Hydroponic capital: socio-natural innovation and the intensification of glasshouse agrifood production

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Hydroponic Capital: Socionatural Innovation and the Intensification of Glasshouse Agrifood Production

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This article develops the concept of hydroponic capital in order to explain the emergence of socionatural innovations aiming to enhance food security and production efficiencies in glasshouse agrifood production clusters. It does so through an archaeology of the knowledge regimes involved in technology innovations and examines the regionalized and transnational networks of crop scientists, growers, and extension workers involved. How hydroponics resulted in an intensification of the circulation time for capital and a reduction in the scale and costs of labor inputs is explained. In doing so, advances in economic geographic understanding of innovation through an engagement with agrarian political economy and political ecological debates to explain how hydroponic capital developed through the combination of different innovatory knowledges seeking to grapple with plant pathologies and cropping systems across regionalized networks of actors are discussed. Hydroponics was a way for growers to overcome biophysical barriers to production and labor rationalization problems. The article combines an understanding of the dynamics of labor and capital in agrarian systems, since they struggle with crop biophysicality, with the granular processes of knowledge deployment by which innovation takes place to overcome these biophysical barriers in agrifood supply chains. Unlike much existing innovation research focusing on the combination of different knowledge bases, why different forms of innovation knowledge were combined to overcome biophysical barriers in agrifood innovation is explained.
Acknowedgments

I am very grateful to the Leverhulme Trust for funding the Major Research Fellowship “Fields of Glass: Labour, Techno-Science and Biopolitics” (MRF-2020-029), from which this article is derived, to Liam Campling, and to editor Jim Murphy and four journal reviewers for extremely helpful comments on earlier versions of the article. The article has benefited greatly from their input. Colleagues at the West Sussex Records Office provided excellent assistance to enable access to the archival materials that form the basis for this article.

“What the space shuttle is to aviation, this is to farming.” So begins a report featuring a fifty-one-hectare hydroponic glasshouse facility in California. Hydroponic growing, we are told, is a “tomato nirvana” of high productivity, high quality, significantly reduced pathogenic presence, and all-year-round production utilizing computer-controlled cropping technologies to optimize temperature, humidity, CO₂ (carbon dioxide), and crop nutrient levels. Soilless farming, vertical farming, and hydroponic cropping are seen as the latest brave new worlds of agrifood production and food supply security (Grewal, Maheshwari, and Parks 2011; Resh 2012; Rut and Davies 2018). Hydroponics are today central to attempts to create total ecologies of controlled cropping environments in protected agrifood production, providing a basis for scientific control and rationalization of ever-more efficient food systems (Harvey, Quilley, and Beynon 2002). However, the emergence of large-scale hydroponic glasshouse production dates to the 1970s. In the UK, for example, Van Heyningen Brothers (VHB), headquartered in the heart of the south-coast glasshouse complex in West Sussex, which provides the focus for this article, occupied eighty-one hectares of glasshouses until 2002 for tomato production, supplying 35 percent of the UK market in the early 2000s (Harvey, Quilley, and Beynon 2002). More recent developments include the UK’s largest hydroponic glasshouse production facility, the fifty-five-hectare Thanet Earth facility in Kent. What Kropotkin (1898) characterized as the fields of glass of emergent hyperefficient agrifood production complexes, had become, by the late twentieth century, large-scale, highly capitalized glasshouse ecologies.

This article examines the sociotechnical processes that established the basis for what I call hydroponic capital. Hydroponic capital represents a set of socio-natural and technological relations that came together to produce today’s hyperefficient glasshouse agrifood ecologies. By hydroponic capital, I am referring to the development of large-scale, capital-intensive, industrialized systems of glasshouse agrifood production, at the heart of which are hydroponic, soilless

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1 https://www.youtube.com/watch?v=bRyBKwqLzI8.
technologies maximizing yield and plant productivity. Hydroponic capital is distinct from other forms of capital intensification in that, through replacing soil-based production, it enabled a full-scale sociotechnical transformation of the organizational structure of glasshouse agrifood production, and the enhancement of relative surplus value by reducing labor inputs. It did so by creating a new technological infrastructure to control biophysicality and human labor inputs, leading to a rationalization of the labor process of crop production (cf. Rogaly 2008; Guthman 2014).

Hydroponics was a strategy to intensify the circulation time for capital while reducing labor inputs into the agrifood production process (cf. Prudham 2005; Gibson and Warren 2020). It did so by enabling the multiplication of the number of cropping regimes over an annual cycle by significantly reducing labor requirements through the eradication of soil sterilization and enabling automated plant irrigation. Hydroponic capital simultaneously became the basis for an expansion of the sector to an industrial scale by enabling larger-scale operations and the consolidation of grower ownership of capital due to the higher capital investment costs involved. Hydroponic capital, like capital in general, is a social relation, and my explanation for the development of hydroponic capital involves understanding the commercial and technological logics that created highly capitalized soilless growing systems seeking to overcome the biophysical barriers (cf. Mann and Dickinson 1978; Guthman 2014) and labor rationalization problems in glasshouse agrifood production.

Following Baglioni and Campling (2017, 2447) in their exploration of “ecological indeterminancy,” hydroponics can be read as “a permanent struggle to standardise, control and simplify nature and the uncertainties of natural environments through continuous socio-technological innovation.” In explaining the process of hydroponic innovation, I develop debates on regional innovation systems focused on the complementarities between different types of knowledge bases (e.g., Asheim and Gertler 2006; Asheim, Grillitsch, and Trippl 2017) to enhance understanding of the sociotechnological transformations underpinning hydroponic capital. While much of this innovation research tends toward a typologizing of distinct and overlapping knowledge bases (Grillitsch, Martin, and Srholec 2017), or in parallel work, of agricultural innovation network actors (Klerkx, van Mierlo, and Leeuwis 2012), this article argues that the combination of different agents and mechanisms of knowledge interaction in hydroponic innovation needs to be explained. I explain this combination through the attempts by a localized network of scientists, growers, and extension workers to grapple with the biophysical barriers involved in glasshouse cultivation—the very ecological indeterminacy that hydroponics was seeking to overcome. It was precisely through this localized network of interactions between growers, support workers, and scientists that the combination of different knowledge bases—particularly analytical and synthetic knowledge (Asheim and Gertler 2006; Asheim, Grillitsch, and Trippl 2017)—in the innovation process establishing hydroponic capital was necessary. I therefore provide an archaeology of the scientific and grower knowledge production system that created the sociotechnical basis for hydroponic capital and explain how the innovations around hydroponic capital required a set of collaborations and knowledge exchanges in the process of technology development that were seeking to overcome the biophysical and labor input barriers to the intensification of agrifood production.

Protected agrifood production takes different forms around the world—from the extensive plastic covered fields of Almeria, southern Spain, north Africa (Aznar-
Sánchez, Galdeano-Gómez, and Pérez-Mesa (2011), and China (Morgan 2021), to the capital-intensive glasshouse facilities in northern Europe and elsewhere (Harvey, Quilley, and Beynon 2002), which provide the focus for this article. Moulton and Popke (2017, 714) argue that glasshouse agrifood production is designed to “intensify the management of and control over the agricultural milieu” through “new forms of control and surveillance over the life processes . . . [of] crop cultivation” (Moulton and Popke 2017, 722). As such, the glasshouse “ecology” allows “intensifying control over the metabolism between human agency and the vital life properties of growing plants” (Moulton and Popke 2017, 727). Hydroponics also provided a basis for the reconfiguration of the relationship between capital, technology, and labor, and has been critical to the development of intensified, highly capitalized glasshouse production in northern Europe and the US. The development of hydroponic capital via a discussion of the causalities, agents, and mechanisms through which hydroponic innovation occurred is examined in this article. How hydroponics innovation arose from an articulation of state-funded technoscience, grower capital, and ecological processes in a regional glasshouse complex in South East England is also explained. I further explain hydroponic innovation by extending agrarian political economy frameworks seeking to understand agricultural exceptionalism; that agrifood systems are distinct in that they are “fundamentally dependent on biophysical production” (Guthman 2014, 63); and “nature-centred production” in which “nature is a source of risks, uncertainties, and rigidities” (Prudham 2002, 146). Moulton and Popke (2017) emphasize how glasshouse agrifood production involves a particular response to these metabolic interactions between the application of living labor to the natural processes of plant growth at the heart of biophysical, nature-centered agrifood regimes. I argue that these human-biophysical interactions focused, in the case of hydroponics, on intensifying the circulation of capital. By reducing labor inputs, hydroponics critically enabled an increase in the number of phases of crop production and a reduction in the time that the realization of capital investment took.

The article draws on a rich archival corpus of material associated with the actors in what, by the mid-1980s, was one of the main regional concentrations of glasshouse agrifood production in the UK, located on the southeast coastal plain, and the primary site globally for early innovation in hydroponics. Glasshouse production in West Sussex covers around 260 hectares (West Sussex Growers’ Association [WSGA] 2021), constituting 9 percent of the total glasshouse area in England.2 The cluster is estimated to employ around 10,100 full-time equivalent workers and generates just under one-quarter of UK horticultural output (WSGA 2021). The article draws on material held at the West Sussex Records Office (WSRO) archives in files, documents, and photographs associated with the regional growers’ representative body; the WSGA, the archives of what was the main state-funded research institute for glasshouse production in the UK, if not the world; the Glasshouse Crops Research Institute (GCRI); and material deposited in leading growers’ archives that were central to the development of hydroponic technology. It is through this archival record that I reconstruct the socio-technical innovations leading to the development of hydroponic capital and the struggles with biophysical ecological indeterminacy that were at their core.

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In the following section, I set out a theorization of hydroponic capital through an understanding of how innovation in agrarian systems seeks to overcome biophysical barriers and reduce labor inputs in order to intensify agrifood production. I explain the deployment of different forms of knowledge by the range of actors in the innovation space of glasshouse hydroponics. The section following examines the emergence of hydroponics as an alternative to relying on soil fumigation and sterilization technologies. This is followed by a section explaining the articulation of different forms of knowledge in hydroponic innovation, deployed to overcome the biophysical limits of glasshouse food production. The article concludes with a consideration of how analyses of regional innovation in agrifood production and beyond need to explain the particular knowledge and actor combinations attempting to overcome the biophysical barriers to the development of hydroponic capital.

Theorizing Hydroponic Capital

Hydroponics is “the science of growing plants without the use of soil, but by use of an inert medium, such as gravel, sand, peat, vermiculite, pumice, perlite, coco coir, sawdust, rice hulls, or other substrates, to which is added a nutrient solution containing all the essential elements needed by a plant for its normal growth and development” (Resh 2012, 2). Two main technologies have been developed for hydroponic food production: the Nutrient Film Technique (NFT) solution culture and those using substrates, such as rockwool, although they are sometimes combined (Resh 2012; Morgan 2021). The NFT is a closed-loop system (Valenzano et al. 2008; Morgan 2021) defined as “a water-cultural technique in which plants are grown with their roots contained in a plastic film trough or rigid channel through which nutrient solution is continuously circulated” (Resh 2012, 145; see also Cooper 1975; Morgan 2021). It is a closed-loop system in the sense that “the water added is equivalent to the water used in transpiration” and is recycled around the enclosed system (Valenzano et al. 2008, 72). NFT systems, which provide the primary focus for this article, involve the pumped circulation of carefully monitored, nutrient-rich water and trace element solutions flowing through growing beds/troughs, directly feeding plant roots (see Figure 1 and Table 1). NFT systems are primarily used for “rapid-turnover crops such as lettuce, herbs, strawberries, green vegetables . . . and micro-greens, although longer-term plants such as tomatoes will grow in these systems” (Morgan 2021, 61–62) and for which the NFT was initially developed. Hydroponic substrate systems, such as rockwool, differ in that they involve a growing medium, such as stone wool substrate, derived from spinning molten basaltic rock to create a fiber substance to support plant roots, which are fed by a nutrient solution. It is now the preferred substrate for growing tomatoes, cucumbers, and peppers.3 While oxygenation of plants in NFT systems has been a continuing concern for some growers (Resh 2012), according to Valenzano et al. (2008, 74), the NFT gave a higher yield and “a greatly reduced environmental impact” than rockwool and soil-based tomato cultivation systems. A key benefit with all hydroponics is the

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3 ADAS, “Growing Crops on Rockwool,” West Sussex Growers’ Association Newsletter, February 1979. WSRW WSGA 2/2/3 ("WSRW WSGA 2/2/3" refers to the organization of the WSRW archive catalogue system, where WSGA refers to the West Sussex Growers’ Association archive, and 2/2/3 refers to section two/box or part 2/folder 2).
minimization of fungal and other pathogenic problems, although this was not fully eradicated in the early years of development. In addition, hydroponics “allowed precise control of the flow of water and other nutrients over the plant roots … in scientifically

Table 1

Nutrient and Trace Element Solution Compositions in NFT

<table>
<thead>
<tr>
<th>Nutrient solution (1,000 liters):</th>
<th></th>
<th>Trace element solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potassium nitrate</td>
<td>0.67 kg</td>
<td>Iron sequestrine</td>
</tr>
<tr>
<td>Magnesium sulphate</td>
<td>0.47 kg</td>
<td>Manganese sulphate</td>
</tr>
<tr>
<td>Calcium nitrate</td>
<td>0.99 kg</td>
<td>Boric acid</td>
</tr>
<tr>
<td>Potassium phosphate</td>
<td>0.14 kg</td>
<td>Zinc sulphate</td>
</tr>
<tr>
<td>Trace element solution</td>
<td></td>
<td>Copper sulphate</td>
</tr>
<tr>
<td>Iron sequestrine</td>
<td></td>
<td>Ammonium molybdate</td>
</tr>
<tr>
<td>Manganese sulphate</td>
<td></td>
<td>Water</td>
</tr>
</tbody>
</table>

Source: Adapted from Cooper (1973, 1052).

minimization of fungal and other pathogenic problems, although this was not fully eradicated in the early years of development. In addition, hydroponics “allowed precise control of the flow of water and other nutrients over the plant roots … in scientifically

\[4\] K. Lauder. “Nutrient film work at GCRI covers many other crops besides tomatoes.” WSRO Peter Bailey Papers 7/1/2.
determined proportions” (Harvey, Quilley, and Beynon 2002, 109). In what follows, however, I argue that hydroponics developed principally because it was a way to overcome important biophysical barriers and labor rationalization problems in glasshouse agrifood production.

Today, hydroponics research is focused on the development of urban food production (Rut and Davies 2018), the opportunities for hydroponic and vertical farming (Despommier 2010; De Anda and Shear 2017), the significant water savings and environmental sustainability benefits that can be gained from nutrient and water reuse systems (Grewal, Maheshwari, and Parks 2011), and the utilization of fully automated Internet of Things, and machine learning-driven hydroponic cropping technologies (Mehra et al. 2018; Smith 2023). A significant grower and international scientific network has developed around the deployment of hydroponic techniques seen at conferences of the International Society for Horticultural Science and its association publication, *Acta Horticulturae*, and various industry-oriented publications such as *Grozine*. The nexus of institutions, crop scientists, practitioners, and growers engaged in hydroponics provides much of the contemporary architecture for its deployment as the preferred glasshouse cropping technology. But the origins of hydroponic capital lie in a regional cluster in South East England, which provides the focus for this article.5

**Hydroponic Capital as a Socionatural Relation**

In understanding hydroponic capital as a site of innovation and as a set of socionatural relations, I bring into conversation research on agrarian political economy and agricultural exceptionalism, with debates over regional innovation, to explain why hydroponic agrifood innovation took the form that it did (e.g., Fitzsimmons 1986; Henderson 1998; Asheim and Gertler 2006; Guthman 2014; Asheim, Grillitsch, and Tripl 2017). Throughout the postwar history of glasshouse food production, growers have faced the problem of controlling biophysical plant and crop growth, labor shortages and reliance on low-wage migrant workers, and a myriad of cost pressures from rising energy prices to increasing wage costs (Smith 2023). The development of hydroponic capital can be explained, first, as a mechanism to increase the intensification of glasshouse cropping by growers faced with these pressures as a way to reduce labor inputs. Intensification is achieved by enhancing the circulation of capital in a system in which the control of biophysical processes is key. The total ecology of controlled environments of glasshouse agrifood production (Harvey, Quilley, and Beynon 2002) provides a way to understand attempts to intensify grower control over unruly biophysical processes of crop growing and labor inputs in protected environments, and simultaneously to expand the scale of grower operations. Second, I argue that overcoming the exceptional biophysical nature of agrarian production (Gutham 2014) necessitated the combination of knowledge bases in the process of hydroponic innovation as growers, scientists, and extension workers collaborated to innovate beyond the fragilities, risks, and uncertainties of growing glasshouse crops (cf. Benton 1989; FitzSimmons and Goodman 1998; Prudham 2002).

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Central to this analysis are the distinctive social relations that arise from the nature-centered (Prudham 2002) or biophysical (Guthman 2014) characteristics of agricultural production. The development of hydroponic capital requires an understanding of a socially directed process of agrifood innovation. This involved the articulation of state funding, private capital, the labor of growers, and scientific workers attempting to overcome “a unique set of obstacles, opportunities, and surprises . . . to subordinate biophysical properties and processes” (Boyd, Prudham, and Schurman 2001, 556) to the needs of grower capital.

As Guthman (2014, 63) has noted, the “exceptional” biophysicality of crop production—as distinct from manufacturing—rests on a number of “constraints on food production” (see also Mann and Dickinson 1978; Fitzsimmons 1986), including risks over growing conditions (weather and sunlight for example), pests and pathogens, as well as the unruly nature of crop biophysicality (Smith 2023). These constraints are compounded further by the time crops take to grow and their seasonality (Mann and Dickinson 1978), which “limit the extent to which food production can be controlled or sped up” (Guthman 2014, 63; see also Fitzsimmons 1986). The biophysical limits to crop production are thus key to understanding the disjunction between production time and labor time in agrifood industries. Drawing upon Mann and Dickinson (1978), Henderson (1998, 31) argues that this “non-identity” of production time and labor time meant that “every period that capital spends in production without labor applied is a period where value is not being created. This disunity between production and working time is evident . . . when the time during which crops mature in the ground involves little or no application of labor.” The natural growth cycles of plants thus create a barrier to the capitalization of agriculture (Mann and Dickinson 1978). As Mann and Dickinson (1978, 472) argue, “[p]ractically the entire field of agricultural research and development is given over to efforts to reduce the preponderance of production time over labour time,” including hydroponics, which can “be seen as [an attempt] . . . to shorten production time relative to labour time.” My argument here is that in shifting glasshouse production away from pathogenic-prone soils to hydroponic cropping, hydroponics dealt with the nonidentity question not by reducing production time and enhancing value creation within a single cropping cycle; that is, it did not significantly reduce the production time for a single crop (see Okano, Nakano, and Watanabe 2001). Rather, it did so primarily by enabling the multiplication of the number of cropping regimes over an annual cycle by reducing labor time spent on nonproductive crop-legacy activities, such as soil fumigation and sterilization, to eradicate pathogens between harvesting and planting. Overall labor requirements were reduced, enabling growers to control one of the few costs they could: labor costs. As such, hydroponics enabled significant reductions in labor expended (see Table 2) and an extension of the number of cropping regimes over an annual cycle, allowing an intensification of the circulation time for capital and a reduction in labor requirements (Henderson 1998; see Figure 2). Put differently, the intercrop replacement period was reduced, enabling a higher turnover of capital, a reduction in labor inputs, increased yields, and enhanced relative surplus value.

Hydroponics was therefore a technology of innovation that intensified production (cf. Guthman 2014) and the consolidation of grower capital into larger units by speeding up the annual cycle of growing processes (rather than the time for any
individual crop cycle) through multiplying the number of cropping cycles in a year. Through the “intensification of biological productivity” (Boyd, Prudham, and Schurman 2001, 564) hydroponics enabled the “real subsumption of nature” through which “firms are able to take hold of and transform natural production, and use this as a form of productivity increase” (Boyd, Prudham, and Schurman 2001, 557; see also Prudham 2003).

However, the struggles with biophysical processes, including the challenges of dealing with pathogens, of enhancing crop yield, in undertaking all manner of activities in which those involved in innovation of this kind are grappling with plant growing processes with their own logics, necessitated the combination of different kinds of knowledge in the innovation process. While one of the key foci of innovation to establish hydroponic capital was the reduction of labor time in crop production (see Mann and Dickinson 1978), it also necessitated ways to increase control over the whole gamut of biophysical growing processes in glasshouse cropping. In a similar vein to Kloppenburg’s (1988) claims regarding how a biological system is transformed into a vehicle for accumulation through the commodification of seed, and what Reisman and Fairbairn (2021, 691) have identified as the “limits to human activities imposed by the biophysical characteristics of agriculture,” hydroponics was the way in which combined grower/scientist innovation processes sought to transform the biophysical limits of glasshouse agrifood production.

### Table 2

<table>
<thead>
<tr>
<th>Activity</th>
<th>Soil</th>
<th>Hydroponics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Removing irrigation lines</td>
<td>40</td>
<td>-</td>
</tr>
<tr>
<td>Removing old crop</td>
<td>150</td>
<td>100</td>
</tr>
<tr>
<td>Removing heating pipes</td>
<td>Yes</td>
<td>-</td>
</tr>
<tr>
<td>Rotavating</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>Steaming</td>
<td>300</td>
<td>-</td>
</tr>
<tr>
<td>Flooding</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>Applying fertilizers and rotavating</td>
<td>30</td>
<td>-</td>
</tr>
<tr>
<td>Marking out for planting</td>
<td>200</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>740</td>
<td>100</td>
</tr>
</tbody>
</table>

Source: Adapted from Nutrient Film Trials 1974. WSRO AM 1263/1/13.

Figure 2. Hydroponics and the intensification of glasshouse production.
Hydroponic Innovation

But how and why did hydroponic innovation actually come about? In answering this question, we need to situate these broader logics of accumulation, intensification, and increasing operational scale in the context of the more granular processes of hydroponic innovation. Werner (2022, 240) has identified the “challenge of balancing [the] … many moving parts” in any analysis of the economic geography of socionatures, precisely what Mitchell (2021) sought to do in raising the question of causality in understanding complex agrarian systems. In explaining the coming together of these socionatural relations in the innovation process I draw on regional innovation research (e.g., Asheim, Grillitsch, and Trippl 2017). I extend what is a set of largely descriptive knowledge categories of innovation processes in order to explain the regionally embedded, socionatural interactions between actors articulated in localized innovation networks in a glasshouse agrifood complex, since they struggled with biophysical processes of plant life and pathogenic interference to create hydroponics.

Asheim, Grillitsch, and Trippl (2017) draw the distinction between the differentiated knowledge base approach and its development in combinatorial knowledge bases in innovation processes. At the heart of this approach is the distinction between, but combination of, different types of knowledge bases: analytical, synthetic, and symbolic. Analytical knowledge is largely derived from scientific research and the development of know-why in codified knowledge. Synthetic knowledge arises largely from incremental engineering-based innovation processes and the development of know-how, and symbolic knowledge arises from artistic-oriented activity and know-who (see also Asheim, Boschma, and Cooke 2011).

Recent work has sought to move beyond the tendency to draw ideal–typical distinctions between these knowledge categories, arguing that in practice the precise differences between them are difficult to identify (Moodysson, Coenen, and Asheim 2008). Grillitsch, Martin, and Srholec (2017, 463), for example, have argued that “even though analytical, synthetic, and symbolic knowledge are distinct theoretical categories, innovation processes often draw on their combinations.” Existing research seeking to examine the coming together of different knowledge bases in innovation processes has focused on life science industries (Moodysson, Coenen, and Asheim 2008), on new media industries (Martin and Moodysson 2011), on automotive design manufacturing (Van Tuijl and Carvalho 2014), and on green construction industries (Strambach 2017). However, this work lacks an explanation as to why knowledge bases combine, focusing instead on the deployment of tacit and codifiable knowledge (Moodysson, Coenen, and Asheim 2008) and localization of action (Martin and Moodysson 2011), and none deals with agrifood innovation. I argue that an understanding of the combination of different knowledge bases with respect to the deployment of analytical and synthetic knowledge, and the work of key agents (scientists, growers, and extension workers) across both spheres, resulted from the need to manage the biophysical constraints of plant growth, to reduce labor inputs and costs in glasshouse production, and to expand relative surplus value. Knowledge base combination, in other words, resulted precisely from the exceptionalism of agricultural production in grappling with biophysical food production and the use of hydroponics to intensify production. Hydroponics innovation thus became one of the primary mechanisms through which
growers—working collaboratively with scientists and extension workers—sought to overcome biophysical barriers, including eradicating the need for soil sterilization, extending the number of cropping cycles, and reducing overall labor requirements. This resulted in an intensification of cropping, increased yields, reduced reliance on labor, and had the consequent effect of speeding up the circulation of capital via increased growing cycles. The intertwining of different knowledge bases resulted therefore from the particular network constellation of actors involved (such as a close proximity between researchers, growers, and extension workers in southern England), and from the particular biophysical properties of plant growth that they were seeking to overcome.

Starting with the Soil: The Emergence of Hydroponics in Glasshouse Agrifood Production

Guthman (2019, 33) begins her account of pathogens and chemicals in the California field strawberry industry by “starting with the soil.” In parallel with recent work on more-than-human plant agency (Ernwein, Ginn, and Palmer 2021) and soil dynamics (Lyons 2020), soil is understood by Guthman as lively biophysical material in and through which pathogenic activity in crops is spread. Any discussion of the emergence of hydroponic innovations should also start with the soil and its use in glasshouse agrifood production, since this was the main pathogenically problematic and labor-intensive growing barrier that hydroponics sought to overcome. Indeed, until the 1980s, the cultivation of plants in soil was the dominant form of commercial glasshouse agrifood production, and managing pathogenic tendencies of enclosed soil-based cropping was one of the primary barriers to creating a total ecology of control. In South East England, commercial glasshouse agrifood production was historically characterized by numerous, relatively small-scale family-based growers employing small numbers of workers and growing crops in coal- and later oil/gas-heated glasshouses. By the turn of the twenty-first century, capital concentration in operations of increasing scale was becoming the norm, with the average size of growers almost doubling (see Table 3). Small growers were increasingly being replaced on new production sites with larger-scale growers accessing government capital grants for new glasshouse development. Hydroponic technologies became a key mechanism through which larger-scale operations were established.

<table>
<thead>
<tr>
<th>Glasshouse Production in West Sussex, 1985–2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>1985</td>
</tr>
<tr>
<td>Glasshouse area (ha)</td>
</tr>
<tr>
<td>No. of growers</td>
</tr>
<tr>
<td>Av. Size</td>
</tr>
</tbody>
</table>

Given the pathogenic tendencies of crops grown in soil, glasshouse agrifood production before hydroponics required regular, time-consuming, and expensive soil fumigation. Early forms of fumigation involved cumbersome steam boilers and piping systems that allowed for the application of hot steam, or soil baking ovens, in the attempt to eradicate pathogens and other soil-borne diseases (Bewley 1923, 1950). Even in the 1960s, one analysis argued that “steam sterilization is the most effective means of maintaining . . . desirable [growing] conditions . . . [but that costs] of the operation are high” (Hume 1969, 111). A 1956 conference of tomato growers heard in detail about the approach of one typical grower:

After flame-gunning the ground and washing down the houses with Sterizal and Formaldehyde they are trough dug and rototilled ready for steaming. . . . The nursery is steamed throughout, each year. . . . The grids are buried to a depth of from 12-15 inches at the most and the temperature brought up to 212°F . . . and held for at least ten minutes. . . . After steaming a medium long stable manure is dug in.6

Soil sterilization was a very labor-intensive process that delayed planting of the next crop (see Table 2 and Figure 2). Chemical treatments for pathogen eradication (e.g., methyl bromide) were developed in the postwar period to treat soil once a crop had been harvested and plants removed. Despite the pressure from growers to allow continued exceptional use of methyl bromide “as a horticultural chemical”7 it was eventually banned in the EU in 2005 under the Montreal Protocols on ozone depleting gasses. Methyl bromide was estimated to be responsible for 10 percent of the damage to the ozone layer and that “80 percent of Methyl Bromide was used for soil sterilisation.”8 Indeed, it was recognized among growers that alternative forms of sterilization were urgently required (cf. Guthman 2019), not least because energy costs were increasing and labor shortages were common, both adding significant pressure on grower margins.9 The development of hydroponics eradicated the need for regular soil sterilization, allowed for the avoidance of soil quality variability, and also reduced labor time involved in watering and fertilizer application.

The Emergent Innovation of Hydroponic Capital

The development of hydroponic capital was far from a straight-forward process. Innovation around hydroponic technologies was fraught with setbacks and experimentation with alternative systems as scientists and growers sought ways to overcome biophysical limits. Much like Curry’s (2016) discussion of the development of genetic biotechnologies, the dead ends and false starts all led ultimately to new production systems. While the journey toward a total ecology was not smooth, it involved innovations that sought to provide solutions to global food problems and biophysical crop security. As one early proponent argued, the NFT can provide a solution to food production in “countries where over-population, unpredictable forces of nature, or sheer

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7 WSGA, Glasshouse and General Committee meeting minutes, 2 February 1973. WSRO WSGA 1/3/11.
8 WSGA, Glasshouse and General Committee meeting minutes, 26 November 1992. WSRO WSGA 1/3/19.
9 WSGA, Glasshouse and General Committee meeting minutes, 26 November 1992. WSRO WSGA 1/3/19.
barrenness, can cause human misery” (quoted in Anon. 1976a, 37). Closer to home, labor saving and yield-enhancing benefits were emphasized, potentially raising “tomato yields to 150 tons per acre” (Anon. 1976a, 33). Graves (1983, 34) provided a more modest but nonetheless positive assessment of the yield increases being “up to 15 percent more” due to the system allowing “at least two weeks’ extra production” and denser cropping. These benefits would arise from the “complete control” that the NFT allows “over the plant growing process. . . . NFT is seen as offering the precision needed to control the most difficult of all [crop problems] . . . the feeding programme” (Anon. 1976a, 35). For Graves (1983, 14) “[t]he continuous presence of aerated water is probably the most important single factor contributing to the excellent growth in NFT.” However, like other agrarian complexes (Guthman 2019), the interaction between humans and nature at the heart of the development of hydroponic capital was fraught with fragilities, which necessitated the combination of analytical and symbolic knowledge across the various actors involved in the process of innovation to increase the number of cropping cycles and reduce labor inputs.

Hydroponic Innovation in the English South Coast Glasshouse Ecology

Perhaps nowhere was the development of hydroponic capital more focused than in the South Coast of England glasshouse cluster of state-funded horticultural researchers working closely with local growers and extension workers largely in West Sussex. The development of hydroponics began in earnest in the late 1960s and early 1970s with the development of the NFT at the GCRI, the foremost research organization for glasshouse crops in the heart of the South Coast glasshouse complex at Littlehampton. Working closely with local growers, horticultural advisory organizations (Agricultural Development and Advisory Service [ADAS]) and local business associations (WSGA), scientists at the GCRI were at the forefront of developments in hydroponics.

A key breakthrough in the development of hydroponic capital came in the late 1960s. As Norman (1976, 186) argued, earlier “American attempts at commercial crop culture in water solution had failed due to a lack of oxygen in the water and plant support problems. GCRI had solved the oxygen problems by plastic film culture and recirculation of solution which allowed the upper surface of the root layer mat free access to air.” A dense ecology of state-funded scientific and corporate-sector experimentation and innovation subsequently developed, resulting ultimately in the emergence of hydroponic capital in industrialized glasshouse agrifood at scale. By the mid-1970s it was being argued that “Britain currently leads the world in NFT know-how . . . it has been left to the initiative of a small group of south-coast growers, joined by individual ADAS members, research stations and soil scientists” (Anon. n.d.). It was this localized cluster that deployed both analytical and synthetic forms of knowledge in the hydroponic innovation process to challenge the nonidentity of production and labor time.

Developed initially by Dr. A. J. Cooper at the GCRI in the late 1960s, the NFT began as “a simple system of hydroponic culture in which crop plants are grown with their root systems contained in black layflat polythene film, through which nutrient solution is

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10 Earlier work had been undertaken in California (Gericke 1929, 1937, 1940), which the English cluster built on.
continuously circulated” (Cooper 1973, 1048). This system sat above a sloped base separated by a catchment trench allowing the nutrient solution to flow into it for collection and pumping around the system (see Figure 1). The solution initially involved a combination of nutrients (Cooper 1973) that was subsequently expanded (Cooper 1975; see Table 1). NFT research developed out of earlier work led during the mid-1960s at the GCRI on single-truss tomato production (Cooper 1966) and the root/shoot ratio that demanded easy and visible access to plant root systems (Jenner 1980). The single-truss cultivation method was designed to maximize labor efficiency of glasshouse tomato production by pinching the main plant shoot so that only the first truss is harvested, creating labor efficiencies via easier harvesting (Cooper 1966; Giacomelli, Ting, and Mears 1994; Okano, Nakano, and Watanabe 2001). Following work on the nutritional requirements of single-truss tomato production (Cooper 1966), plants were located in NFT systems, described as “plants grown in narrow troughs, arranged in tiers on a framework. The system reduces labour input, minimises mutual shading, provides for the automatic supply of water and nutrients, and reduces cultural operations to three—pricking out, stopping and removal of side shoots, and harvesting.”

Although at times apparently skeptical about the benefits of this research, the GCRI director, Toovey, did articulate the benefits of the work, which had received a provisional patent from the National Research Development Corporation, as “not so much in the high yields obtainable but in the saving in labour and in the control of disease and fruit quality which it permits.” As such, the rationalization of labor in glasshouse agrifood production was at the heart of the initiative. Indeed, the NFT allowed for the replacement of full-time, presumably male, “heavy and dirty work, and all skill” by “part-time female labour.” The precise hourly labor reductions arising from the introduction of hydroponics involved the eradication of soil steaming and are captured in a report to the NFT Working Party (see Table 2). Soil-based glasshouse cropping required around 740 person hours per acre, with the labor requirements for hydroponics just 14 percent of that level. Labor cost benefits were coupled with savings on energy requirements in the context of the 1973 oil crisis “when suddenly the cost of steam sterilization became a major expense” (Graves 1983, 3), and between 50 percent and 38 percent lower input costs than soil and peat growing. Annual yield increases resulted from expansion of the number of cropping cycles and from the direct control of nutrient solutions in

12 In developing this system, Cooper adapted earlier techniques that had been developed in the Netherlands (Jenner 1980).
plant growth. Thus, hydroponics enabled an intensification of production across annual growing cycles through a reconfiguration of the nonidentity of production time and labor time (Henderson 1998; Guthman 2014) (see Figure 2).

These early innovations arose from a combination of scientific-informed processes of analytical knowledge innovation in crop science undertaken by researchers at the GCRI, alongside a set of economic motivations to enhance grower efficiency and reduce labor costs, which involved the application of synthetic know-why knowledge (see Table 4). They set the scene for the kinds of combinatorial knowledge processes that underpinned larger-scale trials and experimental work associated with hydroponic rollout discussed in the next section.

Grower Experimentation and the Fragilities of Hydroponic Rollout

While the NFT was incubated at the GCRI, it was soon being developed in conjunction with local growers. Indeed, despite the apparent continuing skepticism of the GCRI director, grower representatives on the GCRI governing body stated that the NFT should be supported because “growers were most interested in the project” and that trials with commercial growers were starting.  

By late 1973, and following a visit to the US to

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Table 4

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<thead>
<tr>
<th>Knowledge Form</th>
<th>Analytical</th>
<th>Synthetic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of knowledge</td>
<td>Know-how</td>
<td>Know-why</td>
</tr>
<tr>
<td>Ideal typical type of occupation involved</td>
<td>Biologists, life scientists, plant scientists, hydroponic technologists</td>
<td>Growers involved in hydroponics trials, testing and snagging problems</td>
</tr>
</tbody>
</table>
| Actual experience in the hydroponic capital cluster in southern England | • Scientists developing initial specifications on how nutrient flows are absorbed into plants  
• Local growers undertaking methodical work on nutrient and physical attributes of plants and publishing in industry outlets | • Scientists involved in multiple on-site trials to finesse the production set-up over time  
• Scientists moving into commercial growing to adopt NFT systems  
• Local growers involved in hydroponics testing and calibration |

Source: Development and elaboration of Asheim, Boschma, and Cooke (2011) and Grillitsch, Martin, and Srholec (2017, appendices).

18 GCRI, Minutes of the Sixty Fourth Meeting of the Governing Body, 4 May 1972. WSRO WSGA 4 9/1 bundle 1.
view developments in hydroponics, Toovey was also expressing his support for NFT work at the GCRI but recognized there needed to be research on “the nutritional aspects of nutrient film culture” as well as “physiological and pathological problems,” echoing the significance of basic science and analytical knowledge in the publicly funded research base. This led to the establishment in 1974 of the Nutrient Film Working Party (later Study Group) by the regional ADAS office, led by head of the chemistry department at the GCRI, Geoffrey Winsor, and including Cooper and a number of growers, a consistent figure in which was a local grower, Peter Bailey.

The Study Group became the key institution through which analytical and synthetic knowledge were combined in order to attempt to overcome some of the seemingly intractable biophysical barriers that glasshouse hydroponic production threw up. The Study Group became central to the success and dissemination of the NFT, through local, regional, and international study tours allowing growers to exchange emergent practices and solutions to problems of plant growing and nutrient solution optimization, and its commercialization with scientists and other growers. A 1973 article set out the initial satisfactory yields from the first NFT annual cropping at Bailey’s nursery (Cooper 1973). While caution was being advised by Cooper, several initial benefits of the NFT were identified involving low capital costs for set-up; elimination of soil sterilization, preparation, and soil-borne disease; the ability to grow crops all year and to overcome seasonality that hitherto had been a major constraint on continued cropping; raising and controlling root temperatures to optimize plant growth/cost balance; and careful control of nutrition and water uptake (Cooper 1973), as well as elimination of soil salinity, reduced water loss, and minimization of water storage requirements (Cooper 1975). Subsequently, The Grower elaborated the “eight major advantages of NFT cropping” to also include labor cost savings (Anon. 1976c, 40; see also Table 5). One grower who was adopting the NFT explained that the “main reason for . . . interest in NFT was [the] . . . reduced labour by growing at wider spacing and moving old modules out and new ones in had become a problem with a small labour force. NFT gave potential for a very fast turn around.” For this grower, NFT yields were also earlier and of better quality, enabling greater capture of the early season market, which had often been supplied from outside the UK (Anon. 1976d). A review of the economics of the NFT highlighted that the “turn-round time between crops can be much reduced with no sterilisation . . . and no handling of [peat] bags in and out of the glasshouse. This effectively means at least two weeks’ extra cropping and since NFT plants have more vigour at the end of cropping, these extra weeks amount to an

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21 R. F. Potter to Sparkes’ Nurseries, 23 September 1974. AM 1263/1/13; minutes of what had become the Nutrient Film Study Group from 1980 indicate that the group was being chaired by growers but still retained GCRI staff (including Winsor) and also other glasshouse support organizations such as the ADAS and staff from the Efford Experimental Horticultural Station (Nutrient Film Study Group Minutes, 22 April 1980. WSRO Peter Bailey papers 7/1/2).
additional 5 to 7 tons of fruit . . . when prices are starting to rise” (Potter and Sims 1980, 15; see also Graves 1983; Table 2 and Figure 2).

NFT technologies therefore allowed for a fundamental shift in the circulation of capital in crop production by multiplying the number of annual crop cycles and overall growing season length. The disjuncture between production time and labor time within any single growing cycle was not significantly altered, but—as noted earlier—the reduction of labor time expended on sterilization and glasshouse crop legacy work meant that the ratio of labor applied to crop growing intensified the overall production process and allowed the supply of new early season markets and the potential for all-year-round growing. This meant that with “10 percent more yield . . . [the grower] determined the time of bulking . . . so that the best market prices are caught . . . and returns per foot run of glass are better” (Anon. 1978d, 247). The NFT was estimated to produce a 38 percent increase in grower profit rates, compared to peat growing per acre (calculated from Potter and Sims 1980). As an article in The Grower elaborated, the NFT “offers many advantages, but fundamentally there is the over-riding benefit of increased yields, compared to conventional cropping” (Anon. 1976a, 37). As such, hydroponics enabled an enhancement of relative surplus value creation in the agrifood production process and provided a basis on which the scale of grower operations could expand.

However, subsequent reports on these early trials noted significant plant wilt and unexplained root death over time (Cooper 1975), an issue that plagued the early years of hydroponics. In other words, early grower-based trials and the production of synthetic knowledge was experiencing significant biophysical plant growth issues that required a greater articulation between analytical and synthetic knowledge communities. Further work on the NFT was therefore undertaken by the ICI (Imperial Chemical Industries)

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**Table 5**

*The Advantages and Disadvantages of the NFT*

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
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<tbody>
<tr>
<td>Improved root environment control via use of automated or computer-controlled methods</td>
<td>High level grower expertise required, including knowledge of chemistry</td>
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<tr>
<td>Simplification of plant watering</td>
<td>Initial high capital cost for system set-up</td>
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<tr>
<td>Uniformity of nutrient supply</td>
<td>Possibility of recirculating nutrient solution encouraging multiplication and spread of pathogens</td>
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<tr>
<td>Matching of nutrient concentrations to plant requirements</td>
<td></td>
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<tr>
<td>Energy conservation</td>
<td></td>
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<tr>
<td>Enhanced control of vegetative growth in young winter-grown tomatoes</td>
<td></td>
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<tr>
<td>Enhanced control of root temperature</td>
<td></td>
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<tr>
<td>Uniform dispersal of crop protection chemicals</td>
<td></td>
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<tr>
<td>Elongated cropping period due to no sterilization</td>
<td></td>
</tr>
<tr>
<td>Adoption of higher density planting to increase yield per cropped area</td>
<td></td>
</tr>
<tr>
<td>Greater efficiency of water usage in arid areas</td>
<td></td>
</tr>
<tr>
<td>Reduced labor inputs</td>
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</table>

Plant Protection Division’s commercial glasshouse facility in West Sussex, which began to indicate over a three-year trial period an increase of tomato yields from the NFT compared to peat substrate (Spensley, Winsor, and Cooper 1978; Cooper 1979). Indeed, by the late 1970s, the NFT was being “employed in the UK for high value glasshouse crops,” and concerns over plant disease were not found to be any more significant for tomato crops compared to other growing cultures, but root death continued to be a problem in cucumber crops, including pathogenic evidence of *Pythium ultimum* (Spensley, Winsor, and Cooper 1978, 300).

Reflecting long-standing tensions in agricultural science research over whether basic or applied research should be the focus (Agar 2019; Lowe 2021), which partly led to the restructuring of the research base and the closure of the GCRI in the context of 1980s austerity cuts under the Thatcher government, concern continued to be raised in the late 1970s at the GCRI over work on the NFT. The GCRI’s governing body noted that NFT “work was becoming increasingly advisory with little scientific content, and [somewhat ominously] this would need to be watched . . . in the interests . . . of the Institute” (emphasis added). NFT work was, in other words, seen to be insufficiently focused on analytical knowledge and linked too closely to synthetic, commercial knowledge communities created through grower trials. But it was precisely this coupling that was required in order for progress with hydroponic innovation to be achieved, as Bailey’s work attested. By September 1978, Cooper had left the GCRI and “was engaged in setting up commercially four acres of land devoted to NFT.” However, NFT development work continued at the GCRI under Moorby, including expansion into testing the NFT with cucumbers, which was at the core of Bailey’s activity. In what follows I chart the development of NFT hydroponic capital as a nonlinear process of horticultural innovation attempting to overcome the biophysical barriers to crop growing, which required the integration of analytical and synthetic knowledge bases. I explore these innovatory experimentations and their tensions in the effort to create a labor-saving technology that enabled the intensification of growing practices and a realignment of the relationship between production, labor, and dead or crop-legacy time (see Figure 2).

**Combining Knowledge Bases**

Despite the hope that the NFT would provide a cropping solution to all-year growing, early commercial development by West Sussex and other growers, summarized in a 1975 Nutrient Film Study Group paper, was less than positive. One of the main growers found that “[r]oot loss with severe wilting occurred. . . . Improved root growth was achieved by excluding light from the roots by covering with black

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polythene.”27 But the purported enhanced yields from hydroponics were yet to be realized. Other growers reported the presence of Tomato Mosaic Virus leading to poor setting of fruit, algae buildup in the nutrient solution leading to pumping and tube blocking problems, and issues with crop root death. However, production costs were between 39 percent and 51 percent lower for the NFT when compared to soil and peat cropping, as were labor costs. The following year continuing problems were being experienced in work at the largest UK tomato producer, VHB in West Sussex, with documented acidic leaks from equipment, blocked feeder tubes, and significantly lower crop yields per acre when using the NFT.28 Around the same time, a West Sussex Tomato Working Group visit to major producers in Guernsey noted “severe root death” in NFT plants and “scorch at base of stem due to localised high salt concentration” with no discernible yield enhancement.29

Despite the primary focus on tomatoes, given its overall dominant presence in the West Sussex glasshouse cluster, Bailey was also developing the NFT for use with cucumbers, which alongside leafy salads eventually became among the main crops to utilize the NFT. At the same time as the early developments and set-backs with tomatoes described above, Bailey was experiencing what became identified by researchers at the GCRI as pathogenic infection from Pythium paroecandum, not normally associated with cucumber crops.30 An article in The Grower captured the fragility of these early NFT developments: “The doyen of cucumber growers Peter Bailey, after five years of trials with the nutrient film technique of growing is still encountering problems. . . . Bailey who has been working closely with the GCRI methods . . ., professed himself at a loss to know why the failures had occurred” as he was plagued by Pythium root rot and had to remove plants, fully sterilize his facility, but was still experiencing pathogenic problems (Anon. 1976b, 1276). These early difficulties arising from the adoption of the NFT, especially relating to root rot and pathogens, and their potential treatment using substances derived from copper sulphate, led to trans-Atlantic collaborations with growers and researchers in California to identify the problems encountered, where hydroponic research and development was also being undertaken.31 Graves (1983) also reported a range of additional difficulties, including the pH buffering capacity of hydroponic systems like the NFT, which created complexity in plant nutrient absorption; a range of pathogenic root diseases, including Fusarium and Verticillium, which enter via root systems; blossom-end rot, which can arise from incorrect ammonium and humidity levels; magnesium deficiency symptoms; zinc toxicity; and “collar rot,” which “is caused by the evaporation of nutrient solution at the surface of the substrate used for establishing the plant.”32

Despite these set-backs and the initial refusal of the ADAS to give the NFT its full backing, growers were considering that “its potential is exciting enough to justify

backing it with their full resources” with a Kent grower reportedly setting up three acres of glasshouses with the system (Lovelidge 1976, 393). However, continued concerns remained over whether a sufficiently responsive nutrient solution testing analysis infrastructure was in place to allow growers to adjust nutrient solution speedily to maximize cropping. Laboratory facilities at Wye College, Kent, were used, but Bailey was regularly sending samples to Swedish laboratories with results being telexed back via VHB.  

By 1978, despite engaging with growers developing hydroponics in Sweden, Finland, Denmark, and the Netherlands, further set-backs were being identified in relation to manganese and iron deficiency problems impacting plant growth. Bailey’s experimental work found that certain iron chelates were toxic to plants, especially when utilizing Ferric EDTA supplements in the nutrient film solution (Anon. 1978a). However, “[l]arge-scale commercial hydroponic crop production would not be possible without the use of chelated iron” (Tills 1987, 121). Following a switch to Ferric EDDHA, which was less toxic, it was reported that Bailey “thinks he has found the factor which has been holding back nutrient film technique cropping. . . . The secret of the baffling NFT troubles like root death and wilting with consequent loss of yield lies in the iron chelates used in the solutions. . . . Bailey is now using Fe EDDHA having found that Fe EDTA was the cause of his trouble” (Anon. 1978b, 47). This followed methodical recording and documentation of daily nutrient mixes and plant performance in Bailey’s extensive diary entries, in close collaboration with scientists at the GCRI and elsewhere, both directly and as a member of the Study Group, as well as with researchers at UCLA (University of California at Los Angeles) on iron and manganese deficiency in the NFT.  

After adopting Ferric EDDHA “the crop . . . improved out of all recognition” (Anon. 1978b, 47). While yields still appeared to be lower than soil growing (Anon. 1978a), Bailey was hopeful that the NFT would turn out to be “10 to 20 percent better than soil” (Anon. 1978c, 709). But detractors remained. One report raised continuing concerns over the quality of NFT tomato crops. The apparent luxuriant growth of the NFT crops meant that fruit size was being prioritized over crop quality (Davies 1978). Davies contrasted soil-based substrates with the NFT as follows: “[t]he best soil for tomatoes is one that offers some resistance to the tomato plant in getting the water it needs; too much resistance from too high a level of salts and growth suffers to the detriment of yield as well. The problem with NFT growing is the ease with which water is available to the plant. There is no soil to compete with the plant for water” therefore raising the need to introduce salts into the NFT solution to control crop growth.

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34 WSRO Peter Bailey Papers 3/1 and 3/3/1.
35 Lowcock to Wallace (Notes enclosed from Bailey), 16 October 1978, Wallace to Bailey, 1 November 1978, Wallace to Bailey, 14 November 1978, Bailey to Wallace, 29 November 1978 (all in WSRO Peter Bailey 3/5/3). Bailey’s analytical approach to growing was evident from his prior employment as manager at a large Sussex grower (Sparkes/Sussex Nurseries) in the early 1960s. For example, a series of technical reports were published by Sparkes in the 1960s that underpinned a scientific approach to growing equivalent to that found in research institutes such as the GCRI (e.g., Sparkes [1967] Technical report: Controlled flowering of carnations by dusk and dawn lighting, located in Marshall, R. (1968) “Worthing grown”: A study of horticultural production under glass in Worthing and the West Sussex coast. Unpublished manuscript folder held at Worthing Library historic documents collection).
(Davies 1978, 281). Here we see in action the combination of analytical knowledge production between growers, such as Bailey, and scientific workers at the GCRI, alongside continual experimentation in grower trials and tweaks to the nutrient solutions and equipment used as a result of grappling with the biophysical properties of plant growth. This integration of analytical and synthetic knowledge was key to overcoming biophysical barriers in the growing process. This combination came about in large part due to the interactions between clustered actors central to the innovation process via the Nutrient Film Study Group. As Cooper himself articulated,

During 1974 there have been a large number of trials of the nutrient-film technique. Growers, manufacturers, advisory officers and research workers have all contributed ideas which have given a creative variety to the trials. Some ideas have failed but others have resulted in various improvements on different sites. Progress is rapid because of the considerable number of people who have actively involved themselves in development so even these improvements could be well superseded during the coming year.36

By the 1980s, the NFT was being widely adopted in the UK. Burrage (1992, 24) suggested that the “NFT accounted for 10 percent of the cropped area of heated tomatoes,” although soil- and peat-based cropping still remained predominant. In 1982, Graves (1983) was reporting that the NFT was showing rapid uptake in the UK and was being used on forty-six hectares of tomatoes and lettuce, having increased from sixteen hectares four years previously. In the Netherlands it was being used on five hundred hectares in 1982. Graves (1983, 2) argued that “commercially acceptable yields were obtained, and this encouraged the subsequent development of NFT.” However, lettuce producers in the other main UK cluster of glasshouse production in the Lea Valley were continuing to experience growing problems with infection, with a “big vein virus” resulting in loses of half the crop due to “zoospores of a fungus which proved to be very resistant to a wide range of fungicides” (Birch 1980, 18). Once this problem was eradicated the grower—who had introduced computerized mechanization—could “turn a lettuce crop round in four weeks during the summer time and nine weeks during the winter with one man per acre, including packing” (Birch 1980, 22).37 Significant yield improvements were also being reported for the NFT, when compared to soil and peat substrates,38 such that the ADAS felt able to state in its notes to tomato growers presented to the West Sussex Tomato Working Party in 1979 that “[t]here is now fairly strong evidence from both experimental work and commercial crops that a well grown NFT tomato crop is capable of outyielding comparable crops grown either in soil or peat, and provided the system is managed carefully fruit quality is improved.”39 Graves (1983, 5) was predicting wide-spread automation and characterized the total ecology of this “closed system” cropping as one “in which all the variables (e.g., nutritional status, water uptake, oxygen concentration,
temperature) can be measured and therefore controlled.” It was also becoming the basis for early thinking on the development of vertical farming systems (Graves 1983). A brave new world of reduced labor requirements and automation was starting to yield significant commercial benefits to growers as a result of the detailed innovatory activity undertaken in translating different forms of knowledge, and attempts to overcome biophysical difficulties, into growing technologies. But it required higher levels of capital intensity and investment, resulting in the consolidation of capital in the sector, since state grants favored larger growers able to cofund investments. However, the Thatcher government’s dramatic cuts to agricultural and scientific research (Dixon 1994; Myelnikov 2017) meant that by 1985 the ministry of agriculture’s chief scientist was recommending “that there should be no more work on NFT” at the GCRI, since staff reductions started to bite and research programs were rolled back. The consequence was that growers were left to implement the earlier combinatorial innovations that had, by the 1980s, become a standard set of technologies underpinning hydroponics.

Conclusions

The development of hydroponic capital involved a lengthy process of collaboration and innovation among a range of regionalized actors (scientists, growers, advisory workers, industry bodies) in the development of a new set of cropping technologies and processes aimed at pathogenic avoidance and reduced labor inputs. It was not, however, a smooth process, as the objective of creating a total ecology involved very significant difficulties over how to enable NFT technologies to maximize yield and minimize costs, problems that arose largely from the attempt to control biophysical growing processes, including uncertain plant and cropping issues (pathogens, NFT technology that did not respond well to development, etc.). The localized, multiactor cluster collaborations seen in the development of hydroponic capital can therefore be explained as responses to the struggles that scientists and growers had with the biophysical properties of plants, necessitating the combination of analytical and synthetic knowledges (see Table 4). In making this argument, this article has contributed to debates on the economic geography and practice of innovation through a focus on explaining the sociotechnical processes of new technology development that arise through knowledge base combinations (e.g., Moodysson, Coenen, and Asheim 2008; Grillitsch, Martin, and Srholec 2017). As such, through constructing a set of explanations based on the combination of actors and knowledge bases with their roots in dealing with biophysical properties of agrifood production, the article has provided a more causal explanation for knowledge base combinations than that often found in the existing literature as well as extending the sectoral focus of work in this area to agrifood. It has also moved beyond existing interdisciplinary research on agrifood innovation systems, which has tended to categorize network actors, how they orchestrate innovation, and the role of innovation brokers in this process, leading to studies examining how to optimize the organization of actors in the innovation process (e.g., Batterink et al. 2010; Klerkx,

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41 West Sussex Growers Association, Glasshouse and General Committee meeting minutes, 25 July 1985. WSRO WSGA 1/3/16.
van Mierlo, and Leeuwis 2012; Klerkx and Begemann 2020). The article has done so by seeking an explanation for agrifood innovation actor and knowledge combinations as an outcome of the political economy of intensification in association with the management of biophysicality. In agrifood, the innovation process was one in which significant natural limits derived from plant characteristics and pathogenic influences had to be faced, and new techniques and protocols developed collaboratively to establish the basis on which hydroponics became the key mechanism for intensification of production and the recalibration of production and labor time (Mann and Dickinson 1978; Henderson 1998). There is therefore scope to extend this kind of explanatory analysis to why particular forms of knowledge and innovation take the forms they do to the political economic dynamics of other sectors beyond agrifood.

Through this discussion of hydroponic innovation, the article has emphasized how growers and scientists worked collaboratively in their struggle with biophysical processes to intensify crop cultivation in glasshouse horticulture. It was a nonlinear innovation process fraught with false starts and difficulties thrown up by having to deal with the lively biophysical qualities of plants and pathogens. It was precisely the process of dealing with this biophysicality that necessitated the combination of knowledge bases, and resulted in significant labor saving and intensification of cropping in glasshouse food production. As such, the article has extended two main debates. The first contribution relates to the need to provide granular analysis of the precise processes of innovation that enabled a reconfiguration of the relationship between the intensification of the circulation of capital and the production and labor time calculus. The role that hydroponics played in the extension of the number of cropping cycles and the intensification of production, enabling improved yields and reduced labor inputs, has been emphasized. Hydroponic innovation became a way to intensify the circulation time for capital and its realization by reducing the gaps between cycles of crop growing (cf. FitzSimmons 1986), while simultaneously reducing the labor requirements of growers and associated labor costs. It thereby enabled a greater “number of turnovers a given capital can complete within a set period of time” (Mann and Dickinson 1978, 473). In this sense, the article has extended agrarian political economy, economic geographical, and political ecological debates over the commodification of nature time. Through its focus on the temporal speedup of growing processes enabled by hydroponics, as the basis for establishing highly capitalized glasshouse businesses that I have characterized as hydroponic capital, the article has extended treatments of the changing, socially engineered temporality of biophysical growing processes in other sectors such as forestry (e.g., Gibson and Warren [2020] on what they call arboreal time; see also Prudham [2005]). This is done through a focus on the simultaneous articulation of knowledge bases enabling a reduction of labor inputs and an intensification of crop production. Indeed, this was the central tenet of Mann and Dickinson’s (1978) distinction between production time and labor time. However, the argument pursued here has been that through enhancing relative surplus value, hydroponics enabled a different resolution to the nonidentity question, not by reducing production time per se and enhancing the realization of value within a single cropping cycle, but rather by the multiplication of the number of cropping regimes over time as a result of the reduction of time required for soil sterilization and pathogen clean up.
The second contribution relates to the need to better explain the ways in which different constellations of actors and knowledge bases combine in the innovation process (Asheim, Grillitsch, and Trippl 2017), and how understanding the wider dynamics of capital intensification and circulatory speedup emerges from a set of articulated human actors and social agents grappling with the innovation processes in the context of a range of unruly biophysical forces. Technoscientific research and grower experimentation and innovation combined in critical ways, distinct from the focus on biotechnology and seed innovation (Kloppenburg 1988), to create the basis for capital intensification in hydroponics. Knowledge bases combine in agrifood innovation precisely because of the uncertainties of biophysical properties that the innovation process is seeking to overcome. Partly because of this innovation, and despite the complexity of knowledge combinations involved, hydroponics had become the dominant growing technology in high-value glasshouse agrifood production by the end of the twentieth century (Morgan 2021). However, contemporary challenges around labor supply crises and escalating energy costs are today establishing the basis for a new set of innovatory processes, centered around the use of artificial intelligence and robotics technologies in the form of AgTech (Stock and Gardezi 2021; Smith 2023), raising new questions over how biophysicality can be tamed. In addition, attempts to devise new energy-sustainable growing practices in the context of climate crisis are presaging a new era of capital intensification as new investment actors, such as pension funds, enter agrifood (cf. Fairbairn 2020). Hydroponic cultivation, along with computer-controlled climate and labor regulation systems (Smith 2023), however, provide an already existing basis for further rounds of automation and energy sustainability. Hydroponic capital has perhaps come of age.

References

———. 1976d. NFT package deal should be on offer next year, say ICI. *The Grower*, November 4 1976.


