabolic flows with growing precision—remains under-researched. In this article, we explore the phenomenon of automated environmental control at three sites in the UK city of Sheffield: a botanical glasshouse, a luxury hotel and a university plant growth research lab. In doing so, we first show how controlled environments are constituted through specific relations between the inside and outside, which are embedded in inherently political urban contexts and processes. Second, we identify the technical and ecological tensions and limits of indoor environmental control at each site which limit the scope of automation, and the considerable amount of hidden labour and energy required to maintain and restabilise desired conditions. Drawing on these more established examples of ecological interiorisation in a key moment of transition, we raise urgent questions for critical urban and environmental geographers about the possible futures of controlled environments, their practical or selective scalability, and who and what will be left “outside”, when they are emerging as a strategic form of urban adaptation and immunisation in the face of converging ecological pressures.

Keywords: automation, automated environmental control, controlled environments, enclosure, indoor environments, urban political ecology

Introduction

In May 2017, following the hottest year on record, the Svalbard Global Seed Vault was flooded by melting permafrost (Carrington 2017). Located on the Norwegian island of Spitsbergen in the Arctic, the site was opened in 2008 as a fail-safe storage facility to protect the world’s most important seed varieties in the event of natural or human-made disasters. In such circumstances, governments are able to request seeds from the bank of nearly one million samples, which are kept safe at a temperature of -18°C . This controlled environment is meant to be able to operate without human oversight. However, after unanticipated amounts of water ingress caused by the extraordinary warmth threatened the integrity of the vault, significant intervention was required to secure the inside from an increasingly unpredictable outside. This included 24-hour surveillance of the vault, before a \$13m upgrade began to construct a new concrete access tunnel, and a

service building housing emergency power and refrigeration units (Ong 2018). As global temperatures rise, safeguarding the food security in the vault requires ever more intensive socio-technical contingencies to be built in.

The unsettling story of the Svalbard Seed Vault is symbolic of the challenges and contradictions of efforts to create protective, controlled environments as sites of socio-ecological and economic reproduction in an era of climate change and ecological turbulence. Experimentation with technologically advanced controlled environments, which apply techniques of automated microclimatic control in enclosed spaces to create artificial conditions for various purposes, are becoming increasingly common across a range of societal and urban domains. Examples include controlled environment agriculture, scientific research laboratories, touristic indoor ski slopes and tropical islands, and urban eco-domes maintaining environmental conditions for species across the world to be displayed all year round (Marvin and Rutherford 2018). As well as these spectacular cases, more mundane forms of environmental control are proliferating. Air-conditioning for instance has a long history from the factory to the shopping mall, designed to create and maintain optimum conditions for production and consumption (Cooper 2002). Today, air-conditioning is becoming near-ubiquitous in certain urban contexts, and is being stretched beyond individual buildings into the wider outdoor environment (Healy 2008; Hitchings and Lee 2008; Moore 2018). There is, it appears, a growing systemic and infrastructural logic and imperative to the assemblage of the techno-scientific capacities of controlled environments, as a strategic form of urban adaptation and immunisation in the face of increasingly unpredictable ecologies.

This article is orientated by these issues, while expanding the scope of inquiry to encompass a relatively neglected area of research on controlled environments: automation. As an extensive but disparate literature has documented, recreating the outdoors indoors is wrought with problems, uncertainties and idiosyncrasies (Day Biehler and Simon 2011). Nature is difficult to control and simulate, and, as the Svalbard Vault exemplifies, stopping the outside from getting inside is never straightforward. In response, the use of advanced automation is playing an ever greater role in extravagant claims about the potential of controlled environments to overcome natural limits. Yet, automation has its own limits and contradictions, and as the socio-ecological stakes get higher, the promissory intersection of automation and environmental control warrants greater attention from critical urban and environmental geographers alike. Are the claims surrounding controlled environments realistic, and at what scale? How selectively will they be used, and who or what will be left outside? What will be the social and environmental costs of those politically mediated choices, and what alternatives might be foreclosed as a consequence?

Though orientated by these questions, this article is more modest. It examines the phenomenon of automated environmental control through several more established and mundane examples in the UK city of Sheffield. These three cases offer quite different logics of microclimatic control and levels of sophistication. They include a temperate glasshouse which operates as a spectacular indoor public garden, an upmarket four-star hotel for businesspeople and wealthy visitors to

the city, and a university plant growth research facility focusing on food security and the effects of climate change. Fieldwork was carried out between late 2016 and early 2018. Empirical material was gathered through documentary material (including architectural designs, presentations to local governments, control system brochures, user guides, specialist articles, personal diaries and pictures); guided tours with question and answer sessions at each site as part of a larger group of researchers; one or two subsequent visits to each case study for observation; as well as semi-structured interviews with seven key workers, designers, users, consultants and technicians at each site.¹ Through comparative analysis, three major themes emerge, which are crosscut by relational ambiguities and porous boundaries between the inside and outside. The first relates to spatial context, and the ways controlled environments are embedded and co-constituted by the (urban) outside. The second points to contradictions of simplifying non-human natures for the indoors, and the limits of automating ecological processes. The third uncovers the hidden yet vital role of human labour and other inputs in reproducing the conditions of interior climatic stability. In doing so, we provide the contours of a useful analytical framework for more ambitious future research and debate on automated environmental control.

The structure of the article is as follows. First, we review existing literature on controlled environments and their history, and relevant work in urban political ecology, identifying emerging themes and gaps, including the neglected role of automated control systems. Second, the article moves on to the empirical material, in which the three case studies are situated locally and historically in Sheffield's post-industrial landscape, showing how they were shaped and assembled according to particular urban priorities and imperatives of urban regeneration in the 1990s and 2000s. Third, it provides a comparative analysis of the production of the three interior environments for those purposes. This part of the article examines the different logics, potentials, limits and elisions at play in automated environmental control, identifying the kinds of non-human and human interventions needed to create and stabilise the bespoke interiorised microclimates desired. Fourth, we reflect on the empirical analysis and highlight the importance of the outside context of urban accumulation and reproduction imperatives in shaping the inside, how automated systems are mobilised to filter, reprocess or simulate good and bad flows, and the difficulties faced in maintaining stable indoor environments. The conclusion discusses the implications for the article for critical geographers and future research, as ever more complex indoor environmental controls are applied and experimented with, and used to modulate the outdoor urban climate in an era of growing socio-ecological turbulence.

Political Ecologies of Controlled Environments

Contemporary visions of advanced environmental control often represent some of the most techno-utopian imaginaries for overcoming capitalism's ecological contradictions. The promise is often of opening new frontiers, transcending spatial context and making new territories legible for novel forms of intensive and extensive intervention. At their more extreme they include major geoengineering

projects and more fanciful dreams of extra-planetary colonisation and resource extraction (Buck 2012; Höhler 2017; Surprise 2018; Valentine 2012). At smaller scales, the use of digital techniques for environmental and infrastructural control is becoming increasingly common (e.g. Adams 2019; Klauser 2018; Luque-Ayala and Marvin 2016). Capital's reproductive drive to control, manipulate and produce environmental conditions for its own survival is of course nothing new (Moore 2015). However, in an era of growing planetary turbulence and receding frontiers, the increasingly intensive and technologically mediated interiorisation of these processes appears to be a novel and under-researched facet of political ecology. Urban political ecology has long studied how the uneven development of space—and all its associated injustices and inequalities, exclusions and oppressions—is inextricably tied up with the urbanisation of nature (e.g. Doshi 2017; Heynen et al. 2006; Kaika 2005; Tornaghi 2017; Truelove 2011). Despite the field's sprawling scope though, there has been remarkably little attention paid to indoor urban environments, leaving a critical gap in the field with respect to the multiplicity of ecological contexts where people spend most of their time.

In a rare piece of synthesis of work on the indoors as active political ecological spaces, Day Biehler and Simon draw attention to these spaces as “vital sites for the production and reproduction of nature, scale, and environmental citizens” (2011:174). They review work which shines light on the uneven production of indoor environments (Buzar 2007; Crabtree 2006), and how they become sites of embodiment of broader ideologies and processes (Murphy 2006; Van Wagner 2008). They also highlight literature focusing on the co-constitution of indoor space by specific socio-technological-ecological assemblages, through which technologies and natures are animated and generate different effects and affects (Hitchings and Lee 2008; Shove 2003), and studies examining how indoor environments are made (but frequently contested) spaces of surveillance, control and subject formation (Luke 1997; Weber 2002). Finally, they bring together scholarship which unsettles the supposedly strict boundaries often constructed between the inside and outside, by exploring instances of intentional or transgressive bio-physical flows, and by deconstructing the ways interior environments are often discursively distanced from their social, ecological and spatial contexts (Day Biehler 2009; Hitchings 2007; Moran 2008). While this work is rich and valuable, our interest in controlled environments here focuses on their strategic function (in attempting) to ensure continued economic and social reproduction in a context of ecological limits and turbulence, and the kinds of socio-technical systems and forms of control for the creation and regulation of artificial environments.

For our purposes, controlled environments are “enclosed and engineered socio-technical spaces that create specialised ‘microclimates’” which have become “part of a wider systemic concern for configuring socio-technical-ecological conditions through which selected aspects of urban life can be maintained, reproduced and improved” (Marvin and Rutherford 2018:1144, 1146). Their development can be traced to the horticultural sciences, Cold War technoscience and space exploration, and other lab-based disciplines, which aimed to engineer enclosed bio-physical processes and circuits capable of producing optimised microclimatic conditions for different human purposes in inhospitable environments (e.g.

Albright et al. 2001; Anker 2005; Farish 2006; Jull and Cho 2013; Luke 2000; Mennel 2004; Valen 2016; Weber 2006). Efforts to provide “perfect weather” indoors for both production and consumption were vital to the historical development of capitalism. While Victorian-era glasshouses which displayed exotic plants from distant lands were symbols of colonial power and expansion (Preston 1999), the origins of air-conditioning lie in the factory, where, as Cooper (2002) graphically illustrates, technologically mediated manipulation of heat, cooling humidity and the quality of air were fundamental to establishing efficient, reliable and year-round industrial production. Engineers worked to address the problem of variability in the performance of weather sensitive materials by replacing local climate with technical systems of “manufactured weather” (Cooper 2002:44), which became increasingly standardised and prevalent in many industrial settings from the early 19th century. As with broader processes of enclosure, the logic of controlling and reconfiguring indoor space for the purposes of productivity and profit was central (see also Goldstein 2013; Jeffrey et al. 2012; Wood 2002). Similar techniques were deployed in other contexts, such as in cinemas, where air-conditioning enabled the industry to “create an indoor climate superior to the outdoors” (Cooper 2002:108) as it sought to overcome the problem of declining audiences in the summer heat. As controlled environments progressed, the development of digital control and building management systems became central to the capacity to maintain complex environments and reduce the need for direct human intervention. During the 1960s many of the early developments in environmental control systems were developed in the space programme and applied on Earth (e.g. Marvin and Hodson 2016). The Climatron in St Louis, Missouri was for instance the first attempt to constitute climate control to replicate four global ecosystems in a domic environment (see Mumford 2010). Nevertheless, most of these early applications struggled to achieve the claims made for them, and were beset by technical failures, complex feedbacks and unruly human and non-human flows (e.g. Luke 1995).

More recent work considers the urban and infrastructural qualities of controlled environments (Marvin and Rutherford 2018; McNeill 2019), which are becoming more prominent as urban imperatives of maintaining control and building resilience to social, economic and ecological turbulence grow (e.g. Hodson and Marvin 2009; Jonas et al. 2011). Hitchings and Lee’s (2008) concept of “routine human encasement” in Singapore is particularly useful for considering the infrastructural requirements related to the increasingly entrenched and culturally mediated expectations of everyday thermal comfort. Others have showed how numerous emerging forms of social and material encapsulation are deeply tied up with logics of elite securitisation, expressing and reproducing profound spatial inequalities and injustices (Atkinson 2016; De Cauter 2005; Mitchell 2005). McNeill (2019) meanwhile demonstrates the important links between “atmospheric engineering” and “indoor accumulation” in modern cities (see also Gissen 2014). Also focusing on Singapore, he explains how “the provision of ‘scaled’ thermal comfort through district cooling schemes and ‘green’ building techniques has been key in the ability to produce comfortable, hence profitable, hybrids of public and private space” (McNeill 2019:13). Among domains of urban

production, advances in controlled environment agriculture (CEA) represent some of the most ambitious attempts to transcend local context, using highly complex and automated socio-technical systems to artificially replicate and optimise growing conditions for perpetual production. Claims of ever-more sophisticated automation play an increasingly prominent role in the discourse surrounding controlled environments. Though this area has not been studied in detail, other relevant literature suggests that computational power, which promises simpler and more effective solutions, is paradoxically a growing source of complexity, opacity and concentration of power, and often creates more work for operators than it takes away (e.g. Bainbridge 1983; Bridle 2018). Despite sector growth and extravagant claims regarding productivity and efficiency, CEA's economic and technical viability beyond small niches remains unproven (Goodman and Minner 2019).

Taken together, this literature offers a more precise analytical framework for examining our selected controlled environments in Sheffield. This consists of two basic elements. First, drawing on work at the intersection of urban political ecology and studies of indoor environments, the three case studies are understood as politically mediated spaces, embedded within broader social processes and uneven production of nature. Controlled environments seek to create improved ecologies inside, which are necessarily constructed in relation to certain problems, risks or inadequacies of the outside. Unpacking how that relation is constituted, what is valued and what is left "outside", is therefore crucial. One task then is to situate controlled environments within their particular urban geographies, and examine how they are shaped by (and reshape) the constraints and limits of spatial context, including political and economic factors. The second component of analysis focuses on the extent to which the technological systems required to produce a controlled environment—the assemblage of control systems, heating, lighting, humidity control, air filtration, watering and so on—may be constituted as a new urban infrastructure that is stabilised, hidden (until breakdown) and increasingly standardised. Given the claims surrounding controlled environments, it is important to identify the contestations and instabilities that may limit efforts to enclose, control and maintain interior ecologies through technological means. In particular, we explore the role of automated control systems within these socio-technological-ecological assemblages, and their relationships with human labour. Each of these questions is explored in further detail below.

Controlled Environments: Microclimates for Investment in Post-Industrial Sheffield

Sheffield is a mid-sized city in South Yorkshire in the north of England. During the industrial revolution it became the world's largest producer of steel. By the 1970s, over 40% of Sheffield's workforce of 300,000 was directly accounted for by this industry (Crouch and Scott Hill 2004; Winkler 2007). The city was hit particularly badly by the economic crisis which began in the 1970s and the period of neoliberal restructuring that followed (see Brenner and Theodore 2002; Jones and Ward 2002). It lost 70,000 manufacturing jobs between 1978 and 1987, with unemployment peaking at 18% in 1983/84, well above the national average (Crouch

and Scott Hill 2004; Strange 1997). While the local Labour Party's initial response to the crisis and election of Margaret Thatcher's Conservative government in 1979 was to develop a radical programme of interventionist municipal socialism, this strategy was ultimately abandoned (see also Quilley 2000). With harsh disciplinary measures stymying the council's financial abilities to keep pace with the scale of manufacturing decline, the council reluctantly shifted its approach in 1986, adopting a more "entrepreneurial" model of urban development (Booth 2005; Crouch and Scott Hill 2004; Rousseau 2009; Seyd 1990; Winkler 2007).

In this transitional phase, the city council increasingly embraced the role of public-private partnerships for urban regeneration, in order to compete for access to funding streams at different scales. However, this was far from an unbridled success. Major redevelopment of the Don Valley region had mixed results. The out-of-town shopping centre of Meadowhall took more business from the depressed city centre, while the hosting of the World Student Games proved too niche to generate the anticipated private investment, putting the city council into serious financial difficulties as another economic slump hit the UK in the early 1990s (Booth 2005; Dabinett and Ramsden 1999; Winkler 2007). By the mid-1990s it appeared to be paying off, though the social consequences were distinctly uneven and often exclusionary. Under the auspices of the newly formed City Liaison Group (later Sheffield First Partnership), urban leaders succeeded in accessing national and European funds for various high-profile projects (Booth 2005; Winkler 2007). By the time New Labour came to power in 1997 and instigated the so-called "Urban Renaissance" (Imrie and Raco 2003; see also Fuller and Geddes 2008), Sheffield's leaders were already working towards a blueprint of urban renewal, spearheaded by city centre redevelopment of commercial space and high-end flats, investment in cultural assets and creative industries, and a growing role for the two universities (Dabinett 2004; Madanipour et al. 2018; Rousseau 2009). It was into this urban context that the three case studies below were conceived and developed between 1995 and 2005, all completed around the time of New Labour's third and final election win at the national level.

Sheffield Winter Garden opened in 2003 as a temperate glasshouse with a large non-native horticultural collection of over 2500 plants for public display, owned and managed by the city council. The privately owned Mercure Hotel erected next door was completed in 2005. It provided four-star accommodation, together with conference facilities, a spa and swimming pool, and an enclosed glass atrium with restaurants and champagne bar looking into the Winter Garden. Both were built as part of a city centre regeneration project called Heart of the City. Conceived in 1994, the scheme was envisaged as part of a wider strategy to revitalise the city centre to deliver economic growth and jobs through inward investment (Sheffield One 2007). Heart of the City itself was a master-planned mixed-use redevelopment scheme, including new civic and cultural facilities, aimed at attracting private capital to develop high quality office space, a hotel, premium apartments, restaurants and retail (Evans et al. 2007). As one regeneration officer explained:

The biggest driving force of all was to say if we make this environment sufficiently good—and remember how awfully crap it was, the Peace Gardens was just a place for

drunks and dossers; it was not a nice place at all ... [Our plan was] classic regeneration theory: make it attractive, put public space in, raise land values, raise rental values. Whilst you're doing that, it has ripple effects throughout the city centre. (Interview 1)

Heart of the City was seen as part of an urban agenda to address the city centre's problems of urban blight and depressed economic activity, designed to generate "confidence" among politicians, the public, investors and government (Sheffield One 2007).

In addition, the council saw an opportunity in the area, where it owned several assets in the form of land and buildings. One of these, an unpopular municipal building known as the "Egg Box", had effectively been condemned as a "sick building" (see e.g. Murphy 2006), and needed at least £10m to address problems with environmental health and its control systems (Interview 1). Instead, the council decided to demolish the building and use the land for redevelopment, and replaced the lost office space on another site with the country's first Private Finance Initiative scheme, Howden House (Topley 2011; on PFI, see e.g. Hodgkinson 2011). Heart of the City was also shaped in response to the establishment of the Millennium Commission in 1993, set up to administer a pot of public money open for competitive bids, available for nationally important civic projects which could aid urban regeneration (Holmes and Beebejaun 2007; see also McNeill and Tewdwr-Jones 2003). Successfully accessing this public funding stream was vital for the entire project (Topley 2011). Under the extreme budgetary constraints faced at the time the council's political leaders, though desperate to attract private capital, would only support a scheme which would end up neutral on the city's accounts. Though this made for a particularly difficult sell, the council were able to win £22m from the Millennium Commission, alongside £4m apiece from the European Regional Development Fund and Yorkshire First/English Partnerships (Sheffield One 2007).

This public money was mostly used to build the Sheffield Winter Garden and Millennium Gallery next door. The Winter Garden was designed to be a piece of iconic architecture and glasshouse, to house a spectacular collection of overseas plants from temperate climates, and simultaneously act as a walkway and high quality indoor public realm for use by city centre workers, visitors and shoppers, hosting various civic events and exhibitions, pop-up shops and containing a small café. Together with the new "receiving" art gallery, this signalled significant public investment in new cultural assets, as an offering to the "creative", middle and investment classes the city hoped to attract and retain, which had become a core of the overall regeneration strategy (Holmes and Beebejaun 2007; Madanipour et al. 2018; Rousseau 2009). The Mercure (originally Macdonald) Hotel meanwhile, constructed on the other side of the Winter Garden, involved privatising a portion of council-owned land, which was viewed as essential to financing the whole project (see also Christophers 2018). Equally important, however, was the role it fulfilled as a kind of development seen as necessary for urban regeneration, which the city centre was missing and had previously failed to attract: a luxury four- or five-star hotel for businesspeople, investors and other wealthy visitors, and which would raise standards in the hotel and conference markets (Evans et al. 2007).

The Sir David Read Controlled Environment Facility is a scientific research laboratory based at the University of Sheffield. One of the largest of its kind, the facility contains over 50 advanced plant growth chambers and cabinets of varying types, designed to simulate a wide range of climatic scenarios. Opened in 2004, the facility was housed by the Department of Animal and Plant Sciences (APS), and the recipient of £10.5m funding from the Joint Infrastructure Fund (JRF). This £700m pot of money came from public funds, the Wellcome Trust and UK research councils. It was made available by the New Labour government in 1999, and administered by the Office of Science and Technology. The JRF was open for large-scale competitive bids, and was intended for investment in high-tech research equipment and infrastructure (House of Commons Science and Technology Select Committee 1998, 2002). It aimed to revitalise the university sector in response to a perceived crisis of research capacity and international competitiveness, which would negatively affect the sector's ability to access research funding, and attract and retain academic talent and students from abroad. The David Read Facility (DRF) was less of an explicitly urban initiative than the Winter Garden or hotel. It primarily reflected a shift in investment priorities at a national level, where the university sector was viewed as a strategic asset in the global economy, while APS's successful bid positioned the value of such a facility in relation to the growing consciousness of the interconnected global challenges of climate change—specifically regarding agricultural crops, food security, global warming and rising atmospheric CO₂ (Interview 5). Nevertheless, despite the minimal strategic role played by local council, there was a clear urban dimension to this development, embedded within a wider process of economic restructuring and rescaling. Even if the JRF was primarily seen as an opportunity for APS and the university, this was a period when the universities' influence in the city was growing, as investment in the *local* knowledge economy became seen as an increasingly important source of post-industrial, urban competitiveness (see e.g. Addie 2017).

New Urban Atmospheres: Three Controlled Environments

At each site, the constitution and control of a particular interior environment was crucial in enabling certain urban objectives or imperatives to be met. In the case of the Winter Garden, the creation of an indoor space was initially proffered a solution to the lack of decent quality public realm in the city centre. Initially, it was Sheffield's often inhospitable outside environment which drove the decision to build an enclosed space:

In Sheffield it tends to rain. It gets a bit cold and windy. If we've got all this public space, why don't we do a public space, but cover it? Let's modify the environment, so when it is raining, you can go in there and eat your sandwiches! Treat it as a public square. (Interview 1)

The idea for a glasshouse, as an iconic piece of architecture which would offer an aesthetic sense of wonder, interest and educational value for the general public (Browell and Wareham 2005; Ellis 2003), emerged later, spurred by the

competitive nature of accessing Millennium Commission funding. At the same time, the Winter Garden was dressed up in the language of sustainability, not only in terms of the ecology inside, but the low-impact materials it was built with, and the minimal energy inputs required to maintain it (Hennessy and Harris 2004). While this was certainly an expedient narrative, the parameters were really set by cost. It was this that informed the decision for a *winter* garden: an ecology of plant species from temperate regions of the world which would survive a minimally heated environment. To achieve the right kind of atmosphere, the Winter Garden's environmental control has to keep the balance of a stable interior microclimate for people and plants, which is not too hot, wet, hazardous or untidy, while visible upkeep is minimised, to avoid the sense of public extravagance in a context of wider urban austerity (Interview 3). While the most public and open of the three case studies, visitors themselves are subject to a degree of visible surveillance and control. At least one "city centre ambassador" employed by the council is always on site, whose remit includes supporting law enforcement in reducing anti-social behaviour and maintaining the cleanliness of the urban environment.²

Inside the Mercure Hotel, environmental controls followed something of a different logic. The ambience of the hotel was designed to be one of enclosed luxury for wealthy guests. As the building manager described it: "It's like a cocoon ... [The guests are looking for] peace and tranquillity. They like good quality" (Interview 4). The hotel's environment is one that is deliberately insulated from the cold, wet, dirty and noisy outdoors, constituted as an exclusive private space.³ Though there is a green narrative of circularity present, with respect to energy use, waste recycling, and recapturing of heat from the air conditioning systems, these are primarily profit-driven (Interview 4). The environmental control systems operate to add premium value to the enclosed atmosphere. They do this through processes of filtering, reprocessing, heating or cooling flows of air and water from the outside for guests' comfort. Environmental control is also partly necessary for the building to meet a range of regulatory standards and license requirements, while the comprehensive filtering of the city centre air helps reduce the risk of technical failures of the air conditioning system. Yet the complete ensemble of capacities created are mobilised to maintain an enhanced indoor environment, which provides a warm, safe, comfortable and calm retreat for the hotel's guests from the city outside.

In the final case study, the investment in state-of-the-art controlled environment technologies was central to establishing a new scientific research niche at the university. The DRF created an experimental space for expert knowledge production. Conviron controlled environment chambers⁴ were installed primarily for the cultivation of plants over relatively short timeframes. The ability to precisely isolate, control, maintain and accurately repeat and monitor conditions is critical. It allows researchers to conduct experiments which would be impossible in the field, due to uncontrollable nature of outdoor conditions, while at the same time enabling the simulation of microclimates in distant and extreme geographies, as well as past, present and possible future environmental scenarios, from a single urban location (Interview 6). Rather than simply regulating the flows from the outside, the Conviron chambers afford an enhanced capability to simulate entire artificial

insides which differ considerably from the unamenable outside. In fact, one feature of the indoor capacities of the DRF is that it requires various air and drainage filters and a strict regime of waste management, to stop potential biohazards such as GMOs produced inside from escaping (APS 2017). Unlike the Winter Garden and Mercure Hotel, which maintain and regulate conditions within broad parameters relative to the outside, the assertion here is of being able to transcend local environmental context (Figure 1).

At each site, environmental control has been automated to some degree, programmed through different building management and control systems. These digital control systems are networked with timers and sensors collecting environmental data, measuring the relevant ambient conditions, and act to increase or reduce certain flows as required, by opening or closing valves and vents, activating pumps, fans, heating elements and so on (Table 1). Monitored and operated through a wall panel underground, the Winter Garden's building management system (BMS) is used chiefly to regulate the indoor temperature within broad parameters. The overriding logic of this relatively basic system has been to maintain low-cost environmental control, while minimising the need for human labour. Described as a "semi-intelligent thermostat" by the council's city centre operations manager (Interview 2), it controls a number of automatic windows and vents. Combined with fans and aspirator screens, this also encourages air circulation, dissipation of humidity through evaporative cooling, and even distribution of heat. When the temperature drops below a preprogrammed level, the BMS activates an underfloor heating loop in Sheffield's district heating network, which provides a frost-free function by circulating water heated in a nearby waste incinerator. More recently, an element of automated irrigation has been introduced, saving considerable time against a backdrop of post-2008 austerity and local government cuts, which has seen the city centre horticultural team shrink from seven to just four people.

The Mercure's BMS is operated using software installed on a desktop computer in the building manager's office. From here, the systems which filter, reprocess and circulate air and water via two large plant rooms are programmed, monitored and adjusted. Air and water is filtered and treated, and heated or cooled according to indoor and outdoor temperatures, through various heat exchangers, chillers and air handling units, before being pumped around the hotel and expelled. The level of automation is relatively basic, set up as a series of largely closed systems enabling zone control for the bedrooms, the atrium, conference rooms and spa area. It is intended primarily to provide large-scale and low-cost reprocessing capacity over precision. The BMS is designed simply to circulate warm, fresh and clean conditioned air to the rooms, clean and hot water for the guests, as well as the ability to operate a luxury underground spa and swimming pool. The automation of environmental control in the DRF is the most advanced and complex of the three sites. Microclimatic conditions can be monitored by researchers via digital screens on the outside of each chamber, but overall control is maintained through a networked Argus system. Using this centralised control system, three lab technicians manage over 50 different walk-in and reach-in chambers, and can programme temperature, CO₂ levels, relative humidity, light,

Table 1: Sheffield controlled environments

Controlled environment	Components	Key environmental flows/controls	Purpose
Winter Garden: council-owned “temperate glasshouse”	<ul style="list-style-type: none"> • Singular indoor temperate glasshouse • Semi-intelligent Trend IQ4 building management system • Various air and soil sensors • Automatic windows, vents, fans and aspirator screens • Frost-free underfloor heating connected to municipal district heating network • Partially automated irrigation system 	<ul style="list-style-type: none"> • Temperature (above 4°C) • Humidity and air circulation • Plant irrigation and nutrients • Plant growth and waste • Pests and diseases (e.g. aphids, weevils, caterpillars, fungi) • Human visitors and users 	<ul style="list-style-type: none"> • Iconic urban architecture and indoor attraction • Multifunctional public space and walkway hosting civic events, exhibitions, pop-up shops and café sheltered from outdoor weather • Microclimate to enable year-round horticultural display of 2500 non-native plant species
Mercure Hotel: private “cocoon of peace and tranquillity”	<ul style="list-style-type: none"> • Hotel bedrooms, semi-public atrium with bars and restaurants, conference suite, underground swimming pool and spa (sauna and ice rooms) • Schneider building management system and individual room controls • Large-scale air-conditioning system and water filtration and heating systems connected to district heating network 	<ul style="list-style-type: none"> • Temperature (adjustable but set at 22°C in rooms, 24°C in atrium) • Water (reprocessed and circulated) • Air (reprocessed and circulated) • Waste • Human guests and visitors 	<ul style="list-style-type: none"> • Luxury hotel and conference venue for businesspeople, investors and wealthy visitors • Exclusive and protected premium atmosphere for hotel guests
Sir David Read Controlled Environment Facility: “deserts to arctic inside”	<ul style="list-style-type: none"> • Over 50 Conviron plant growth chambers and cabinets • Energy substation • Networked Argus control system and individual digital monitoring panels • Irrigation systems, lights, CO₂ and humidity systems, fans, pumps, drains, filters, sticky mats, heaters, coolers, sensors, alarms 	<ul style="list-style-type: none"> • Temperature (−20°C–40°C) • Relative humidity • Light (broad spectrum day and night) • CO₂ levels • Water and nutrients • Air circulation • Pests and disease (e.g. aphids) • Biohazards (e.g. GMOs) and waste • Human researchers and visitors 	<ul style="list-style-type: none"> • University facility to enable “world-leading” research on crop growth, food security and climate change • Experimental space for expert scientific knowledge production • Simulation of precise and differentiable environmental conditions for short-term plant growth and monitoring

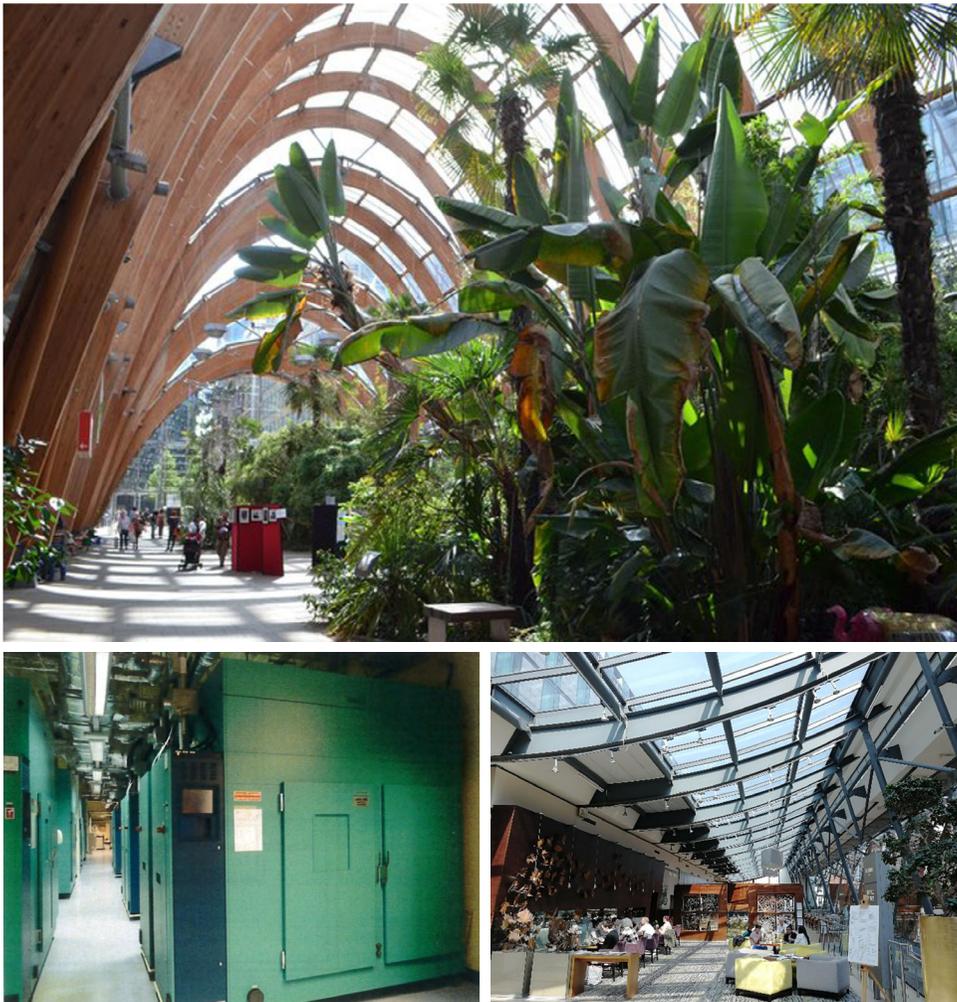


Figure 1: Winter Garden (top); DRF growth chambers (bottom left); Mercure atrium (bottom right) [Colour figure can be viewed at wileyonlinelibrary.com]

watering regimes and so on, while the control of outflows is managed through air and drain filtering systems. The claim made is that this level of automated environmental control, which enables researchers to assemble and modify bespoke microclimates with extreme precision, affords the simulation of practically any environment on the planet, from “tropical plants, sub-arctic plants, past global atmospheric conditions and future growing conditions”.⁵ Newly installed equipment can even be programmed track and simulate real-time climate data from the UK Met Office.

Automated Environmental Control and Its Limits

Despite the various claims attached to the indoor microclimates of each of the three sites, environmental control is far from complete or seamless. Nor is the

automation of key processes underlying it. Problems are encountered by those responsible for oversight. Transgressive and obdurate natures, technological constraints, and other contingent factors routinely necessitate additional inputs and interventions to maintain stable interior conditions, which muddy the boundaries between inside and outside, human and non-human, natural and artificial. In both the Winter Garden and DRF the very nature of an artificially enclosed ecology creates particular challenges for plant growth and health. As the lead landscape architect of the Winter Garden put it: “controlled environments are not good for plants” (Interview 3). Keeping the single-glazed glasshouse cool and comfortable when it heats up during summer has proved more difficult than the risk of cold. The ceiling fans designed to push hot air back down and out of the building were not powerful enough to do so. Lack of weathering in the forms of wind and rain affects root growth, leaving many of the plants soft and weak, and especially susceptible to outbreaks of pests and disease from outside. Caterpillars, aphids and weevils are among the pests that go “absolutely rampant” in the Winter Garden according to the landscape architect, because “there’s no balance in an indoor environment” (Interview 3). Ironically, many of the plants would survive and even thrive outdoors in Sheffield. Yet stopping them from dying or appearing sick has been the overarching priority in the Winter Garden’s interiorised microclimate, designed and organised for aesthetic rather than ecological purposes. This is equally the case in the DRF, where contamination is a frequent problem. Researchers are required to go in regularly to feed, measure and monitor progress of their work, and it is not uncommon for researchers to enter the facility with aphids, sciarid flies or thrips on their clothes from outside, an outbreak of which can destroy entire experiments.

As this highlights, it is often the actions or inactions of humans—always contingent components of these indoor ecologies—which disturbs the smooth functioning of the DRF, be it through a door left open too long, or a forgotten valve. Similarly, in the Mercure Hotel it is the human occupants who tend to disrupt the carefully managed internal climate. The hotel’s necessarily standardised definition of a luxury indoor atmosphere is not always shared, and what constitutes a comfortable temperature is constantly contested by guests from all over the world. The system is not set up to allow for precise control, and complaints about being too hot or cold are frequent. The lack of easy modulation of indoor flows and creation of an environment that pleases everyone leads many guests to try to override the controls in their rooms, for example by manually closing vents, which the building manager explains cumulatively unbalances the air conditioning circuits (Interview 4). Yet even with the most technologically advanced environmental control systems, there are significant limits to (re)creating “real world” microclimates. None of the DRF’s chambers are able to combine all conditions at once, but are designed with respect to specific variables, such as extreme temperature or CO₂ concentration. There are trade-offs related to the size of the chamber and degree of control which is possible. The larger the room, the harder it is to maintain uniformity. Users explained how control of day and night is relatively crude, and the full spectral qualities of natural sunlight are especially hard to mimic (Interviews 5 and 6). Soil and sand are often too heavy for the chambers and

building to handle, meaning plants are grown in vermiculite instead, which in turn constrains possible watering regimes.

At the Mercure Hotel, the building manager frequently sees the need to tinker with the temperature:

22° is supposed to be 22°, but you know it's not. If it's -4 outside, and it's 22 inside it doesn't feel like 22. It *feels* cold. We look at it every day, and we always tend to look a few days in front as well on the weather. We've always got the weather up. See, tomorrow night might drop to -4 or 5. So we have to lift it and give it a couple of degrees. (Interview 4)

This mistrust of the numbers as an accurate indicator of sensuous experience is partly understood to be technologically mediated: "It's just the way the system's been installed and designed really. If you're blowing air around, and moving air always feels draughty, no matter what temperature it is" (Interview 4). For the building manager, the BMS—which replaced an obsolete Siemens model—is overly complex for the hotel's purposes. Consequently, he explains, rewiring circuitry is unnecessarily time-consuming, and when certain parts break and need to be replaced, the hotel is contractually obliged to use expensive proprietary programming software and services provided by the manufacturer.

Technological breakdown is a recurrent problem at each of the sites, particularly the DRF, where researchers push environmental control to extremes:

Our experiments last two or three months, for example, at high light, high humidity, with a watering system. So the cabinet's been absolutely thrashed ... I've had the whole watering system leak, flooding out the [building] ... That has happened before ... The humidity's failed; cabinets have just switched off. (Interview 6)

With so many components and processes, the potential technical issues are endless, as described by one DRF technician:

Any moving parts can fail. Lights fail. Motors fail. Pumps fail. Doors can fall off. It's like servicing a car ... The network and computing side it; that can go wrong. There's the hardware, that can go wrong: the electrics, there's relays, diodes; ... the lighting circuit, the cooling circuit. Essentially anything can go wrong! (Interview 7)

Environmental control at each site remains subject to myriad human, ecological and technical contingencies, which make visible all manner of supportive processes and inputs necessary for the continued reproduction of interior ecologies.

In order to address these many limitations and risks, there are a host of hidden infrastructures and interventions called upon to maintain environmental controls. The controlled environment chambers of the DRF are extremely energy intensive, because of the need to artificially recreate sunlight for plant growth. Consequently, the facility necessitates its own substation, and researchers are obliged to meet overheads in full through external grants. They are also advised to switch day and night in the chambers to reduce costs, since 80% of power consumed during the photoperiod (APS 2017:8). To reduce risks of contamination, entry and exit to the labs includes sticky mats and an airlock which uses negative pressure, designed to suck loose matter off people's clothes into the air filtering

system. Fly traps are used to monitor pests, and if possible infestations are removed with biological controls, such as wasps, Hyposure and Ambsure, so as not to destroy the experiments. In the more permeable Winter Garden, managing pests is more of a matter of routine, with predatory parasitic wasps and nematodes introduced at particular times of year.

These examples point to some of the additional inputs needed to sustain these fragile enclosed ecologies. To minimise the danger of plant death and failure in the Winter Garden, all the specimens were subject to a rigorous selection and two-stage acclimatisation process in greenhouses and nurseries further south. They also needed several years of skilled horticultural aftercare, gradually passed from contractors onto the council. A team of gardeners implement a complex watering regime, and almost continuous process of pruning. According to the operations manager, “just keeping on top of things” is a constant proactive programme of work, and irrigation alone could sustain a full-time gardening job (Interview 2). Large Norfolk Island pines which stand at the centre of the building have had to be strung up with cables, after the trees ended up bending over because of the lack of wind. To offset other effects of the absence of weathering, the gardeners are frequently required to use platforms to get up and clean the plants by hand, to remove build-up of fungi, dust and dirt that present risks of infection, which would normally be washed or blown off. City centre ambassadors patrol the Winter Garden too, keeping the area clean of rubbish and debris, while stopping members of the public from damaging the plants or building. The operations manager at the Winter Garden has resisted involvement of voluntary groups, which he feels would give ground to the idea of the work as non-skilled gardening, and a “dilution of the sector” (Interview 2). Yet the work is already devalued in certain ways by its invisibility, with as much work as possible done outside the long opening hours, including during the night.

In the Mercure, the backroom labour remains hidden in separate parts of the hotel too. Behind the digital interface of the BMS at the building manager’s desk there is a constant, proactive and reactive labour process going on, needed to maintain the environmental control systems, augment its limits and respond to complaints. Some of this is highly skilled and complex work for engineers and electricians, identifying and fixing an array of components from fans to transformers to control panels. Some involves intense and dirty manual jobs, such as the regular need to crawl into the large vents to change the external filters, which clogged up with “pigeon feathers, fluff, muck, grit”, would otherwise collapse and harm the AC system (Interview 4). The experimental nature of the DRF actually undermines scope for standardisation and automation. While the researchers’ experiments require them to feed, water, measure and intervene in the plants’ growth in various ways, they remain heavily reliant on a number of support staff, three of whom are employed primarily to oversee the technical side of the controlled environment facility. In addition to a heavy workload of ordering supplies, servicing the equipment and managing the facility in line with its strict regulatory requirements, the technicians are continually called upon by researchers for their engineering and computing skills. These are needed to set up the conditions, investigate and fix various problems with the machinery, and come up with

bespoke solutions to whatever issues arise for those carrying out experiments. In cases of breakdown, the technicians are expected to be available to address any problems with the system almost immediately, with the most senior automatically alerted to any errors by SMS during the day or night.

Microclimatic Control for Fragmented Urban Reproduction?

Our case studies reveal how controlled environments are actively constituted and embedded in the ordinary city, shaped by local context and questions of urban reproduction. Two prominent themes emerge. The first relates to the importance of the political economy of the urban context and environment—broadly conceived—in shaping the development of controlled environments as strategic dimensions of urban development. The second concerns the role of automation and its limits in the creation, regulation and control of new enclosed ecologies and microclimates. First, as sites of strategic land development, each was constructed to fulfil a particular role in Sheffield's regeneration and urban reproduction, in which the controlled environment constituted a specific indoor microclimate or atmosphere as a resource. By situating each site in their wider historical urban context, it is clear how the material and discursive construction of these different indoor environments was embedded in and shaped by the UK's urban regeneration agenda of the time. Urban reproduction, as envisioned by urban elites in this moment of post-industrial decline, austerity and inter-urban competition, demanded a brand of urban entrepreneurialism which could rejuvenate the built environment, stimulate inward investment, and attract the right kinds of people to the city during a period of neoliberal urban restructuring. The interiorised natures produced were shaped and carefully modulated to address what was identified as inhospitable or absent opportunity within the prevailing urban environment, for the purposes of reproduction and accumulation (Gissen 2014; McNeill 2019; Weber 2002). In all this, the co-constitutive relationship between the urban inside and outside was crucial, reaffirming the importance of this often neglected area of urban political ecology.

Second, the role of automation was important across the three sites. Each control system relied on some degree of automation in producing and regulating specific microclimatic conditions. In the Winter Garden, the relatively basic level of automated environmental control was designed to meet an imperative to reduce the need for human labour and the overall costs of maintaining the indoor horticultural ecology under the pressures of significant financial constraint. While simple, automated environmental control in the Mercure Hotel contributes to an enhanced and protected indoor atmosphere of luxury, by reprocessing and filtering particular flows from the outside. The David Read Facility depends on the most sophisticated degree of automated control. In this case, the precise automation of particular inflows and outflows is critical to the chambers' capacities to transcend the local context, and simulate extreme, distant or non-existent ecologies for the purposes of experimentation. The claims associated with each site are pitched differently, yet in every case automated environmental control meets its limits.

Controlled environments are persistently unruly. Efforts to selectively simplify complex ecologies through technological means tend to meet human and non-human resistance. Influxes of pests and diseases, human interference and the problems linked to lack of “natural” weathering are all examples of the difficulties of managing enclosed environments and artificial equilibriums. In addition, there are issues around technological failure and breakdown, and the need for constant maintenance, fixing and reprogramming. Expert but often hidden and devalued human labour is quickly revealed to be an essential component of each system, as all kinds of proactive and reactive interventions are required to correct, manage and supplement the work of the machines. What is revealed by exploring under the hood is not only the tensions and contradictions of indoor environmental control, but what and who is valued within these socio-technical-ecological assemblages.

This study and its findings contribute to debates on controlled environments in a vital moment of transition, and provides a framework for future research. As recent literature shows, there is an increasingly ambitious, systemic and infrastructural rationality to the use of controlled environments as a form of urban immunisation and reproduction in the face of socio-ecological turbulence (Marvin and Rutherford 2018). The socio-technical, socio-ecological and socio-spatial logics, processes and effects of this trend have not yet been researched in detail. In this unfolding landscape, unravelling the complex sets of relations and emerging tensions between the human, technological and ecological dimensions of automated environmental control is an important task for urban and environmental geographers. By examining these more established and mundane sites of environmental control in Sheffield, this study has revealed some of the key questions this research agenda should address, which are outlined below. As exemplars of a transitional phase, the cases also provide insights into the new (and continuing) challenges and vectors of controlled environments, as more extensive and intensive forms of microclimatic enclosure emerge. For instance, the Winter Garden highlights the dilemmas and difficulties of interiorising complex ecologies, requiring highly selective and bespoke socio-technical systems, which limit the scope of automation. This has important implications as more domains of social life are moved inside. As the *Mercure's* exclusive and protective atmosphere crucially signals, controlled environments frequently materialise an uneven and privatised logic of the enclave rather than collective security. Who and what is left or kept “outside” of sanitised indoor environments remain pressing questions for critical scholars. The DRF meanwhile demonstrates the resource intensity sitting behind more advanced forms of automated environmental control, and efforts to recreate ecological conditions with ever-more precision for productive purposes, such as in controlled environment agriculture.

In conclusion, we identify several major implications for future research on controlled environments. First is the importance of developing theoretical work on the relations between indoor and outdoor environments in urban political ecology. Increasingly, the partial and selective reconstruction of outside ecologies inside is being used to create new volumetric spaces as strategic resources for urban reproduction. As we have shown, controlled environments are embedded in variegated urban contexts which shape and constrain their application according to inherently political imperatives. Understanding how, by whom and for what ends existing

urban environments are problematised as risky or inadequate, and how urban needs are constructed and defined as requiring interiorised responses is a crucial element of this work. Second, our work also suggests enduring contradictions and imbalances sit below the surface of controlled environments. More fine-grain studies may demand new conceptual and methodological tools. As claims grow as to the potential for automating and optimising ecological security under extreme conditions, the ability to disentangle and scrutinise the complex blending of social, technological and ecological processes which animate controlled environments becomes more urgent. Third, this article has shown obvious constraints on the infrastructuralisation of controlled environments. At each site, highly specific socio-technical systems have been developed to try to precisely create and maintain often fragile sets of ecologies in response to particular human and non-human requirements. There are clear limits to the attempts to automate the necessary filtration and articulation of material flows. Multiple failures, breakdowns and instabilities require active and substantial amounts of human intervention and labour in order to temporarily stabilise the desired environmental conditions. The need for constant maintenance and bespoke solutions has implications for attempts to standardise and scale up operation and management of controlled environments. This suggests the rolling of controlled environment infrastructure as strategic capacity will continue to be selective, fragmented and unevenly distributed. Here again we see the need for further empirical work on new domains of ecological and microclimatic enclosure, such as controlled environment agriculture, and the kinds of solutions they offer for collective security in the face of profound socio-ecological turbulence.

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Endnotes

¹ While fieldwork was generally straightforward, gaining access to the university facility required significant and protracted negotiation, as a result to the sensitivity of some of the activity carried out there, which includes strictly regulated GMO research.

² See www.sheffield.gov.uk/home/your-city-council/city-centre-ambassadors

³ For background on Sheffield's issues with air quality and pollution, see www.sheffield.gov.uk/home/pollution-nuisance/air-quality

⁴ See www.conviron.com

⁵ See Conviron promotional video of DRF facility: www.youtube.com/watch?v=WGoRkXFrxWI

⁶ Sources: Winter Garden (www.geograph.org.uk/photo/5070602); DRF induction manual (APS 2017); Mercure (author's photo).

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