NUFFIELD UK

# A Nuffield Farming Scholarships Trust Report

*Award sponsored by*

**The Worshipful Company of Gardeners & The Worshipful Company of Fruiterers**

The Worshipful Company of GARDENERS

DEUS DAT INCREMENTUM

The Worshipful Company of FRUITERERS

# Where next for soft fruit in the UK?

**Dr Richard Harrison**

**June 2019**

**NUFFIELD FARMING SCHOLARSHIPS TRUST (UK)**

**Awarding life changing Scholarships that unlock individual potential and broaden horizons through study and travel overseas, with a view to developing farming and agricultural industries.**

**"Leading positive change in agriculture"**

"Nuffield Farming" study awards give a unique opportunity to stand back from your day-to-day occupation and to research a subject of interest to you. Academic qualifications are not essential, but you will need to persuade the Selection Committee that you have the qualities to make the best use of an opportunity that is given to only a few – approximately 20 each year.

Scholarships are open to those who work in farming, food, horticulture, rural and associated industries or are in a position to influence these industries. You must be a resident in the UK. Applicants must be aged between 22 and 45 years (the upper age limit is 45 on 31st July in the year of application). There is no requirement for academic qualifications, but applicants will already be well established in their career and demonstrate a passion for the industry they work in and be three years post tertiary education. Scholarships are not awarded to anyone in full-time education or to further research projects.

Full details of the Nuffield Farming Scholarships can be seen on the Trust's website: www.nuffieldscholar.org. Application forms can be downloaded but only online submission is accepted.

Closing date for completed applications is the 31st July each year.



ISBN: 978-1-912059-14-0
Published by The Nuffield Farming Scholarships Trust
Southill Farm, Staple Fitzpaine, Taunton, TA3 5SH
Tel: 01460 234012
Email: director@nuffieldscholar.org
www.nuffieldscholar.org

# A Nuffield (UK) Farming Scholarships Trust Report

Date of report: June 2019

*"Leading positive change in agriculture. Inspiring passion and potential in people."*

| | |
|---|---|
| Title | Where next for soft fruit in the UK? Addressing the yield gap and providing a path to 500 t/ha |
| Scholar | Dr Richard Harrison |
| Sponsor | The Worshipful Company of Gardeners & The Worshipful Company of Fruiterers |
| Objectives of Study Tour | This study tour considered how to improve efficiency and productivity in the soft fruit industry in the face of increasing uncertainty (political, environmental & economic). Key objectives were to:<br><br>1. Understand some of the key developments in research and technology<br>2. Estimate whether it is realistic for deployment, on farm, of new technology and whether these are sustainable<br>3. Identify the barriers to new technology being adopted and potential solutions |
| Countries Visited | UK, USA, Canada, Netherlands, South Africa |
| Messages | 1. Genetics is an easy way to make environmentally sustainable yield gain in horticultural crops- we have more tools than ever before and the UK is well-placed to lead<br>2. Energy consumption in agriculture is rising and new production systems must 'design to avoid' and be developed with an awareness of wider energy and sustainability policies<br>3. It is currently very hard to say what is good and bad; more sophisticated lifecycle analysis and digital twinning is needed to quantify externalities of production and shape the design of new systems<br>4. In a new UK agricultural policy landscape there could be further direct incentives to lower fossil fuel energy and transfer to renewable usage through a "produce or reduce" energy incentivisation scheme for green energy.<br>5. Every consumer is responsible, but largely unaware of our actions. Technology could help raise awareness of sustainably produced fresh produce and help shift consumer behaviour |

# EXECUTIVE SUMMARY

Horticulture is often highly productive and uses cutting-edge technology to find new and innovative ways of extending cropping seasons. High value crop production is often energy and resource intensive, especially in our cooler northern climate. I conclude that through the use of new genetics tools, designing higher yielding plants is possible and has the potential to make environmentally sustainable yield gains, especially in soft fruit crops such as strawberry that lend themselves to intensive production systems. Scientists and breeders have more tools than ever before and the UK is well placed to lead in this area.

However, it is also clear that nationally and globally energy consumption, including in horticulture, is rising, driven by increasing demand for year-round supply of fresh fruit and vegetables, growing populations, increasing affluence and relatively low-cost energy. In intensive horticulture, heat predominantly comes from the combustion of natural gas, without a widely deployable, cost-effective renewable alternative. New production systems must 'design to avoid' fossil fuel usage; current systems founded on what makes 'economic sense' do not fully integrate the true externality of costs. If this problem remains unaddressed, it is possible that in the short-term, horticultural-associated emissions will rise not fall, and in the long-term, total energy demand and cost (at least in the UK) may render intensive horticulture uneconomical. This would be disastrous for both food security and for access to affordable nutritious food. As a consequence, improved tools and analyses, such as dynamic life cycle assessment (LCA), coupled to novel modelling and digital twinning approaches, are urgently needed to quantify externalities of production and provide evidence for where research efforts and potential interventions to enable low carbon, low energy alternatives should be directed. In a new policy landscape there could be further, evidence based, direct incentives to lower fossil fuel energy and transfer to renewable energy usage through a 'produce or reduce' incentivisation scheme, as used in other areas of the world.

More generally, I conclude that every consumer is responsible for our current food system, but we are largely unaware of our actions, or are unable to act, either due to cost or lack of high-quality information. Technology could help both address the latter issue and raise awareness, facilitating a shift in consumer behaviour, but it is also necessary that there is a greater joining up of policy, to ensure that the many unintended consequences of our current interconnected food and infrastructure network are mitigated. This requires coordinated action from the whole food chain, otherwise it is highly likely that as a nation we will miss our targets for decarbonisation and climate change mitigation despite the potential to sustainably intensify domestic production.

# Contents

# DISCLAIMER



**DEDICATION**

To Nicola, Millie, Thomas and Thérèse- my life is incomplete without you; thank you for helping me on my journey.

**CONTACT DETAILS**

Dr Richard Harrison
NIAB
73 Lawrence Weaver Road
Cambridge
CB3 0LE

Email- richard.harrison@niab.com
Twitter- @harryinashed

Nuffield Farming Scholars are available to speak to NFU Branches, Agricultural Discussion Groups and similar organisations

*Published by The Nuffield Farming Scholarships Trust*
*Southill Farmhouse, Staple Fitzpaine, Taunton TA3 5SH*
*Tel : 01460 234012*
*email : director@nuffieldscholar.org*
*www.nuffieldscholar.org*

## Introduction

### Background to scholar and project

I began my career with a degree in Biological Sciences at the University of Lancaster. I was drawn to biology through a sense of wonder at how order could assemble from chaos and a desire to understand both the rules of life on earth and the fundamental processes that could lead from nothing, to life itself, to complex, thinking organisms. I pursued a route in biology that was heavily guided by mathematical modelling of complex systems. Firstly, in my PhD at the University of Manchester, modelling and testing the organisation and environmental dependency of metabolic networks, and secondly, in a Medical Research Council fellowship in population genetics at the University of Edinburgh. In this latter post I explored how populations evolve, how natural selection can be quantified at the molecular level, and how these tools can be used to understand the process by which order can evolve from random chance.
Due to the influence of my wife, Nikki Harrison, my interests began to focus around how we have exerted selection on plants through the domestication process, which took me into the sphere of plant genetics. Approaching the end of my time in Edinburgh and based upon my growing interest in crop domestication, I found myself applying for a job that demanded a slightly firmer grasp upon the practical application of genetics, my scientific specialism. That job was at East Malling Research (now NIAB EMR) where I found a wide range of practical questions that could be addressed by the latest thinking in genomics, informatics and genetics, skills which I had developed in the previous seven years. My work focussed on providing practical solutions to plant improvement through the examination of fundamental processes. I was helped along the way by a few key individuals in the fruit industry who shared this worldview, in particular Richard Harnden of Berry Gardens, whose enthusiasm, support was gratefully received. In horticulture, I saw fascinating biological questions which, if answered, could also help the industry improve productivity and sustainability. In 2016 I was promoted to lead the genetics department at NIAB EMR. In this role, which was more strategic in nature, I was looking for ways to further my experience and at the suggestion of NIAB's CEO, Tina Barsby, I applied for a Nuffield Scholarship.
I focussed the application on my observation that in terms of yield per hectare, there is an 8-10 fold difference between tomatoes and strawberries. Reading around the topic a little and knowing a reasonable amount by now about strawberry breeding and genetics (and the programmes at East Malling), I calculated the theoretical yield potential to be somewhere around 500 tonnes/hectare. I therefore framed my Nuffield topic around assessing: 1) what further research was needed to reach this step change, 2) what the barriers to adoption of new technologies were, 3) how sustainable intensification of production would be (as often intensification increases the input of energy) and 4) how the UK's changing position in the world would affect the agri-food sector, in particular fresh fruit production, and whether it would increase or decrease the need for intensification.
Through my studies and throughout this report, it became clear to me that the third and fourth of these points were by far the most important. Therefore, much of my report is framed around the changing global patterns of wealth and prosperity (detailed in Appendix 1) and the steps required for truly sustainable intensification, which must be a system in which genetic innovation (Appendix 2) and renewable energy (Appendix 3) are harnessed, net emissions of greenhouse gases are zero, and the negative externality costs of our current food system are internalised.

# UK strawberry production and market

## Market overview and consumer demand

Against a backdrop of declining UK consumption of fresh fruit and vegetables, soft fruit shows positive growth year on year (figure 1).

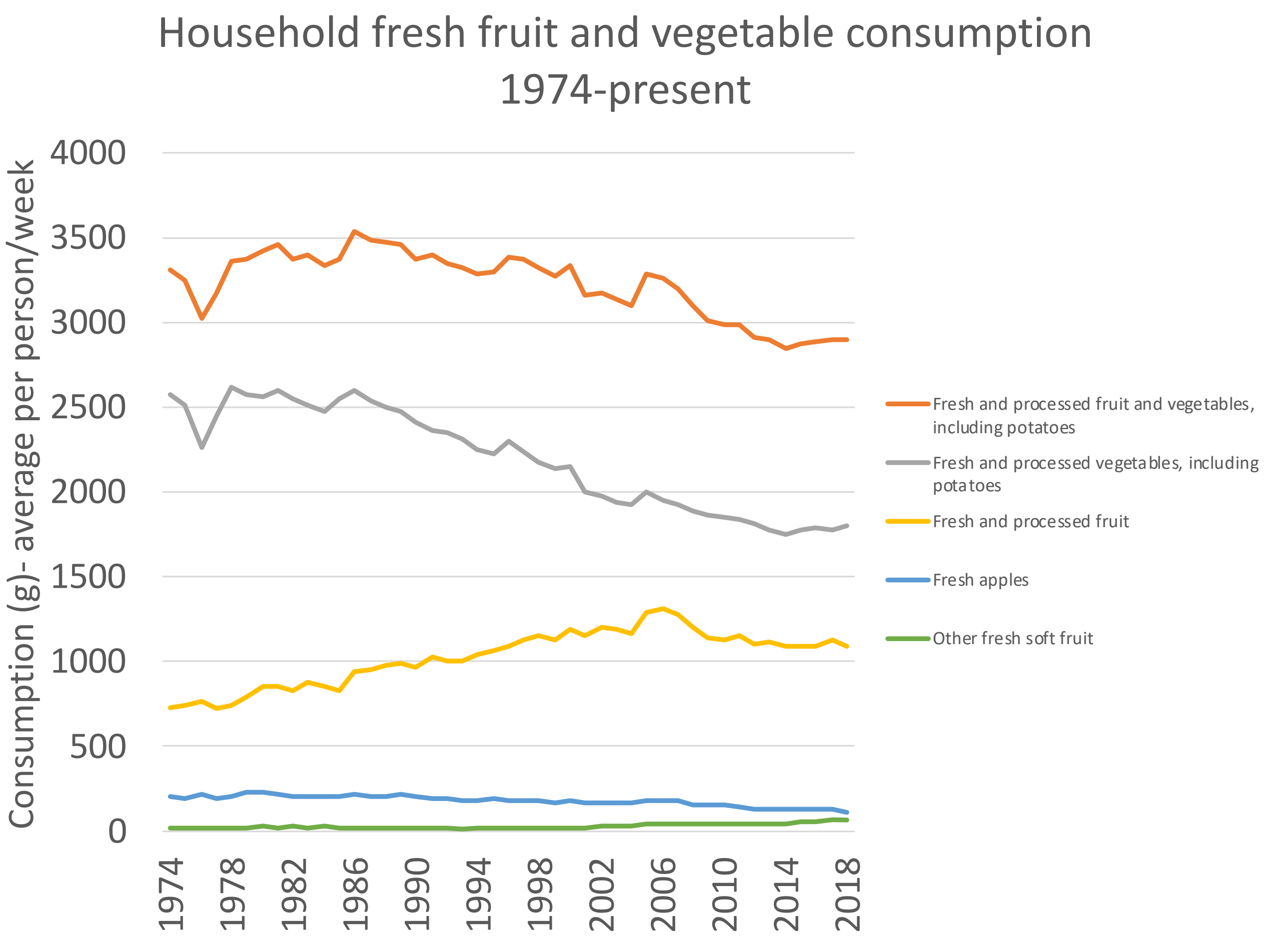


***Figure 1****. Soft fruit shows a positive trajectory in terms of per capita weekly consumption in the UK, but only makes a small contribution to diets. Raw data from ONS and Defra.*

Over the past thirty years there have been significant changes in the way that fruit is produced in the UK. The nadir of UK fruit production occurred around 2003, by which time the cropping area had decreased by around 15000 ha from its 1985 value. Strawberry production in the UK has transformed over the past fifteen years, which can be reflected in the U-shaped profile in cropping area (figure 2).

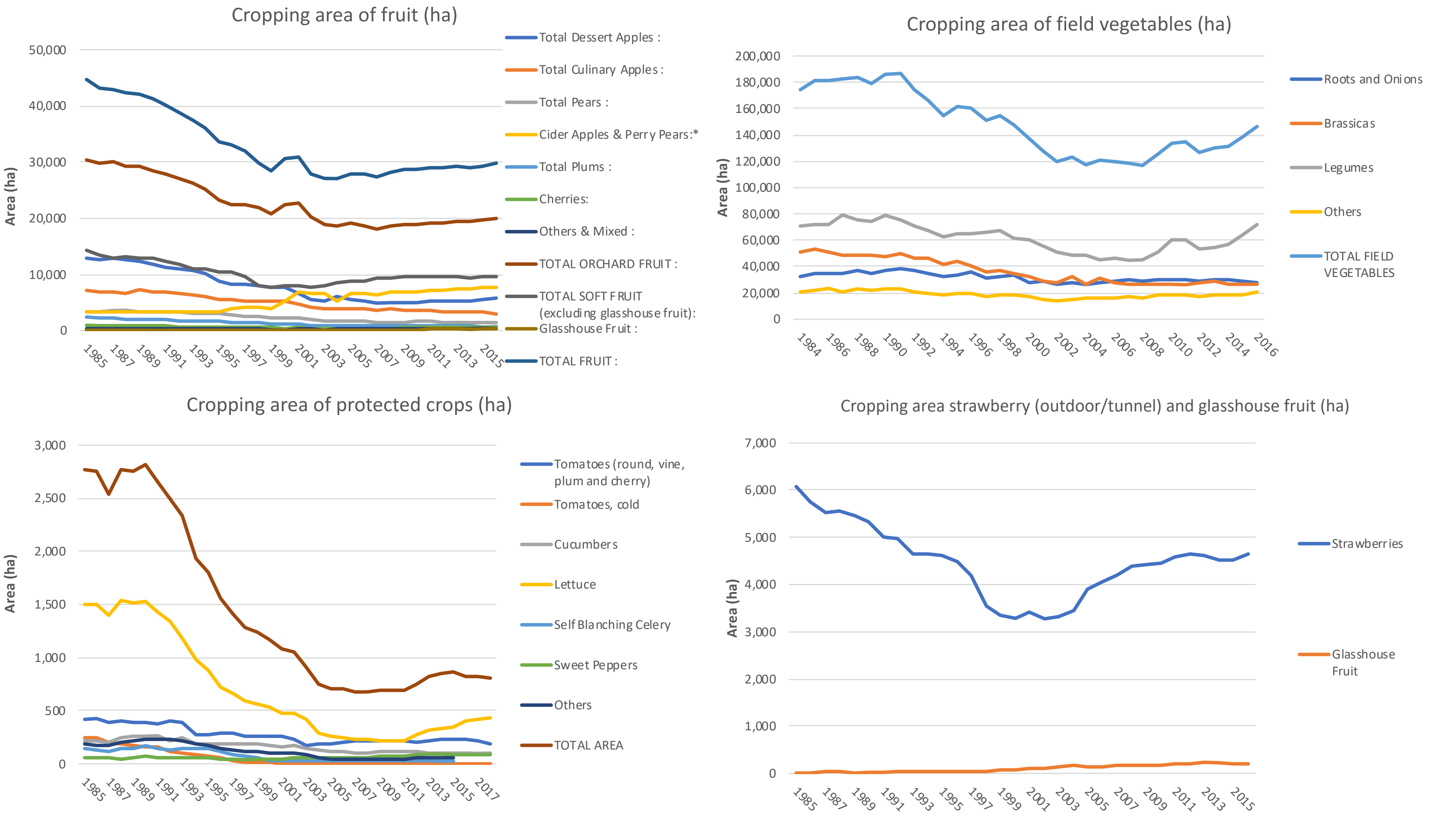


***Figure 2**. Cropping area of horticultural categories in general has declined, though strawberries show a slightly different pattern, due to the transition from open field to polytunnel production. Raw data from ONS and Defra.*

While a decline in growing area appears to have been a trend across vegetables and protected crops, there have been large changes in the level of intensification of tomatoes, with yields doubling between 1985 and 2000. Over the period 2000-2015 strawberry yields more than doubled on average rising from ~11.5t/ha to 26 t/ha. However, yields remain some 16 times lower on average than tomato (figure 3).

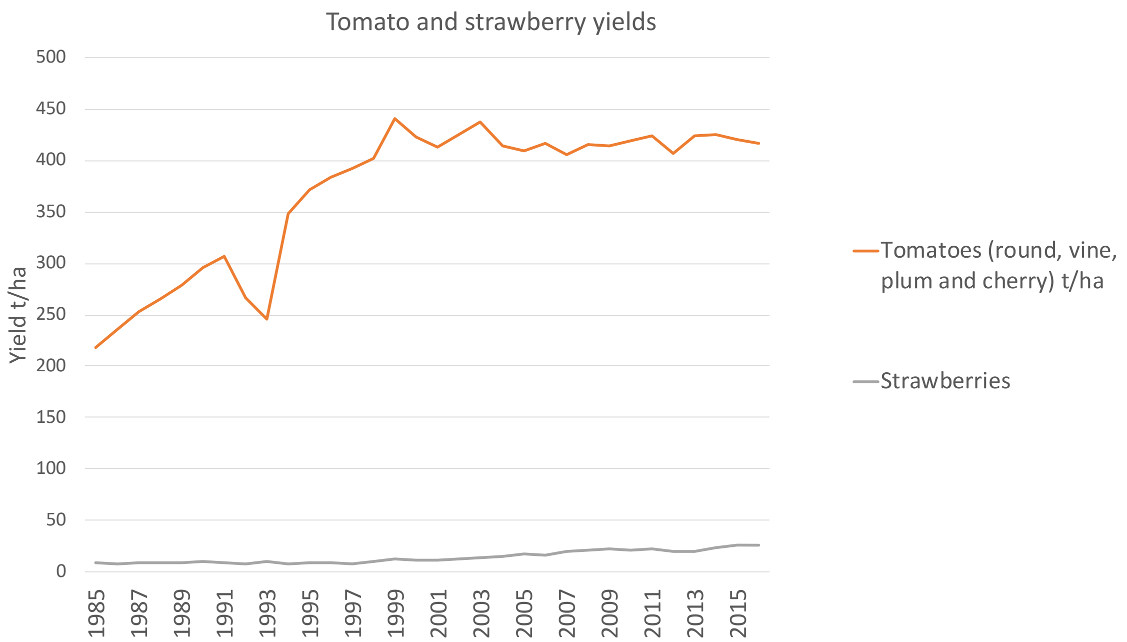


***Figure 3.*** *Tomato production has shown large increases in yield over the past thirty years, but has remained largely constant since the early 2000s. In contrast, strawberry yields are increasing, albeit from a much lower base. Raw data from Defra Basic Horticultural Statistics.*

Soft fruit now represents around 22% of all consumer fruit purchases in the UK and consumption has more than doubled between 1996 and 2015 (Pelham, 2017). Imports and exports have remained fairly static over the past 10 years, while home production has grown significantly. We are now around 70% self-sufficient in strawberries (figure 4).

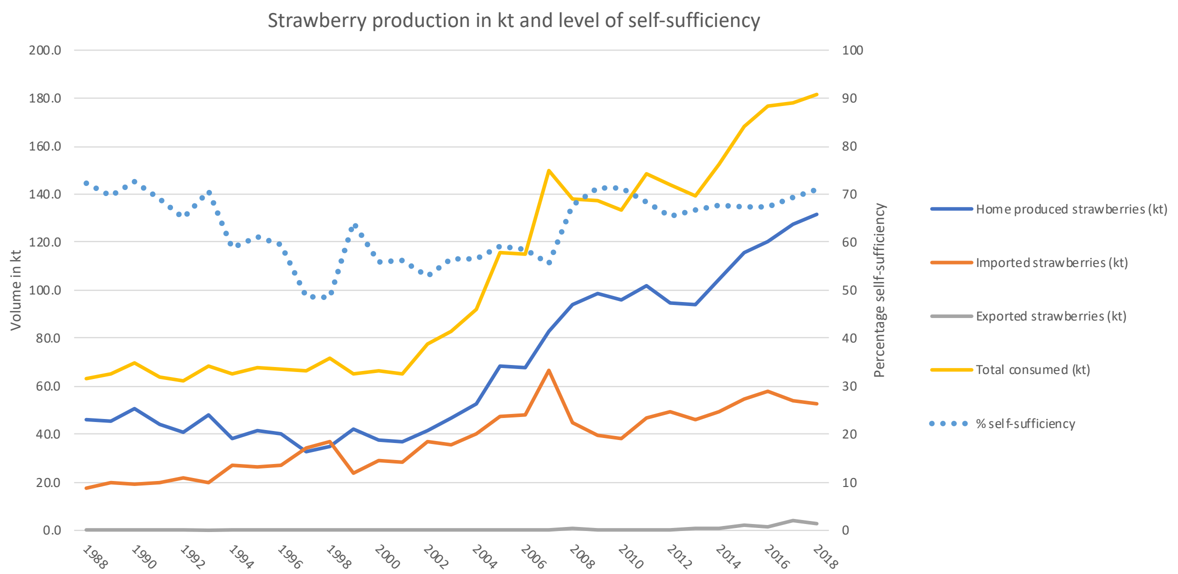


***Figure 4****. Production and import of strawberries and levels of self-sufficiency. Raw data from ONS and Defra.*

While not conclusive, as many factors can affect price and consumption, a relationship can be seen between levels of consumption and price per kilogram of strawberries. Taking all available data, a highly significant negative correlation can be seen (Spearman rank -0.84) between per capita consumption and inflation-adjusted price per kilo (figure 5). This is suggestive of a strong relationship between price and consumption.

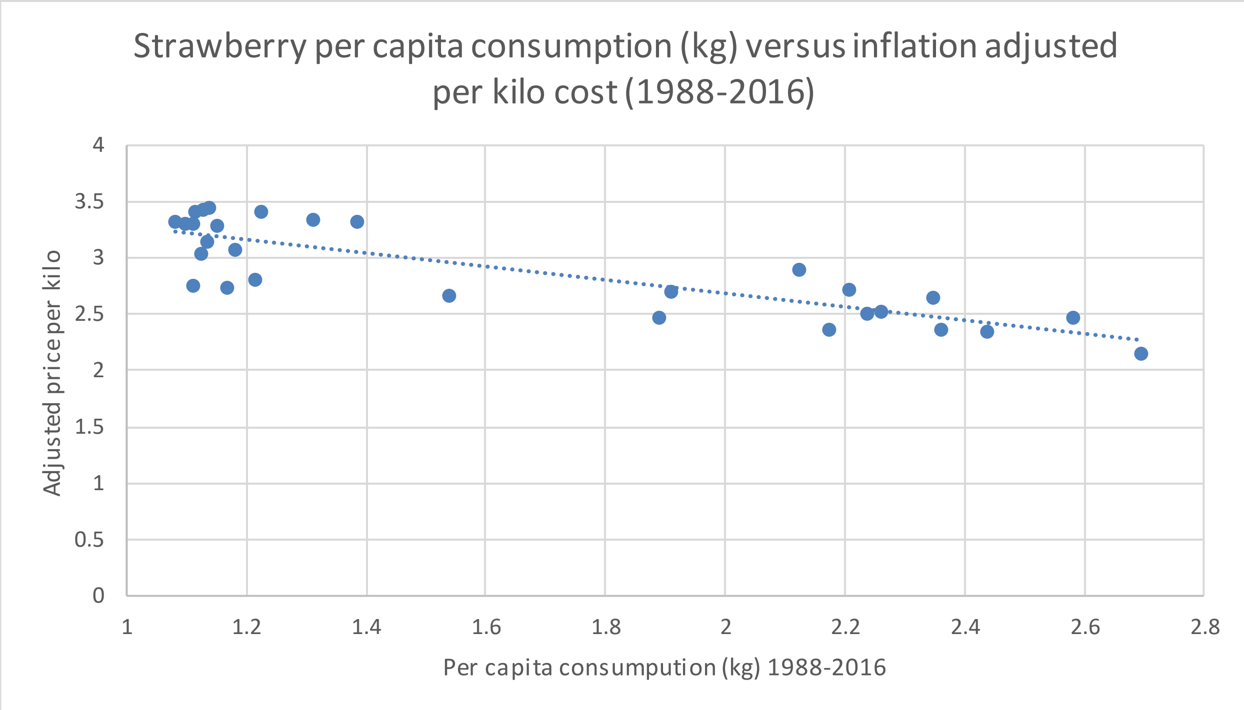


***Figure 5.*** *A strong negative relationship is observed between per capita consumption and inflation adjusted price per kilo of strawberries Raw data from ONS and Defra* (ONS & Defra, 2018).

Over time, the price of strawberries has decreased in real terms between 1988 and the present day, which may in part explain the rise in consumption that has been observed (figure 6).

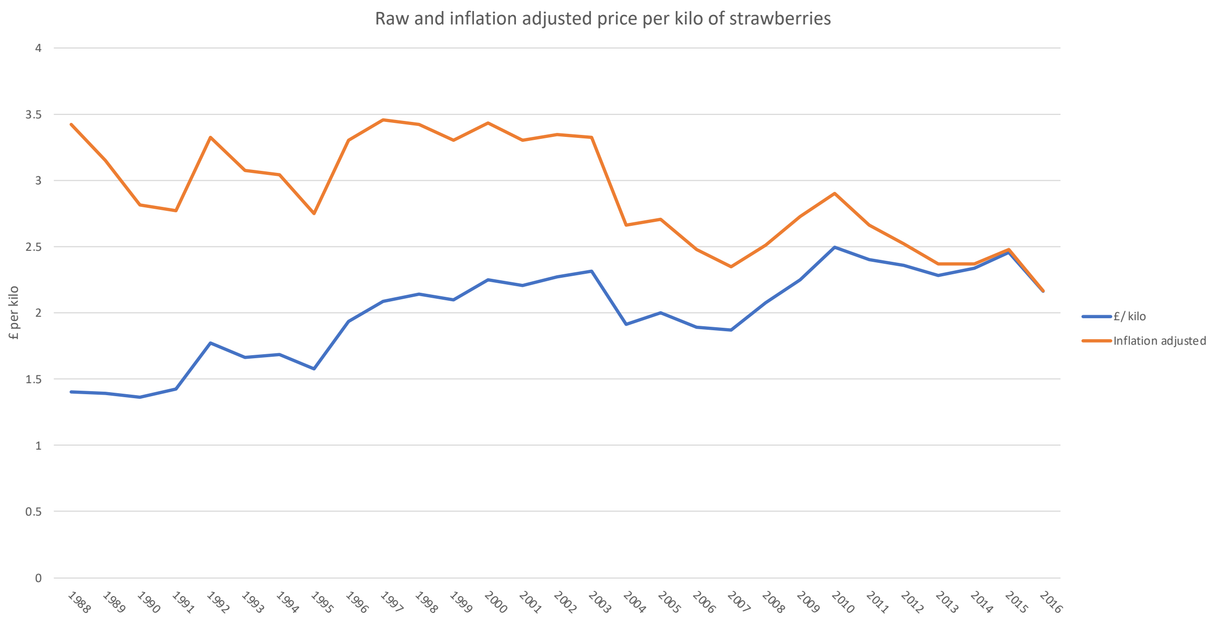

***Figure 6****. Raw and inflation-adjusted prices of strawberries per kilo Raw data from ONS and Defra*.

## The importance of horticultural produce in health and society

The consumption of fruit and vegetables are crucial to a healthy lifespan. The Eatwell guide [1], produced in 2016, illustrates well the need for boosted consumption of fresh fruit and vegetables. It is estimated that for every £1 spent on food there is an additional cost of £1 incurred to society, through damage to the environment and to our own health. Poor diet has an enormous effect on long term health and many chronic conditions are directly attributable to a poor diet (Poppy & Baverstock, 2019). Worse still, a recent survey by the food standards agency revealed that in the UK around 4 million people could not afford to buy the Eatwell diet[2] highlighting a major social challenge. The EAT Lancet commission goes even further and states that 'Food in the Anthropocene represents one of the greatest health and environmental challenges of the 21st Century'[3].

There is therefore an assembling consensus that affordability of horticultural produce and the design of the food system is crucial for the effective and economical functioning of society and our health (Miller et al., 2016; Poppy & Baverstock, 2019).

## Changing supply chains

In recent years, after enjoying many years of highly profitable production, there is once again a squeeze on producers, and margins have significantly tightened. From the wide range of conversations that I have had with the UK industry during my study tour, there appear to be multiple factors affecting profitability, some of which are pre-farm gate and some are as a result of our national supply chain. Post farm gate, the primary problems appear to be with the constant retail pressure to lower prices. This is driven by supermarkets attempting to depress food prices despite significant inflationary pressures since Brexit. Inflation pre-2016 was close to 0% while post Brexit, this rose to 3% and has stabilised at around 2% in recent months (March-June 2019). Rather than passing the cost to the consumer, supermarkets have attempted to strip cost out of the supply chain, which has impacted margins. Secondly, the intensifying price war between the established supermarkets and rapacious discounters has further contributed to a reduction in profitability. The established supermarkets fall into two camps, those propping up failing retail businesses and those with large real estate holdings with 24 hours multi-choice offers. These can be contrasted with more nimble discounters that hold fewer product skews (especially premium offers) and generally have different supply chain compositions. In recent years these pressures have led to the loss of 'middle men' in the supply chain (marketing desks) and supermarkets have preferred to go 'direct' to growers. This has altered the dynamics in the supply chain significantly, and many soft fruit growers I spoke to were concerned about a 'race to the bottom' as has happened in other horticultural sectors. This should be of concern to everyone, as stripping out margin from the supply chain seriously hampers businesses in the key areas of capital investment and research and development. If sustained, over the longer term this strips skill out of the sector and decreases resilience to future market changes.

## Production - broad overview

Pre-farm gate there are other forces that are acting to alter the constitution of a typical soft fruit farm. Today a typical soft fruit farm would grow strawberries in vented polytunnels, on a raised gutter system in substrate bags. They would typically plant around 40,000-60,000 plants per hectare (depending upon the variety), first as a programmed crop, where cold-stored plants are sequentially planted to even out production, optimising the cropping window to gain the most favourable price (despite the yield penalty of this cropping system), and then often overwinter for a second year June 'main-crop' which, with a typical crop, would mature at the 'peak' of the season, but provide higher yields. All harvesting would be manual, using migrant labour, who typically live on the farm, but packing would increasingly use automation. The grower may choose to grow a selection of 'day neutral' (also known as everbearing) plants, which have a

[1] https://www.nhs.uk/live-well/eat-well/the-eatwell-guide/
[2] https://www.theguardian.com/society/2018/sep/05/four-million-uk-children-too-poor-to-have-a-healthy-diet-study-finds
[3] https://eatforum.org/eat-lancet-commission/

far higher yield and produce crop throughout the summer, rather than just in June. Again, a careful trade-off between yield, market supply and labour costs will be considered when deciding how much 'June bearing' and how much 'day-neutral' to plant. Increasingly automated irrigation is used, the most sophisticated systems using models that take into account the plant's demand for water through the use of feedback loops between in-crop sensors and the fertigation system. The most advanced growers may have their irrigation system 'talking' to their venting system in their tunnels to optimise plant performance through dynamic temperature control. The very best growers may achieve yields of 60 tonnes per hectare on a second-year main crop. A small fraction of growers grow in glasshouses, though at present this represents a tiny proportion of the acreage. They often focus on out-of-season production and command a higher price for their crop.

### Labour

Ask any farmer what their biggest concerns are for the coming season and it is likely that the list you will get will start with the largest line items in their budget and continue in descending order of direct costs: labour, loan repayments, substrate, fertiliser and chemicals, energy and water. Throughout my travels, I have found that for most strawberry growers the supply and cost of labour is a primary concern, whether in North America, mainland Europe or the UK.

For many in the UK, concerns over the availability and increasing cost of seasonal labour, even putting BREXIT to one side, are hastening the drive for efficiency and intensification. Anything that increases picking efficiencies can mean the difference between a profitable season and a loss making one. Two large changes that have been seen over the past ten years are the uptake in 'table-top' structures in polytunnels, allowing pickers to stand, rather than crouch, while picking, and varieties with a simplified truss architecture, with fewer, well displayed, larger fruit per plant, both increasing picking times and decreasing class II fruits.

### Water, fertiliser and energy

Energy, usually does not enter into the conversation when it comes to the cost of production. For the vast majority of strawberries being produced, once plants are out of cold storage and in their coir bags in polytunnels, there is no supplemental heat applied to them, nor supplementary lighting. The growers simply need fuel for the tractors, sprayers and irrigation rigs. The situation is very different in glasshouse production systems. The better growers have invested in combined heat and power systems at times when there were favourable energy contracts, which in part allow them to operate profitably despite significant energy costs. This is explored in much greater detail in Appendix 3, while a broader look at energy is explored in Appendix 1.

### State of the art

One of my first visits within the UK as part of my Nuffield scholarship was to Tiptree farms. One reason in particular I had wanted to visit Tiptree was their recent investment in a new generation of growing systems for strawberry, their *Next Generation System* (figure 7). Their system maximises the production area, cropping 100% of the area due to a novel cantilevered system allowing a plant density of up to 200,000 plants per hectare, though in practice the density used is far lower. Farming in the driest part of Essex, the rainwater capture system maximises capture of rainfall, allowing abstraction to be minimised. André, the farm manager, told me that they are around 90% sufficient in water from rainwater and that they have cut their irrigation requirements from 150L/kg of strawberries to 50L/kg. A fully enclosed but passively heated system, with automated roof venting and fans, allows a longer production system, with the ancillary benefits of reducing pest and disease pressure by maintaining airflow and reducing the opportunity for pest invasion. Through conversation with André and Chris Newnham, the joint MD of Tiptree, the system is a success, so much so that they're planning on rolling it out across the business. They reported yields in excess of 110 tonnes/hectare in this system.

***Figure 7***. *The novel cantilevered growing system at Tiptree effectively doubles the plant density.*

## Is there a yield gap?

Given that the industry average sits at around 25 t/ha and the Tiptree system is able to deliver over 100 t/ha, it is heartening that a four-fold yield improvement can be delivered from agronomic improvements alone. This alone is enough to justify the conclusion that there is a significant yield gap on many grower sites. In Appendix 2 I look at some of the genetic innovations that could be coupled to improvements in agronomy to both close the yield gap and drive innovation in growing systems. Appendix 2 elaborates some of the parallel research that I was carrying out as I travelled around visiting different production systems around the world.

# Global horticultural production and innovation

It was important for my study that I received a wider view of production than I had so far seen. I therefore decided to visit South Africa, California and the Netherlands to see different elements of production in these countries and form a view on the various factors affecting production in these areas. Each has its own particular challenges and I was keen to explore how learning about these challenges may inform reform and progress in the UK. Some of this text is adapted from a blog post I wrote while travelling in South Africa. Before you read this chapter, it may be worthwhile reading Appendix 1, to get a broader view of some of the differences between global economies.

## Farming for export in South Africa

### South Africa- Cape Town

On arriving in Cape Town in March 2018 the evidence was everywhere that this is a city in crisis (figure 8). Prominent notices were strung up around the airport and large displays highlighted the importance of water and the current major scarcity. Coming from the UK, it's hard to truly appreciate what water scarcity feels like, although in the South East of England we have been perilously close at times to standpipes in the streets.


***Figure 8**. Cape Town airport, March 2018.*

At the time of my visit the Sunday Times[1] stated that there had been no significant rainfall in the past three years, this is against a reported average of 788mm[2] – actually more than reported for my home in North Kent[3] (650mm). Some action has been taken – the same Times article reports that Cape Town residents have been able to cut their water consumption by 60 percent in three years - indicating that things can certainly be done to reduce water needs when collective action (and nudge policies) are used effectively. However, more is at play here than first meets the eye. Yes, there is a severe water shortage, but there is also (I was told by several) an infrastructure issue due to increased migration into the outskirts of Cape Town (into the townships and camps) and therefore a 'double whammy' of drought plus increased demand. This latter feature - demand due to population increase - is one that cropped up time and time again in different guises during my visit.

## The University

Having spent a couple of days working in Cape Town (and being very careful with my water consumption), I headed East to Stellenbosch. While in Stellenbosch I took a little time to meet some academics at the university. I was kindly hosted by Prof. Rouvay Roodt-Wilding, a population geneticist in the Genetics Department at Stellenbosch. I met some of her colleagues and we discussed a little about mutual research interests. Of importance for my Nuffield was that very little is done on soft fruit in the university or in the ARC- the government-funded research institutes, meaning that most of the systems that have been developed in South Africa (SA) have been transplanted from the UK.

***Figure 9**. The road to Haygrove Heaven*

[1] *Source*: https://www.timeslive.co.za/news/south-africa/2018-03-19-drought-stricken-cape-town-counts-the-cost/

[2] *Source:* http://www.saexplorer.co.za/south-africa/climate/cape_town_climate.asp

[3] *Source:* https://www.metoffice.gov.uk/research/climate/maps-and-data/regional-climates/index#rainfall

## Haygrove Heaven

From Stellenbosch I drove to Hermanus, in the Hemel en Aarde valley, where Haygrove Heaven is situated (figure 9). I met the co-owner, Sean Tager, who was kind enough to talk through the Haygrove SA business with me and its impressive growth over the past ten years. Serving both the domestic market and the export markets in Europe and, increasingly, Asia, the businesses goal is to serve production windows that maximise price. To my surprise, strawberries are a minor focus of the business, with raspberries providing the major market both domestically and internationally. Sean explained that there is not really a strawberry culture in SA and so with limited demand prices remain high, in turn limiting market access. Most of their strawberries are grown at the Eden site, which was next on my list to visit.

## Haygrove Eden

At Eden I had the pleasure of meeting Dirk Rabie, the farm business manager for Haygrove Eden. Dirk is passionate about what he does and despite having only 7 months in the job, has a firm grasp on all aspects of production. Without giving too much away, the whole operation is impressive and is a really a well-integrated operation. Unlike many UK grower businesses, Haygrove SA take high-health plants from micropropagation through to mother stock and propagate all of their own material for production. This allows them total control over most aspects of production. Furthermore, an aligned business, Haygrove Tunnels SA, produces the structures under which fruit is produced, allowing innovation in tunnel design and production to go hand in hand. Dirk and I had an extensive conversation about the propagation and growing of strawberries, which I shall spare you the details of, but suffice it to say, they are doing a lot of things right and in some ways much better than we do back at home.

## The wider issues

Whether it is apples, blueberries, citrus, raspberries or strawberries, fruit in SA is an important part of the economy. However, there are a number of challenges which need to be addressed for the South African industry to remain buoyant:

- Water and a changing climate
- Labour – wages and unions
- Markets- tariffs, other competition and new markets
- Land and politics

## Water and a changing climate

Irrigation is the norm in SA for apple and berry production with about 5000 cubic meters of water needed per hectare, per year, in many growing regions for apples. Often, this is not a particular problem as farmers have dug their own reservoirs and boreholes. However, as one grower put it to me, “irrigation is a supplement, not a replacement”. In many regions of the Cape, water restrictions are not as severe as Cape Town, but even so, rainfall has not been normal. As I was driving from Cape Town to George (and back) I saw many reservoirs that were over 2/3 empty (though to be fair it was not the rain season). For strawberries (where natural rainfall doesn’t impact upon a covered crop), everything I saw indicated that water is used responsibly; the norm is to irrigate 4-6 times a day to a point where there is 10% run off. Haygrove has a particularly sophisticated system of irrigation scheduling though - relying on dynamic advice from a dedicated on-site team. It will be the confluence of a more variable climate and an increasing population that really will define the sustainability of fruit cultivation.

## Labour, wages and unions

The employment offered by growers is valuable, as the work pays a reasonable wage and employs large numbers of people. Haygrove alone employs around 2500 every year and runs special schemes for training and development of skills within the business - their *Bright Futures* project. Many who have gone through the Haygrove system have then gone on to set up their own operations, in joint venture programmes with Haygrove, growing both the market and the opportunities for upskilling still further. This is clearly something to be proud of, as it embeds skills locally. However, whether it is the people serving dinner in the hotels, filling up the cars, acting as parking assistants or picking fruit, it is clear that there is still an enormous wealth gap in the country. This is most evident on the outskirts of every town, where (depending upon the size of the town) the associated informal settlements and townships are large. Here you will find many living in poor conditions - some with no access to water and electricity. This is the cause, in many cases, of strikes, which in many ways are not directed at the employer, but at the government. While there is ample evidence of government action - I saw many townships where corrugated shacks had been replaced by neat houses and community facilities - it is the constant influx of migrants that places pressure on development. Looking at the government's own statistics[1] migration is set to increase by ~500,000 in the Western Cape by 2021 (currently at 6,510,300- mid 2017- national population ~57 million). There is of course still mass unemployment in SA – quoting from the government's National Development Plan 2030[2], unemployment is as high as 46.6% for black youths aged 15-24. This poses enormous challenges for the government, as (working under the assumption of a traditional economic model) the economy must grow more quickly to provide jobs. Across Africa populations are growing- some estimates project a doubling of growth by 2050 from 1.2 to 2.5 billion[3]. This is coupled with the fact that although the middle class is growing, it is not growing as much as previously thought. Somewhere between 50 and 75% of the population are either poor, or experience times of hardship, leaving only 1/4 people considered to be securely middle class (contrast that with middle income ranges from 64% in Spain to about 80% in Denmark).

### Markets- tariffs, other competition and new markets

The market for strawberries is a contrast to the raspberry market in South Africa, with a largely export-driven raspberry market, but a strawberry market focussed on domestic production. This is largely due to air freight costs (for value) and the shorter shelf-life of strawberries when compared with other crops. The market in SA is serviced by about 350-400 ha in total (the majority of which is in the North of the country)- contrast this to the UK which had around 5000 hectares, back in 2011[4]. This means that production is approximately 7% of that of the UK- when taking the population size differences into account, 10% of the UK. Strawberries are a brutal business in SA- as Dirk said to me "they keep you humble". This is primarily due to the glut of fruit in the market during the main season and the lower value per kilo than other fruits, which means that margins can be slender.

### Land, politics and prices

The land situation in SA is receiving a lot of attention of late[5], though interestingly every farmer that I spoke to said they were unconcerned about a Zimbabwe-style land grab, citing the fact that Cyril Ramaphosa is a popular choice (and respected as a man of integrity) and that (at that time) he had an election to win (and therefore might be looking for some short-term populist policy). What is more important to note though is that land is relatively expensive, which does serve as an effective barrier to entry (as it does in so many countries). Furthermore, populist policies can sometimes not go the way the government of the day expects (referenda especially!) and so a part of me wonders whether there are risks attached to the current course of action.

## Conclusions

As a result of my trip, I was left slightly more puzzled as to what the future may hold for the South African berry industry. My initial thoughts were that over the coming decades there will be a shift from export to serving a growing domestic market, primarily because there will be shifts in the viability of exports over the coming decade- environmental footprints, competition and tariffs being three major drivers of change. If the middle class grows in SA, berry consumption will probably rise, which in turn could drive profits for

[1] *Source*: http://www.statssa.gov.za/publications/P0302/P03022017.pdf
[2] *Source:* https://www.gov.za/issues/national-development-plan-2030
[3] *Source*: https://mg.co.za/article/2017-10-26-00-a-quarter-of-the-world-will-be-african-by-2050
[4] *Source:* https://vegetablegrowersnews.com/article/tunnels-varieties-double-uk-berry-yields/
[5] *Source:* https://www.independent.co.uk/news/world/africa/south-africa-white-farms-land-seizure-anc-race-relations-a8234461.html

smallholder farmers (if perhaps they joint venture with larger businesses). I am not the only one to think this- others have pointed to this market opportunity[1] and the potential for high-value horticulture to transform lives; all the evidence that I have seen suggests that it already has.

However, there is a flip side to this. Exports could suffer (for the same reasons as outlined above) but internal markets could fail to grow. What then? This would be as a result of things like the failure of the poor to rise into the middle class- climate, immigration and population growth are the three spectres that hang over the potential feast.

## Environmental pressures in California

Having been to California many times on the airport-hotel-airport cycle I was keen to spend time there and to explore aspects of innovation and the nexus of water and energy. I saw California as an analogue of what life might be like in a more energy hungry, resource insecure world.

Innovation in clean tech is badly needed in California; 20% of the state's entire energy budget goes on pumping water – and of that, 60% is directly attributable to the agriculture and food supply chain. It is well known that California has water problems. Abstraction is causing parts of the state to sink and boreholes are drilled to depths of 3km to abstract water in some farms.

I was keen to visit Fresno, America's big small town, as I had read about a number of initiatives being run out of Fresno State University that were focussed on enhancing sustainable production. Fresno is part of the Cal-State university system of 23 campuses that has around 500,000 students at any one time. Hosted out of the Fresno site is the Water-Energy-Technology Center (WET) (figure 10).


***Figure 10****. The Water & Energy Technology Incubator- taken on a day without the torrential rain, which dominated my visit.* Source: http://www.fresnostate.edu/adminserv/facilitiesmanagement/projects/wet.html

---

[1] *Source:* https://www.emmagazine.co.za/farming-for-a-more-fruitful-economy/

There I met Jeff Macon, one of the business development managers at the WET Center, where he explained to me about a flagship programme run out of Fresno, the *BlueTechValley Innovation Cluster*. This $60M 6-year programme operates on a hub and spoke model (with *BlueTechValley*)- the Central Valley Innovation Cluster being the main hub. It has received $5M of funding to run an innovation network focussed on clean energy with the mantra of supporting ventures that 'produce or reduce', that is: supporting businesses that aim to either produce clean energy or reduce electricity usage.

This funding was supplied by the California Energy Commission (CEC) which collects funds from fossil fuel-based energy producers and distributes it to so called 'clean tech'. The role that the network plays is to connect industry to other components in the *BlueTech* programme, for example the *Calseed* programme. This programme funds businesses (at 100%) up to $600k per venture in two phases- a concept award for $150k for prototype and concept for phase II 450k for business development. The fund is around $35M of the $60M programmes, so funds a lot of ventures. In the past 2.5 years *BlueTech* has funded 230 ventures - 100/yr - doubling the previous intake. The scale of this funding is impressive, given the broad parity in GDP (~2.7 trillion) between the UK and California and the fact that agriculture makes up only 2% ($45,000,000) of the state's annual GDP[1]. For comparison, in the UK the GDP share of agriculture is more like 0.6%, down from 1990 levels of ~1.3%[2].

I was interested in following through whether this funding ever leads to successful start-ups maturing into larger companies. Through contacts at the California Energy Commission (see next section) I was able to visit DBL Ventures (Double Bottom Line) in San Francisco. This venture fund looks at making investments that are both financially and environmentally rewarding. Here I met with Mark Perutz one of the investors for the fund. He explained to me that DBL looked to make later 'series B' level funding, which led to something of a chicken and egg scenario in the agricultural space, as many ag start-ups never reach this phase of the investment cycle, having been swallowed up earlier in the investment pipeline by large corporations (e.g. Monsanto, Cargill etc). This is interesting, as this highlights the dominance in the market of global agribusiness and its capacity to shape the clean growth agenda in the current investment landscape.

### Conclusions

During my visit I learned a lot about the extreme environmental pressures that growers face in terms of their access to water. This has led to energy intensive operations to move water around the state of California, which in turn has led to problems in the use of fossil fuels. Redistributive taxation is funding some clean growth opportunities which are being moved through into industry, facilitated by innovation clusters and venture funding opportunities. However, it is unclear how this is feeding through into the grower base, as many small businesses are acquired by larger (often less innovative) businesses early in their development cycle.

## Indoor production in the Netherlands

In the Netherlands, agriculture makes up around 4.4% of GDP, in real terms around the same as California's amount (EUR 45 billion). This relative importance of agriculture and horticulture has meant that the Netherlands is considered a hub of horticultural innovation. During my time in the Netherlands I spent a couple of days at Wageningen University at both the main campus and the Bleisweig experimental station, as well as returning to the World Horti-Center, which was also a destination as part of the Nuffield CSC.

At Wageningen I met Dr Anja Dieleman, a senior scientist in plant physiology, along with Dr Bram Vanthoor, a specialist in modelling of greenhouse environments, and Pieter de Visser, an expert in plant-light interactions. As part of my research I had read a number of Bram's papers from his time as a PhD student,

---

[1] *Source:* https://www.statista.com/statistics/304869/california-real-gdp-by-industry/
[2] *Source:*https://www.theglobaleconomy.com/United-Kingdom/Share_of_agriculture/

where he had developed and extended a model of greenhouse designs (figure 11). This approach to modelling out a whole system appeared to me to be exactly the way in which production systems should be designed and appealed to me, as it was reminiscent of the approaches that I had taken to modelling metabolism at the cellular level during my own PhD. Indeed, this system has now been turned into a product by the Greenhouse Technology group called *Kaspro* and has been used to design greenhouse production systems around the world.

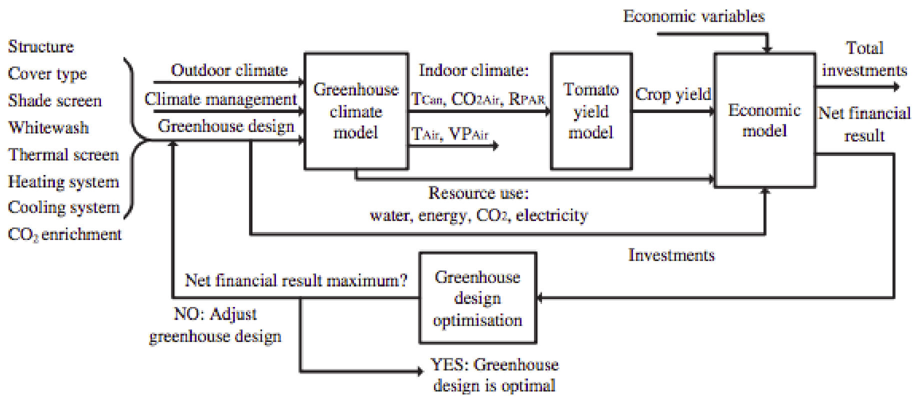


***Figure 11**.* reproduced from (Vanthoor, Stanghellini, van Henten, & de Visser, 2011). *An overview of the model-based greenhouse design method. The method focuses on the optimisation of the following eight design elements: the type of greenhouse structure, the cover type, the outdoor shade screen, the whitewash, the thermal screen, the heating system, the cooling system and the $CO_2$ enrichment system. The key components of the method are a greenhouse climate model, a tomato yield model (Vanthoor et al., 2011), an economic model and an optimisation algorithm.*

Our discussion focussed around how models may be used to develop high intensity cropping systems. Their research has shown that tomato yields of 100kg/m2 (that's 1000t/ha) are possible by manipulating source/sink relationships in the plant through the use of different light recipes. We spoke about the 'multiple goal' modelling approaches that Bram and the team he worked with developed, and how these may be extended to encompass sustainability metrics.

I learnt about some recent work that the group has been carrying out on the *Fossil Free Greenhouse*, which was a project that was just beginning at the time that I visited. This was a project, underway at the Bleiswijk campus, which I was unable to see at the time of my visit. I did, however, see the current progress in indoor production of soft fruit.

Following my visit in June 2018, the now renamed *Greenhouse 2030* is reported to have been operational since April of 2019, and is focussing on strawberry, gerbera, freesia and pot anthurium. The objective of this project is to use no fossil fuel in the heating source, with all heating components being fully electric and energy-efficient LEDs being used for lighting. As a closed loop system, no water is discharged from the greenhouse, meaning that the environmental impact of runoff and chemical discharge is fully mitigated[1].

Innovation comes from both the private sector and the public sector. Some of the largest European glasshouse manufacturers are based in the Netherlands, as well as many of the major growers, suppliers,

[1]*Source:* https://www.greentech.nl/news/working-towards-a-fossil-fuel-free-future/

and importers and distributors of fresh produce and flowers. For example, the Netherlands is the third largest exporter of tomatoes in the EU, despite the fact that the climate is unsuited to outdoor tomato growing.

***Figure 12**. At both Wageningen and the World Horti Center I saw a range of protected crops and growing systems, as well as initiatives to train and attract talent into the sector. Bottom left is a robotics laboratory at the World Horti Center, in which students can develop robotics systems for trial in the research glasshouses*

At the World Horti Center (figure 12), I saw a model of research, training and commercial development that I have never encountered within the UK. Part technical college, part research centre and part commercial exhibition centre, the Horti Center is a space in which businesses, researchers, future high-skilled labour and growers can all interact and learn from one another.


***Figure 13**. Closed loop irrigation systems and greenhouses offer significant energy and water savings.*

In the space of a short afternoon I was able to see most of the major manufacturers' offers across the indoor production sector and learn about the developments that are reaching commercial application (figure 13, 14). More broadly, I was able to learn about the larger infrastructure projects that are going on around the port of Rotterdam to use waste energy in glasshouse production, and the large-scale exploitation of geothermal energy (that parts of the Netherlands are lucky enough to have access to).


***Figure 14***. *LEDs offer opportunities more efficient solutions for fully indoor farming*

## Conclusions

The Dutch capacity for research, development and production vastly outweighs our national capability in applied horticulture and product development. Led by central government, the decarbonisation funding incentives are strong and existing technological developments (such as highly sophisticated modelling approaches) are being used to develop sustainable systems of production. These require electrification of heating systems either energy harvesting (e.g. heat pumps and geothermal pumping) or generation.

# The thirst for energy in the quest for precision

## The global direction of travel

Something that struck me early on in my Nuffield journey was the realisation that the direction of travel for strawberry production is to intensify, for all the reasons highlighted in the previous section on the shifting UK market. As part of the run-up to my Nuffield, I visited large tomato producers in the UK and saw the cutting edge of UK production, the use of natural gas fuelled Combined Heat and Power (CHP) systems, largely installed due to the greater efficiency than a gas boiler, and the benefits of exemption of certain systems from the Climate Change Levy. At the outset, I had very little knowledge about the environmental impacts of glasshouse-based production, or indeed the energy expenditure that was involved. Some of the calculations that I did throughout my study are presented in Appendix 3.

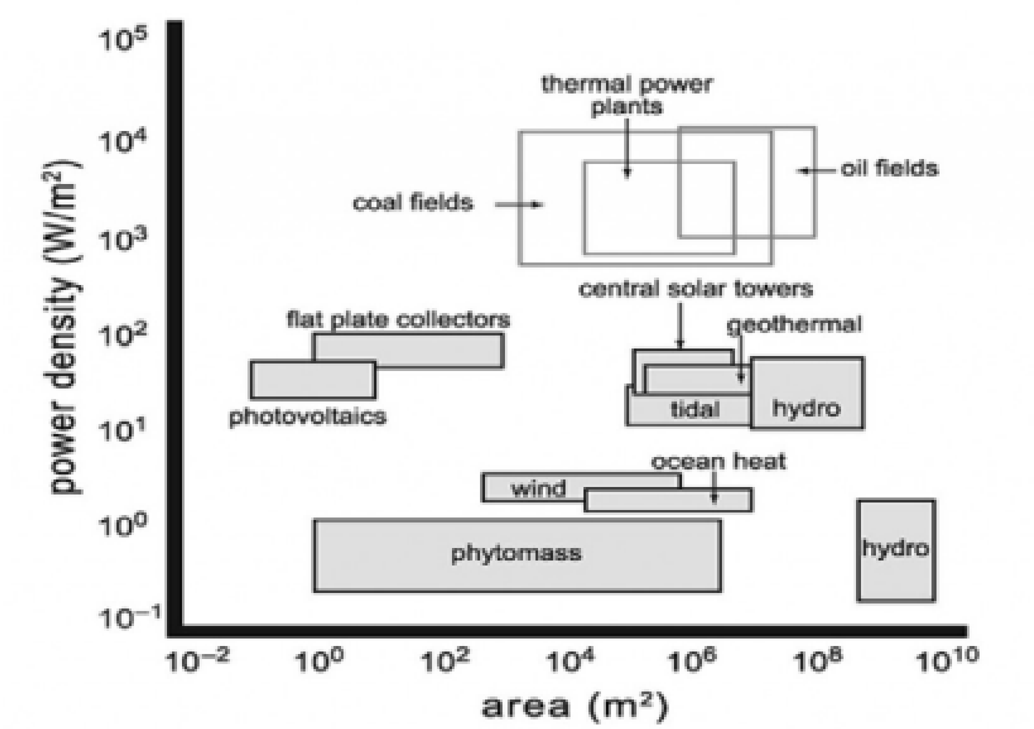


***Figure 15****. Plot of power density of fuel source, thermal energy production system or renewable energy production versus the land area required. What emerges is that almost all renewable solutions are much less energy dense (W/m2) than non-renewable sources.* Reproduced from (Smil, 2010)

Along the way, there were several pieces of reading that particularly influenced my thinking. One author was Vaclav Smil. In particular, two of his books, *Energy Transitions: History, Requirements, Prospects* (Praeger 2010) and *Power Density: A key to understanding energy sources and uses* (MIT Press 2015), have shaped my thinking. The key factor to keep in mind is whether there is sufficient land for net carbon sinking (i.e. not plantations of trees for phytomass), growing food and generating energy, given our current energy usage. Another author was the late David Mackay, whose 2009 book *Sustainable Energy – without the hot air*, was a go-to guide for statistics (MacKay, 2009). *Figure 15* and table 1 outline the large differences in power density between both renewables and non-renewables. The take-home point is that there is often an order of magnitude more land required in order to generate the same total amount of power by renewables when compared to non-renewables.

**Table 1:** Power densities of renewable and non-renewable energy sources

| *Fuel type* | *Power density W/m2)* |
|---|---|
| *Gas* | 200-2000 |
| *Coal / Nuclear* | 100-1000 |
| *Solar (concentrating)* | 4-10 |
| *Solar (PV)* | 4-20 |
| *Wind* | 0.5-4.5 |
| *Wood* | 0.6-0.6 |
| *Bioethanol* | <0.5 |

*Sources*: Mackay (2009), Smil (2017) and (van Zalk & Behrens, 2018)

I use this data, along with other insights into our energy future to make some projections about what new growing systems may look like in the future. I outline these in Appendix 3.

## Duck curves and dragons- the fantasies of supply and demand

While travelling through California, I had the opportunity to visit both the California Energy Commission (CEC), the state department responsible for implementing energy policy and the Laurence Berkeley Labs (LBL), an energy research centre in the hills around Berkeley. The federal equivalent of the CEC is the Department of Energy (DoE). The CEC funds the largest energy research programme in the US outside of the DoE, with around $130 million of funds raised from taxation on electricity producers and $24 million from gas producers. The major focus is reducing fossil fuel usage while 'benefiting Californian rate payers.' Around 60% of funds go to reducing energy usage of buildings, with around 40% going into industrial agriculture and water use. This is the source of the funding for the WET Center that I visited in Fresno. This type of hypothecated 'Pigouvian' tax is one that has long been used in Europe under the name of the European Emissions Trading System.

As mentioned in earlier sections, California uses a lot of energy for pumping water. I was told that wells are now being sunk to a depth of 1000 feet, with a capital cost of $1m per 1000ft. Much of our discussion around agriculture was around mitigating the usage of electricity in water usage. When I broached the matter that the process of abstracting water was deeply unsustainable, this was acknowledged, but the general view was that it would be difficult to change within the current legislative environment and the lack of ability to monitor and enforce on farms and the fact that deep well pumping is unregulated. The LBL estimate that there are between 1 and 2 million deep wells in California, illustrating the scale of this environmental (and energy) issue. In my conversation with Arian Aghajanzadeh from the LBL, he told me that precision irrigation was actually leading to more problems, as growers were expanding their holdings and increasing overall water usage.

Talking more widely, two further issues became apparent in terms of current challenges faced by Californian energy producers. The first was the rapid growth in energy demand. This was the first of three occasions that I was told that the Californian grid cannot cope with the rise in electric vehicle demand. I learnt about the initiatives being undertaken for a smart-grid and demand management approaches.

The second issue was the rapid growth in electricity usage for indoor cannabis production. In California demand for energy was soaring and US-wide by 2011, cannabis production was responsible for around 1% of total electricity demand. This was projected to be around $6,000,000,000 in energy costs, with a usage of around 5000kWh/kg (from the analysis above, calculations show tomatoes are 7kWh/kg). Arian

Aghajanzadeh from the LBL told me that there is currently around 7million square feet of cannabis production (around 65 hectares) in California alone.

Arian initiated me into some of the key metrics used in energy usage, the duck curve (figure 16).

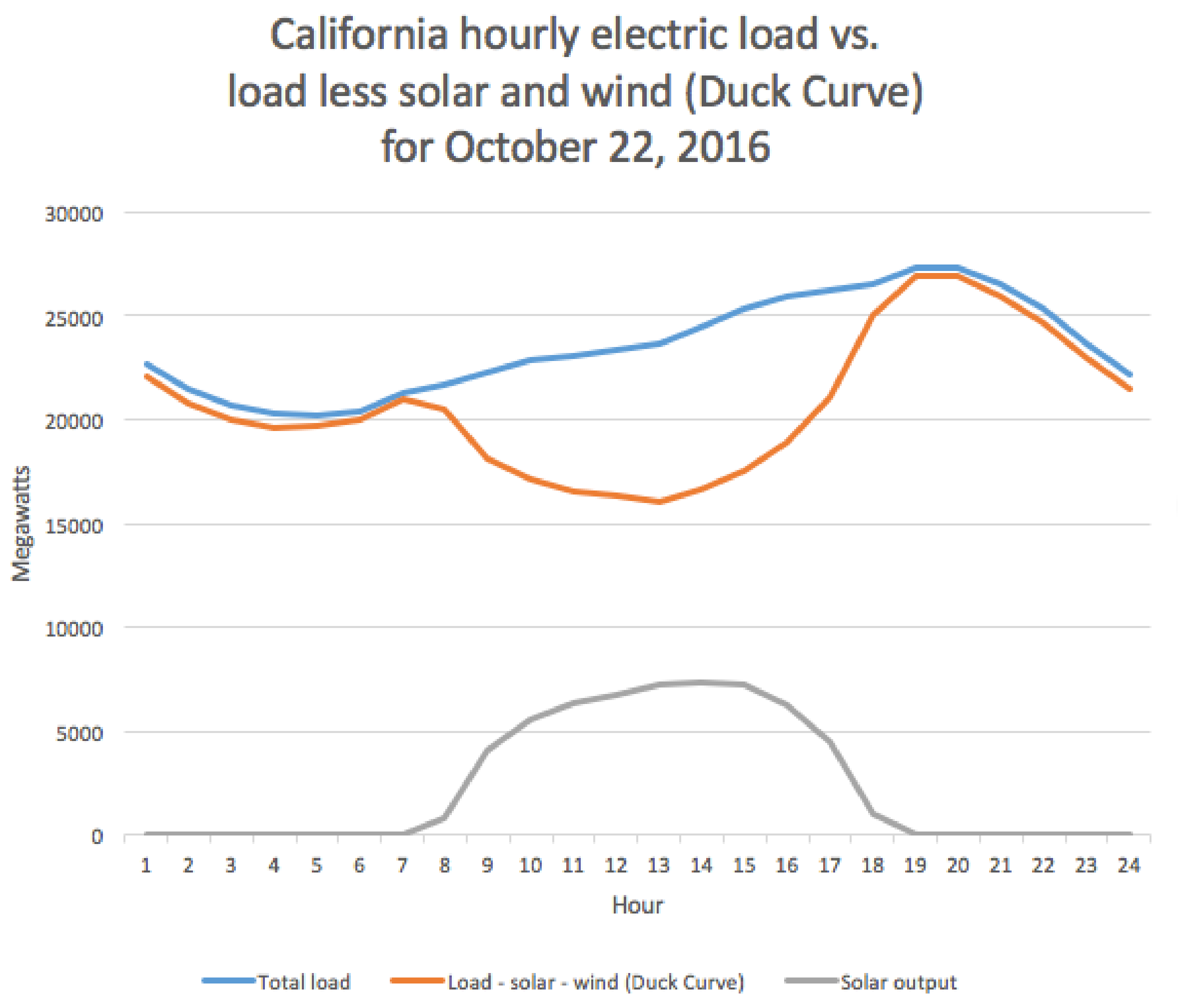


***Figure 16**. The **Duck curve. Blue curve:** Demand for electrical power, **Red curve:** supply of electrical power from non-renewable sources, **Gray curve:** supply of solar electrical power. Data is for the State of California on October 22, 2016 (a Saturday), a day when the wind power output was low and steady throughout the day. Note the red curve's steep rise from 17:00 to 18:00 as the sun sets, requiring some 5 gigawatt of generating capacity from non-renewable sources to come on line within one hour.*
*Source*: Wikipedia- author ArnoldReinhold based on dataset from
http://www.caiso.com/market/Pages/ReportsBulletins/DailyRenewablesWatch.aspx

He explained to me that the supply-demand problem is only increasing with the growth in electric vehicles, as owners come home and plug in after work and that the duck curve (named after the shape of the curve) was becoming more dragon-like in shape, with a steeper energy demand curve (red) for currently non-renewable sources, given the absence of large scale storage of renewables.

## Energy in the UK

Understanding energy use and energy policy in the UK has been exceptionally challenging and as a non-expert in this area I am cautious about providing too much opinion, for fear of having missed one or more crucial pieces of evidence.

Reviewing the evidence, it is clear that renewable energy plays a large part in electricity generation (table 2) now making up almost exactly 1/3 of our electricity mix in 2018.
**Table 2**. 2018 Energy mix for electricity generation *Source*: UKgov

| ***Electricity generation in 2018*** | ***TWh*** |
|---:|---:|
| *Coal* | 16.8 |
| *Nuclear* | 65.1 |
| *Gas* | 131.5 |
| *Renewable* | 111.1 |
| *Total* | 333.9 |

The largest of this renewable capability is currently from solar installations, however offshore wind is the most rapidly growing sector (table 3).

**Table 3**. Renewables capacity in the UK for electricity generation and percentage of total electricity Source: UKgov

| ***Capacity from sector*** | ***Total Capacity GW*** |
|---:|---|
| *Onshore wind* | 12 |
| *Offshore wind* | 8 |
| *Solar* | 22 |
| *Tidal* | 0.018 |
| *Other* | 2 |
| *Power plants* | 90 |
| *Total renewable GW* | 42.018 |
| *Total GW* | 134.018 |
| *Percentage renewable* | 31.35 |

It is very important to note that electricity generation is a relatively minor part of our total energy usage and that industrial, residential and transport sectors utilise a lot of non-electrical energy. Again, trying to contextualise this energy usage, I summarised the total energy usage in the UK (table 4), converting it perhaps more understandable units, the cup of tea and the Big Mac™.

**Table 4** -Total energy use in the UK. Source: UKgov and own calculations

| ***Energy use*** | ***Total used TWh / year*** | ***Per capita kWh /day*** | ***Per capita Cups of tea*** | ***Per capita GJ/yr*** | ***Per capita Big mac equivalents / day*** | ***Per capita Troglodyte ratio*** | ***Effective number of Troglodytes*** |
|---:|---:|---:|---:|---:|---:|---:|---:|
| ***Electricity generation*** | 301 | 12 | 895 | 16 | 20 | 1.6 | 108,360,000 |
| ***Other*** | 1,362 | 57 | 4,048 | 74 | 90 | 7.4 | 490,352,400 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| ***Grand total*** | 1,663 | 69 | 4,943 | 91 | 110 | 9.1 | 598,712,400 |

In energy terms, we boil the kettle enough times per person to make around 4000 cups of tea per person per day, or to provide us with the calorific equivalent of 90 big macs. These are silly units to use, but illustrate the point that the vast majority of the energy that we consume is neither to feed or water ourselves, but to 'do other things' that only humans do. Looking at this another way, the author Vaclav Smil estimates that prehistoric, European, stone age man (10,000 BC) used around 10GJ of energy per year to survive, around 12 Big Macs per day (Smil, 2017). This is the requirement for food and fuel that living without fur and at the top of the food chain seems to require. If we take that around 3GJ of this was for food, the rest, around 7GJ, would be for fuel and other uses such as pottery. This would have all been derived from solar-fuelled processes. At the time, the world supported a population of around 5 million humans. Taking today's energy usage in the UK alone for the current population of 66,000,000 and asking how many prehistoric humans our current energy consumption would have supported, we arrive at an estimate of 598,700,000 (0.6bn) people- nine times more than our current UK population (table 4). By the time we reach the end of the medieval period in Europe, our energy usage per capita had jumped to more like 50GJ/annum. Smil quotes the average 2005 American as using around ~370 GJ/annum. However, we can see that based on the current UK governmental figures, our domestic use (and that is of course only part of our total use) is around 90GJ/annum.

Trying to drill down further into what is happening within the agricultural sector was challenging. I wanted to get an insight into where current sources of energy use were in horticulture and what was being done on farm in terms of generation and storage. The current status quo is that many intensive production systems use combined heat and power from gas turbines. The next most-viable alternative is anaerobic digestion for heat and $CO_2$ production. These systems are routinely in use throughout protected cropping. With reasonable reliability and a predictable level of heat output, these are viable solutions right now. However, unless a waste stream is used, these are effectively biomass sources and therefore have low energy density (this is something I detail further in Appendix 3).

In order to see if there is likely to be any scope for electrification or solarisation of growing systems, I attended a *Growsave* event, part of an AHDB programme run by FEC energy, providing information on energy use and saving, cooperation and reducing costs. This provided some information about how the current energy market interfaced with indoor production sector and the ways in which energy technologies were starting to appear on farm and why they were there.

The focus of the event programme was on the various incentives currently around battery storage, a technology with a very poor energy density and very high cost. I learnt that the current costs for setting up a 500kWh battery system were around £300-400k. This would be expected to be around 80% efficient and as an investment, buying power low and selling high would yield a return of £5.4k per annum. From the data I have gathered we see that our total per capita consumption of electricity is around 12.5kWh per day from a total energy use 69kWh/day per capita. Of that potentially 50% of our demands are after dark and before dawn (let's say 6kWh per capita), that means this system (delivering 400kWh) would serve 67 people at a capital cost of around £5k per person, a huge cost.

Most battery installations at present are therefore used in a different way for 'grid support' which is more like smoothing out demand and supply and trying to minimise events such as Triads. The energy provider SSE defines a Triad as:

*The three half hour periods of peak power demand across the National Grid in a year (from November to February). These three points are used to calibrate the system costs, which are passed on to industry.*

These are important to consider if your business is a heavy user of energy because as SSE states:

*Triad charges to business can range from around £15-£40 per kilowatt depending on where you are in the country. So, in any half-hour on a cold day in winter when there's a chance of a Triad, it makes sense to minimise your power consumption.*

Batteries are also used to supplement power demand for unanticipated fluctuations. This is called a Short Term Operating Reserve (STOR). The national grid website says:

*At certain times of the day we may need access to sources of extra power to help manage actual demand on the system being greater than forecast or unforeseen generation unavailability.*

This is another use for batteries, as there is an availability payment is £3-5/MW/hr and a use payment of £60-80/MW/hr. When not used, the electricity can also be sold on the market, as operating a STOR is not 24/7 service- there are seasons and windows.

There are various other services dynamic frequency responses (DFRs) where the frequency of the grid falls due to outages or excess demand, again batteries are useful here. There are a multitude of combinations that these schemes can be used in 'stacking' in order to generate a viable business model, but it is clear at present that battery technology is not appropriate for storing energy for use overnight, more as a side investment, if you have some land spare and are able to connect into the National Grid.

FEC energy (now NFU energy) presented information about heat storage, which is already in use as part of many CHP systems. Assuming that a high efficiency boiler powered by renewables (i.e. biomass- though see the calculations on energy density) could be used in tandem with water tanks to store excess, this could be used for night time heating. The rough rule of thumb was 200m$^3$ of water storage needed per hectare of salad crop. It may also be worth storing heat from biomass boilers in order to maximise the efficiency of the boiler cycle, which when considered as a system, means that the efficiency of the process increases[1]. This is perhaps useful, as it could be imagined that storing heat on farm in large tanks is a good way to deal with intermittent, or highly variable prices.

**Table 5**. Calculations of current and future energy usage under different electrification scenarios

| *Variable* | *Value* |
|---:|---:|
| *Percentage of total power used for electricity generation* | 18.1 |
| *Percentage of electricity from renewables as % of total UK energy use* | **5.67** |
| *Fold increase required for total electrification of all services* | 5.53 |
| *David Mackay's UK renewable electricity generation capacity estimate (kWh) per capita* | 18 |
| *David Mackay's best-guess 'sustainable' total energy use (kWh) per capita* | 70.3 |

David Mackay (2009) estimates that our total, per capita, electricity generation capacity from renewables is around 18kWh per day. We are currently using around 12kWh per day, 1/3 of which is from renewable sources. I am optimistic on this score that he was perhaps a little too pessimistic about our total domestic generation capacity and that with systems like offshore wind the total capacity may be somewhat higher. He also estimates our total sustainable energy budget per day at around 70kWh using a mixture of carbon capture, nuclear, biomass, imports etc. By my calculations (table 5) this is about our current energy usage in the UK per capita- down significantly from previous years; in 2003 this was more like 125kWh/day. It is therefore possible, if we do not increase our total energy expenditure, that the UK could have a fully

[1] *Source*: https://www.growsave.co.uk/userFiles/37__modern_heat_storage.pdf

decarbonised electricity system and a fully sustainable energy system. However, this of course does not include any imported materials and as a service economy and not an industrial economy we consume a lot of imported goods. For this to make any difference at all one would have to hope that action was global and other countries also decarbonised at the same rates.

## Conclusions from my travels

On farm deployment of renewables (e.g. batteries) is mostly an economic decision, rather than one of providing new sources of power on farm. Electrification, or partial electrification of heating is currently one solution for the substitution of gas (from renewable or non-renewable sources) - recalling the extremely poor power density of biofuels and phytomass-derived products. However, solar + heat stores may be a useful future mix to consider. Anaerobic digestion is a solution that works now, but relies on either a persistent waste stream that cannot be mitigated, or suffers from a similar issue to biomass solutions.

Rather than firm conclusions we are still left with questions. Do we have enough renewable energy (and land) to serve any demand for increased indoor food production? Do we have enough capacity on the grid for the massive increase in electrification of processes? Do we have technologies that can deal with the fluctuating supply and demand and can growing systems take advantage of this?

I explore two elements of growing systems further in this report. In appendix 2 I review the role that genetics could play in driving forward efficiency. In appendix 3 I then integrate this with my findings about what could be unlocked by the dual innovation of enhanced genetics and improved growing and energy systems.

# Recognising our respective roles

What then should each of us do to try to bring about a sustainable shift in production?

## Scientists

As a scientist, I have realised that we must think earlier about impacts that our science could have and see our part in bringing about sustainable changes in practice. I feel somewhat ashamed that I had not fully grasped the scale of our current challenges in the field of my own research before embarking on my Nuffield scholarship. The fact that I did not have pertinent statistics at my fingertips to carry out the calculations needed to arrive at the approximate solutions presented here, meant that my thinking was largely constrained by the knowledge and work of my peers, who, it turns out, were as equally constrained as I was. Having talked to most of my contemporaries about my findings, they were equally unable to either present or contextualise their work in the broader societal challenge. We are often shaped, by both our nature and nurture as scientists, into people that can doggedly (and perhaps to draw on a stereotype myopically) pursue a narrow problem in enormous depth. This naturally has both benefits (as problems do need solving) and weaknesses (we fail to see why we are solving the problem in the first place). Therefore, broadening and contextualising the work that we do into systems that we see around us requires a different type of training other than is currently prevalent in some areas of bioscience and engineering. The silos are often deep between the sciences of environment, crop breeding, environmental economics and applied research, and often the lack of a common language between everyday policymakers and scientific practitioners is enormous.

My observation is that those working at a high level within government, academia and industry do have a good grasp of the problems, but these are often people of a certain age, who have accumulated a wiser worldview as a result of many years of work. We need to find and fund shortcuts to enable people embarking on their careers to correctly frame their work into the challenges that as a society we need to address. Opportunities for multidisciplinary training could rapidly improve awareness within the scientific community and is something that should be fully embraced within crop sciences. My personal belief is that agricultural science needs to shift to a discipline that uses multiscale models at its core, to both quantify the effects of different future food systems and coupled with novel approaches to modelling, simulate new systems. I currently question whether the way in which we fund and deploy our research funds will allow us to rapidly repurpose and reposition the agricultural sciences in this way.

## Governments

In the UK we have been excellent at defining the problem of shifting to a sustainable energy future, from which many other sustainable practices must flow, and more recently, enacting legislation that mandates a solution to the problem. However, it appears that within government there are such large disconnects between major areas of policy, that as a nation it appears that we are struggling to address the scale of the challenge ahead of us and provide a coherent plan towards net zero, which ultimately (alongside future global trading arrangements) will shape agricultural and horticultural practice. How then do we move to a system where every single policy decision takes into account the true cost in environmental and economic terms, and instead of maximising one over the other, finds an optimum? Much as I have described for the problems in science of taking our daily actions and contextualising them into the 'bigger picture', I suspect the same is true in government, as with any complex system, specialisation of function (into different government departments) inherently leads to disconnection from the 'whole'. It is possible that the recently announced environment bill (which seeks to optimise for economic and environmental impact) may change this, as it will force all decisions to be evaluated in the light of 'net zero' but as ever the devil will be in the detail.

However, it appears clear to me that government could immediately play a greater role by implementing a sensible policy of providing direct incentives to decarbonise through Pigovian approaches to taxation, hypothecating tax revenue (much like the current levy on farming) and spending it on decarbonisation (Note- as I was finalising this report the 'polluter pays' principle has come to the fore in the new environment bill). However, as pointed out by vocal economists such as Dieter Helm, this must be matched by import tariffs that internalise the externality cost of goods and services purchased from aboard if we truly want a low carbon life, rather than a false sense of satisfaction that we are morally superior and everyone else is a sinner. When taken as a whole this could provide an argument for a carbon consumption tax, rather than a carbon production tax. However, import tariffs (which of course would only hurt us) are only necessary if multilateral action on decarbonisation is not taken. There are others (Sam Fankhauser, Director of the Grantham Research Institute) that point to the fact that there are such large export growth opportunities in low-carbon products that it may be foolish to start an economically harmful trade war through raising tariffs when, through trade, effective spread of low carbon products and services may be a more effective way of globally shifting change.

Another key area that requires some attention from government is the approach to regulation of all forms of genetic modification. Regulation, where it should exist at all, should be focussed on products, not technologies. Where, in approaches like gene editing, genetic mutations induced by targeted gene editing cannot be differentiated from spontaneously occurring mutations, there appears to be no case for regulation at all. Although not a magic solution, gene editing is an important part of the toolkit and one that, if rapid progress is desired, should not be off the table.

It is, though, not all bad. During my travels and the write up of this report it is clear that the government is beginning to take steps in the right direction in defining what a sustainable food system may look like. The national food strategy, the agriculture bill, the rewilding agenda and the 25-year environment plan all have the opportunity to radically change our food system. There is of course risk attached to these policy innovations and the potential for unintended consequences is high, but if the science and the models can provide objectively modelled scenarios on which to base future we have the opportunity to both achieve our own national ambitions for our food system, but also place ourselves favourably in the wider global context to deliver solutions.

## Incubators, accelerators and start-ups

Hand in hand with an escalating carbon tax must be the rapid capitalisation of ideas that can drive up efficiencies of production. From my observations in San Francisco, although funds are beginning to flow into the area of agriculture, the model appears to be quite different to the 'tech' or 'medical biotech' fields. Although there are some examples of well-capitalised start-ups (for example Inari), much of the real innovation that is needed to decarbonise crop production, or scale breeding efforts in new high-efficiency growing systems is either trapped at the small start-up stage and relatively starved of capital, or being bankrolled by large multinational companies (e.g. Pairwise), which is funded by Monsanto. The traditional routes of scaling funding (at the series B levels) are in the words of one investor that I met 'waiting to see' rather than investing, which is arguably holding the sector back.

I wonder whether more needs to be done to incubate and nurture start-ups through the development of patient capital. In some ways, government is more likely to be able to rapidly scale this than traditional venture funding. I would like to see more agritech incubators attached to aligned research institutions, potentially supported by redistributed funding (e.g. through carbon taxation), able to access research expertise and resources that are available within the university and public sector, echoing the models I saw in California.

## Private finance sector

In the same vein, philanthropic funding, which is often more long term, is becoming a major source of investment for bold, sustainable ideas. It cannot be overstated what an effect people like Bill & Melinda

Gates are having on both discovery science with sustainable ambitions and clean energy production. In his 2018 letter *What I learned at work this year* Bill Gates states:

*Global emissions of greenhouse gases went up in 2018. For me, that just reinforces the fact that the only way to prevent the worst climate-change scenarios is to get some breakthroughs in clean energy*.

Putting his money where his mouth is, a fund he is involved in, *Breakthrough Energy Ventures*, is investing in a range of companies addressing the major drivers of climate change. Looking at their website, affordable solar, geothermal energy, battery technology, grid-scale energy storage and alternative protein are all investments within their portfolio.

It is hard to see how more philanthropists can be engaged in the agri-food sector, but perhaps in combination with the approaches I outlined to training multidisciplinary 'big-thinking' scientists, synthesising research across subject boundaries, the ideas might just captivate some more capital.

## Consumers

As a consumer I have very little idea of the energy consumption that my food has, nor the wider sustainability of any particular item of food I buy. The presence of vocal 'single issue' advocates in the media means that more people are probably concerned about the fact that their punnet of strawberries is in a plastic packet than the fact that they have (if they come from the West Coast of the US or South Africa) five times as much $CO_2$ by weight than their actual weight. One exercise that I did not have time to carry out was to try to calculate the range of emissions associated with a 'typical' shopping basket and contrast that by provenance, production method etc (during proofing of this document this website became available)[1]. Is the environmental footprint of Californian almond milk worse or better than grass-fed milking cattle from Wales? I can almost be certain that the water footprint and energy cost, and therefore the emissions, are higher from imported almond milk than that for cows' milk, and yet this is often sold as an ethical, environmentally friendly alternative to milk. The 5p carrier bag tax is a classic example of a nudge policy that has reduced usage dramatically. Could it be possible, through a small 'nudge' tax on food miles- clearly signposted on food change shopping choices?

## Growers

It is easy to lay blame at the feet of the farmer for unsustainable practice, however in my opinion, it is very wrong to do so. I am struggling to recall a farmer and grower that I have met that actively farms (rather than manages) who doesn't care deeply about the environment. However, this is tempered by the fact that farming businesses must be profitable and as we have explored, profitability and sustainability are not always happy bedfellows.

As discussed earlier in this report the pressures on farming businesses are extremely high at the moment, driven by rising labour costs and stripping of value from the supply chain in the name of cheap food. This hampers the ability of the industry to make investments on the scale of those required for significant change. Engaging farmers in clean growth requires access to capital and in some cases (e.g. intensive horticulture) completely different systems in which to grow crops. As these (at least to the scale that I highlight in this report) do not currently exist, these are both risky and likely to be extremely expensive to initially implement. I therefore see the grower's role as one of that of (at least in the short term) trying wherever possible to mitigate unsustainable parts of their growing operation while in the longer term making economically viable steps towards new growing systems. What is crucial is that growers are helped to remain 'in control' of their own destiny and not victim to others further up the supply chain attempting to offset their own emissions. For me the closest system that I currently see as a sustainable is the one being operated by Tiptree (headed up by Nuffield scholar Chris Newnham). This is a completely passive

[1] https://www.bbc.co.uk/news/science-environment-46459714

system, but managed to achieve around 5x the national average yield (at 100t/ha) already and through conversation with Chris, this may top out with our current varieties at around 150t/ha. With new varieties this could get higher still to around 250 t/ha- half way there and it makes economic sense right now!

## What is next for me

*The trouble is that once you see it, you can't unsee it. And once you've seen it, keeping quiet, saying nothing, becomes as political and act as speaking out. There's no innocence. Either way, you're accountable.*
*Arundhati Roy*

My Nuffield experience began in July of 2017, my journey began in November 2017 and formally ends in November 2019. In the early part of 2019 media coverage and the ensuing debate about mitigating humankind's impact on the planet rose to prominence, due in part to several landmark reports from the IPCC, the CCC and in parallel the beginning of direct action and demonstration, especially by the young. To me this feels like a global re-awakening after a decade of stagnation and parallels my personal journey over the past two years. I started my Nuffield journey thinking that the path for increasing yields in strawberry would be a reasonably simple case of embracing the approach taken in tomato production. What I recognised was that if a sustainable path is to be pursued then a total re-think is required. I had not anticipated how deeply this would affect my thoughts around my own role.

My abiding feeling from this experience is, as the apposite quotation at the beginning of this section says, that the things that I have seen cannot be unseen. Many of the problems and challenges that I describe within this report are those that my generation must solve. If I am lucky, I have thirty working years remaining and should retire in around 2050. If I am unlucky, I may either be dead, or depending upon how you look at it, have further working years ahead beyond 2050! Within that time period, we must totally stop burning fossil fuels for fuel, close the loop on our materials chains (extraction, production, reuse) and ensure that we have the right technologies and evidence to accurately design 'net zero' systems across our entire infrastructure.

We must also in parallel address the challenges of protecting and restoring biodiversity, which will in addition to political action, require our food systems to have a much-reduced impact upon the landscape and in all likelihood a far smaller geographical footprint. We must also design systems, especially across food and farming that are resilient enough to cope with the changes to the climate that we have already brought about and ensure that those resilient systems are fairly designed and distributed throughout the world. These challenges cannot be underestimated. As I write this, although the rhetoric is moving in the right direction, to give a single example, there are signs that deforestation is again increasing in the Amazon, after many years of reduction, driven by a right wing, populist political movement and an aggressive economic growth agenda. As well as timber, an underlying driver of deforestation is that there is increasing demand for land to produce animal feed for export to emerging and established global economies. In a microcosm, this particular issue also highlights the spread of misinformation, and biased reporting of solid evidence is rife and leads to uncertainty over which is the best course of action to take and who to trust. Many media sources are reporting large forest fires as a wholly new occurrence; they are not (though they happen to be more intense than usual this year). This then drives climate change denialists to point to factual inaccuracies in reporting, undermining the scientific evidence base (rather than the poor reporting), while ignoring the wider issues of deforestation altering both local climatic patterns (i.e. rainfall and C-sequestration) and the more general problem of loss of habitat and carbon sinking potential. More than ever there is a need for trusted, independent sources of information.

I am obviously not alone in feeling that we currently face one of the greatest existential challenges to mankind. Are we any better than bacteria that when provided with an abundant nutrient source blindly and rapaciously multiply until resources are spent? Can we stretch beyond our own self-interests as individuals, organisations, countries and cultures to proactively self-regulate to ensure a sustainable future? As an optimist and a scientist I believe we must try, though the evidence suggests that the ecosystem, in part through our own actions, is reaching a state of high entropy and it is our job, through thought, logic and action to be anti-entropic, to create and restore order in a disordered world.

The combination of internal self-reflection and the knowledge I have gained as part of this Nuffield journey has changed my course of action. I am privileged enough to be in a position to hopefully affect some level of change in both the research agenda and within the industry. My conclusion that for berry crops, yield improvements can have a positive impact upon sustainability of the crop, if deployed in the right way, highlights a clear path to pursue. However, my report also illustrates there could be many wrong ways to increase yields and simply following what has been done before in other sectors would be extremely unwise. Although I have seen some promising developments, I am left uncertain as to whether we will be able to effect sustainable changes rapidly enough, or in an economically viable way to maintain the profitability of the industry without wider political action.

Whether right, wrong, or simply arrogant to think that I can change anything, I now wish to work to embed some of the concepts that I have learned more widely into the crop science discipline. In the latter part of my Nuffield journey I became increasingly restless in my current position and began to seek a change. In a very timely manner, the opportunity arose for me to take on a new role at NIAB in Cambridge. This role, as Director of Cambridge Crop Research, is allowing me to participate more widely in shaping the future direction of NIAB's research activity and its application. One particular opportunity is the collaboration with Cambridge University, the Crop Science Centre. Working with the university-appointed chair of crop science, from my position at NIAB, I hope to help in orienting the direction of travel of the wider food and farming sector to a sustainable future through the provision of well-thought out solutions based upon objective, independent scientific research and aligned commercial partnerships. This will require new integrated approaches to science, multidisciplinary partnerships and above all both governmental and industry champions like the many Nuffield scholars I am proud now to call my friends.

## Conclusions and Recommendations

**Conclusion 1:** Genetics is an easy way to make environmentally sustainable yield gains - we have more tools than ever before and the UK is well placed to lead in this area.
**Recommendation 1**: At least half of the increases in yield potential for strawberry could come from genetic innovation. Continuing to fund the pipeline that takes fundamental research into practice is crucial. However, accelerating this to develop varieties that do not match current market demands is challenging. The UK government should consider directly funding breeding or pre-breeding for 'future' crops, as this is unlikely to be met by near-market industry funding.

**Conclusion 2**: Energy consumption in agriculture is rising and new production systems must 'design to avoid' and be developed with an awareness of wider energy policies.
**Recommendation 2:** Multidisciplinary approaches to system design are needed and greater awareness, training and tools are needed to design 'net zero' growing and production systems. These systems (to the extent that they exist) are currently high risk and high cost for all but the bravest or wealthiest. As well as the need to de-risk future development, current practice must be evaluated to avoid increasing emissions through scaling of current unsustainable production practices.

**Conclusion 3:** It is currently very hard to say what is good and bad; more sophisticated lifecycle analysis and digital twinning is needed to quantify externalities of production and shape the design of new systems.
**Recommendation 3:** Expanded and more sophisticated lifecycle analysis, drawing together multidisciplinary teams to not only chart end-to-end costs of current supply chains but to model new sustainable scenarios, based on real world data is important. Government can play a key role in facilitating this, though research funding calls in this area. Beyond this, more effort in multiscale modelling is needed to explore a wider range of supply system options *in silico*; this may extend to the creation of 'digital twins' to model computationally and visually the production systems and farms of the future.

**Conclusion 4:** In a new UK agricultural policy landscape there could be further direct incentives to lower fossil fuel energy and transfer to renewable usage through a "produce or reduce" energy incentivisation scheme for green energy.
**Recommendation 4:** Policy instruments, further to the carbon tax should be developed; any 'polluter pays' scheme should be coupled with funds for investment and the playing field should be levelled for UK growers, perhaps through a border tax on carbon, internalising externality costs for food imports, or alternatively through greater efforts for multilateral decarbonisation coupled to domestic green growth. Greenhouse gas emissions should not be considered in isolation, but as part of a wider basket of sustainability metrics.

**Conclusion 5:** Every consumer is responsible, but largely unaware of our actions. Technology could help raise awareness of sustainably produced fresh produce and help shift consumer behaviour
**Recommendation 5**: Nudge policies, such as printing food miles on food, having small 'token' charges, or colour coding emissions levels on products, could help raise awareness and shift consumer behaviour.

## Acknowledgments

I would like to thank the myriad people that have assisted with this report through generously giving up their time to meet and discuss with me and I apologise if I have omitted anyone from this report acknowledgement, it is unintentional.

Richard Harnden
Tina Barsby
Helen Bates
Chris Newnham
Sue Ireland
Stephen Bernhard
Dirk Rabie
Sean Tager
Rouvay Roodt-Wilding
Nikko Maree
Mike Dossett
Steve Knapp
Jan Enthoven
Pieter de Visser
Emilie Fradin
Thijs van Dijk
Jan Jense
Anja Dieleman
Bram Vanthoor
Ian Boyd
Jon Swain
Arian Aghajanzadeh
Jeff Macon
Frances Houle
Laurie ten Hope
Erik Stokes
Anish Gautam
Virginia Lew
Colin Corby
Mark Perutz
Marion Regan

Thank you also to those within my research group that have helped with discussion and whose science is in-part presented throughout this document. In particular, Helen Bates, Amanda Karlstrom, Magda Cobo-Media, Bo Li and Helen Cockerton. Thank you also to Charlotte Nellist for the photograph of me!

# Bibliography


Consortium, A. (2012). *State of the Art on Energy Efficiency in Agriculture*. EU FP7 Framework.

Csank, A. Z., Tripati, A. K., Patterson, W. P., Eagle, R. A., Rybczynski, N., Ballantyne, A. P., & Eiler, J. M. (2011). Estimates of Arctic land surface temperatures during the early Pliocene from two novel proxies. *Earth and Planetary Science Letters*, *304*(3–4), 291–299. https://doi.org/10.1016/j.epsl.2011.02.030

Dwyer, G. S., & Chandler, M. A. (2009). Mid-Pliocene sea level and continental ice volume based on coupled benthic Mg/Ca palaeotemperatures and oxygen isotopes. *Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences*, *367*(1886), 157–168. https://doi.org/10.1098/rsta.2008.0222

Kendon, M., McCarthy, M., Jevrejeva, S., Matthews, A., & Legg, T. (2019). State of the UK climate 2018. *International Journal of Climatology : A Journal of the Royal Meteorological Society*, *39*(S1), 1–55. https://doi.org/10.1002/joc.6213

MacKay, D. J. C. (2009). *Sustainable Energy: Without the Hot Air* (illustrated, reprint). UIT.

Miller, V., Yusuf, S., Chow, C. K., Dehghan, M., Corsi, D. J., Lock, K., … Mente, A. (2016). Availability, affordability, and consumption of fruits and vegetables in 18 countries across income levels: findings from the Prospective Urban Rural Epidemiology (PURE) study. *The Lancet. Global Health*, *4*(10), e695-703. https://doi.org/10.1016/S2214-109X(16)30186-3

ONS, & Defra. (2018). *Horticulture Statistics* . Defra.

Pelham, J. (2017). *The Impact of Brexit on the UK Soft Fruit industry* . Andersons Report.

Poppy, G. M., & Baverstock, J. (2019). Rethinking the food system for human health in the Anthropocene. *Current Biology*, *29*(19), R972–R977. https://doi.org/10.1016/j.cub.2019.07.050

Smil, V. (2010). *Energy Transitions: History, Requirements, Prospects* (illustrated). ABC-CLIO.

Smil, V. (2017). *Energy and civilization: A history*. The MIT Press. https://doi.org/10.7551/mitpress/9780262035774.001.0001

Swain, J., & Hardy, E. (2017). *Understanding energy influences for UK softfruit production*. AHDB.

van Zalk, J., & Behrens, P. (2018). The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the U.S. *Energy Policy*, *123*, 83–91. https://doi.org/10.1016/j.enpol.2018.08.023

Vanthoor, B. H. E., Stanghellini, C., van Henten, E. J., & de Visser, P. H. B. (2011). A methodology for model-based greenhouse design: Part 1, a greenhouse climate model for a broad range of designs and climates. *Biosystems Engineering*, *110*(4), 363–377. https://doi.org/10.1016/j.biosystemseng.2011.06.001

Williams, A., Pell, E., Webb, J., Moorhouse, E., & Audsley, E. (2008). Strawberry and tomato production for the UK compared between the UK and Spain. In *Towards a Sustainable Management of the Food Chain*. Agroscope.

Wilson, F. M., Harrison, K., Armitage, A. D., Simkin, A. J., & Harrison, R. J. (2019). CRISPR/Cas9-mediated mutagenesis of phytoene desaturase in diploid and octoploid strawberry. *Plant Methods*, *15*, 45. https://doi.org/10.1186/s13007-019-0428-6

Zhu, J., Poulsen, C. J., & Tierney, J. E. (2019). Simulation of Eocene extreme warmth and high climate sensitivity through cloud feedbacks. *Science Advances*, *5*(9), eaax1874. https://doi.org/10.1126/sciadv.aax1874

# Appendix 1 Global drivers

The world is rapidly changing. It is easy for those of us who have grown up over the past forty years to take the rapid pace of change for granted. For the one billion of us currently living in level 4 income countries (see figure 17), cheap imported goods from the far east, media and entertainment on demand, year-round supply of fresh fruit and vegetables—often now delivered to our door in under 24 hours—are all taken for granted along with the things our parents mostly enjoyed: electricity, affordable transport, warm houses, inside toilets, healthcare free at the point of use, an education, birth control and affordable food. However, this is far from ordinary. It is in fact extraordinary and something that we should be mindful of every day. This appendix provides a short primer on global drivers that are shaping our the world we live in and is provided to help frame the data presented in the main chapters of this report.

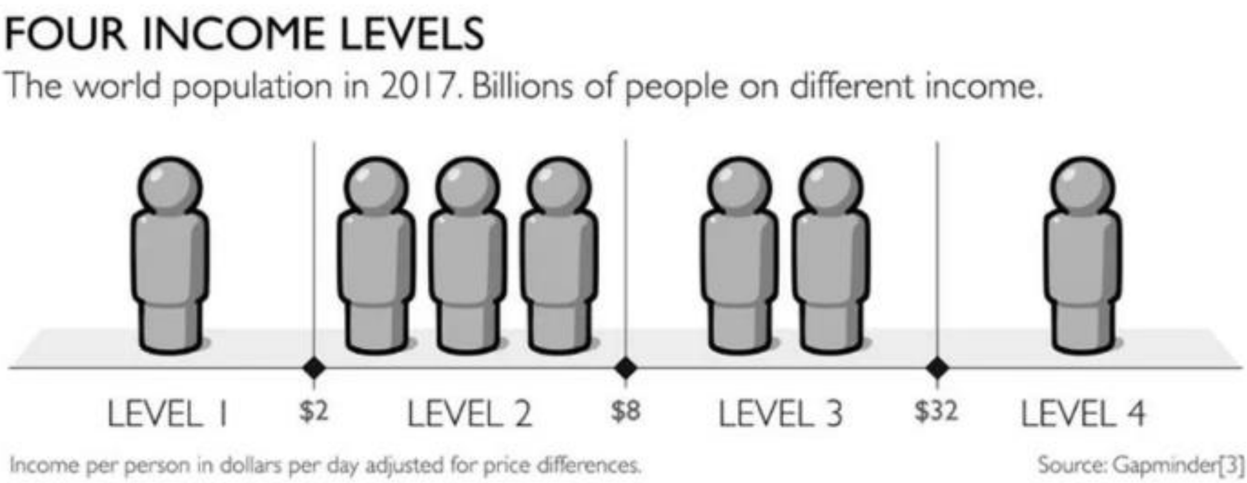


***Figure 17*** *In his excellent book 'Factfulness', the late Hans Rosling defines the global population through a set of criteria based upon both income and access to goods and social services. The proportion of people in each box reflects the current global population, with each figurine representing a billion people. At present, the majority of the global population sit in or between income levels 2 and 3. In the UK we sit at income level 4, with, on average, over $32 per day to spend*. Figure reproduced from gapminder.org

Throughout the course of my Nuffield travels, I have sought to understand what I've seen through numbers as well as through the experiential contact that Nuffield scholarships offer. The combination of listening to peoples' stories, observing their day to day activities and then going and 'running the numbers' where I can, has helped me understand a lot. In this introduction, I run through some of the key global trends that emerge from some of the data I've aggregated, then in subsequent chapters, I draw upon these to make some predictions of what the future could (and should) look like for strawberry production (and horticulture more generally) and some recommendations for positive change. I have written this in a more conversational style rather than as a piece of scientific research.

## Population growth

In my lifetime, the world population has grown from 4.5bn to 7.5bn; that's an extra three billion people on the planet along with me (figure 18).

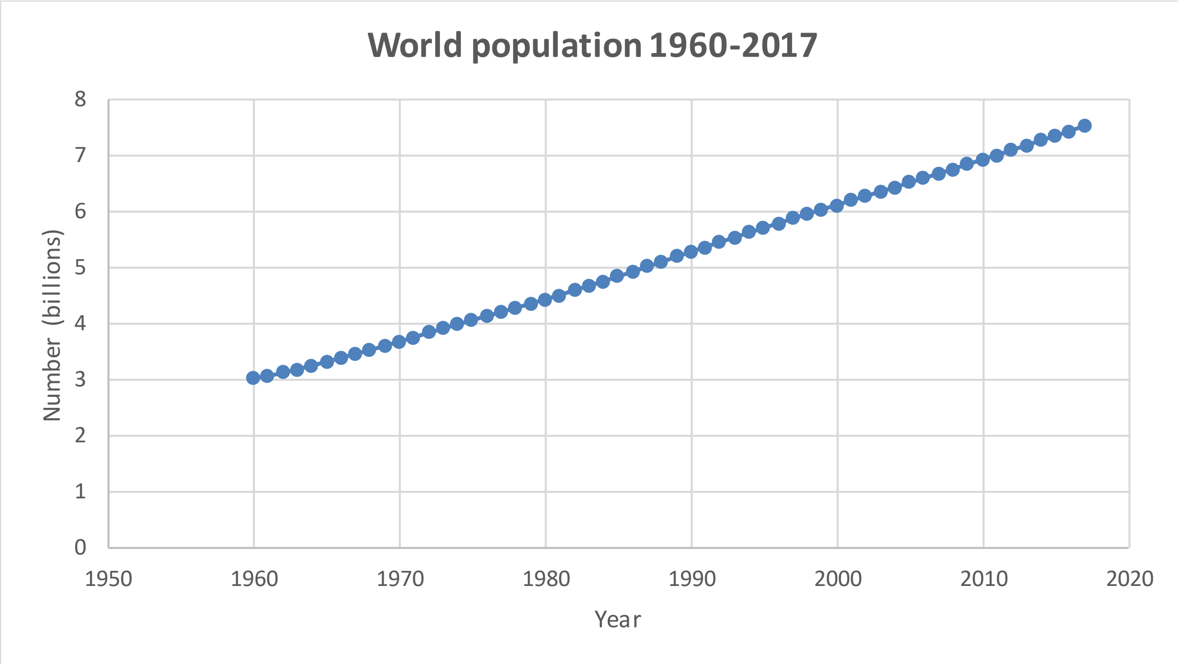


***Figure 18.*** *World bank data plotting the rise in population from around 3 billion in 1960 to our present total of around 7.5 billion.*

Taking these and other data from the world bank and looking at some of the predictions that arise from it, it is possible to estimate the slope over time of the rate of population growth and use that to estimate the continued rate of population growth (figure 19).

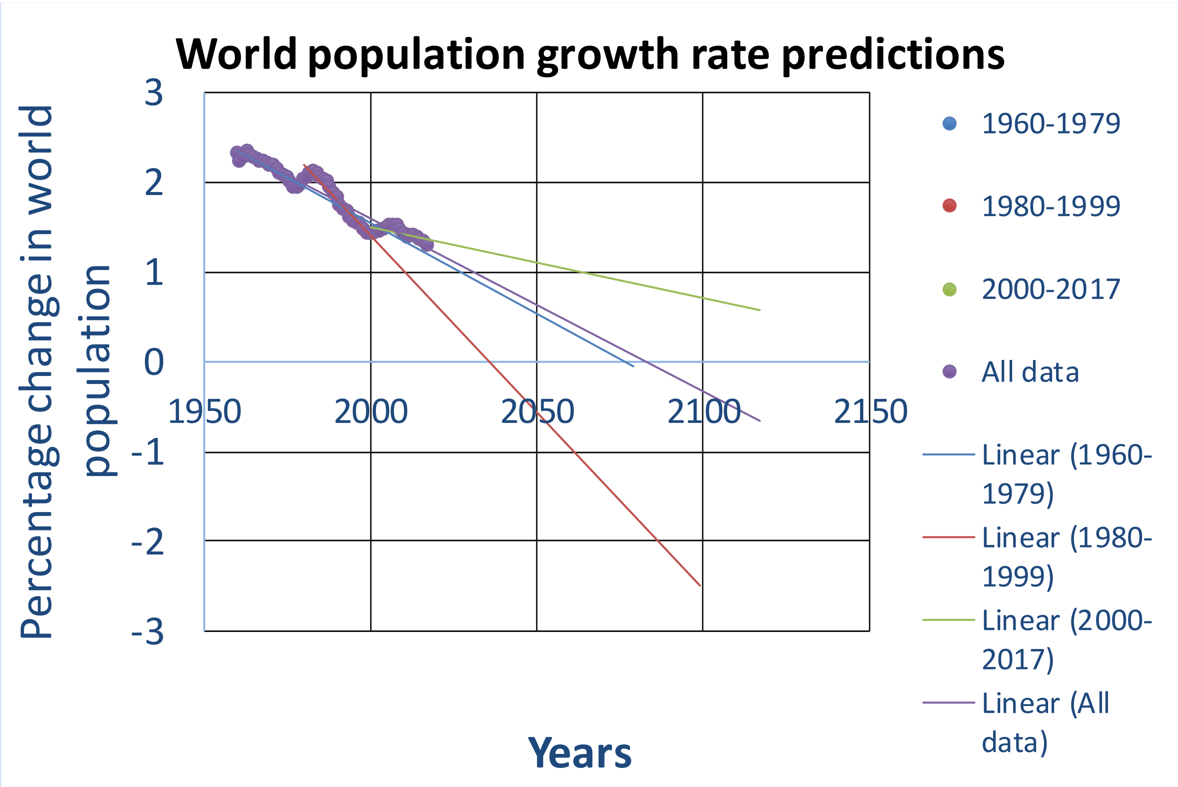


***Figure 19****. Population growth rate projections based upon historic data. Trendlines have been fitted for approximately every twenty years, as well as a trendline for the whole data set. Note that the decline in population growth rate has slowed over the past 17 years.*

The first thing to notice is that all the rates are going down (figure 19). This is a great relief (though note that the latest trendline is the slowest rate of decline).

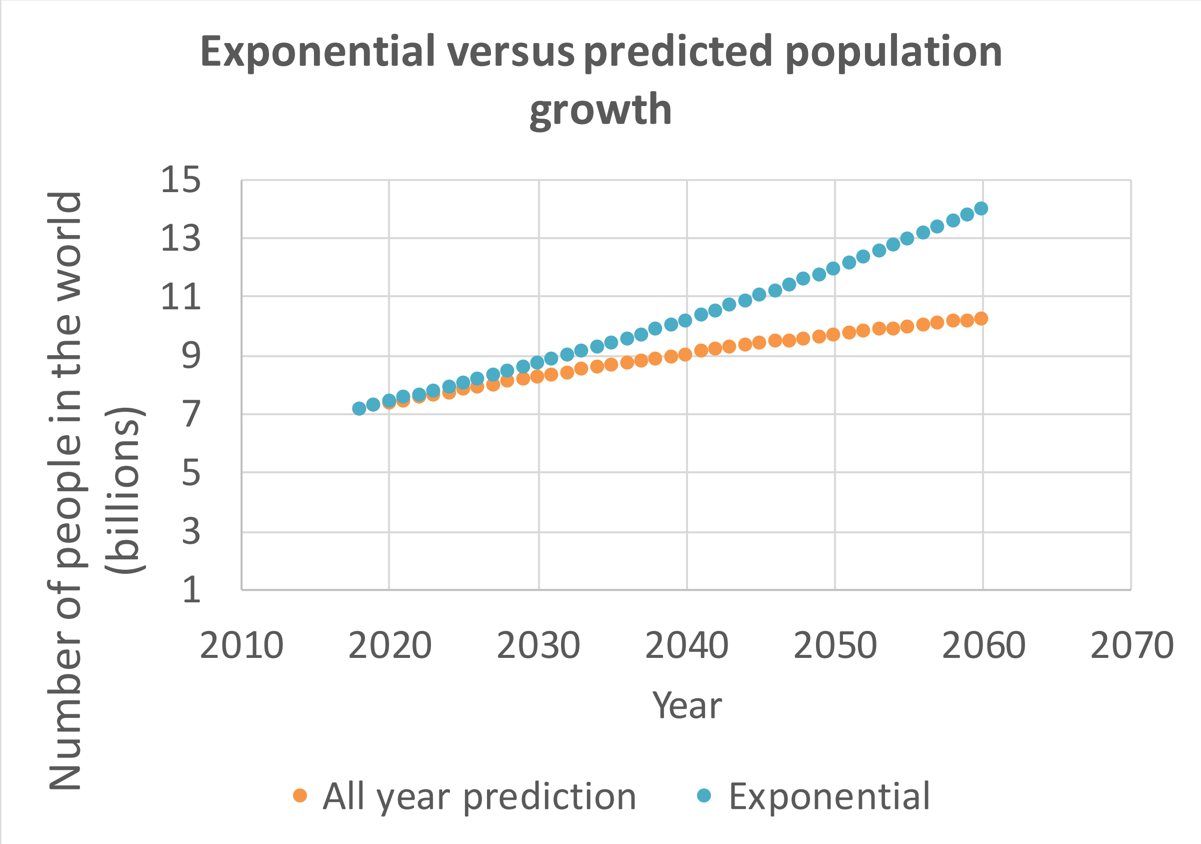


***Figure 20****. Population growth calculated from fitting future growth rates estimated from the available World Bank data. It is apparent that there will be a plateauing of world population, though it continues to grow well beyond 2050. An exponential growth curve is plotted for comparison.*

From this rate, a prediction of the number of people in the world can then be calculated. This turns out to be close to the UN estimates, around 9.7bn people by 2050, taking the all-year fit of the growth rate data (figure 20). 2050 isn't the end though, if the change in growth rate is to be believed (it is always dangerous to extrapolate too far), world population will continue to grow until around 2080, at which point it may then start to recede, as global birth rates, in what will then be more developed countries, continue to decline. Despite the large uncertainty about what will happen in the future, I have kept the likely broad demographic changes in mind throughout this report, as the differences between totals of an absolute quantity and a per capita quantity must always be borne in mind.

## Energy use and emissions

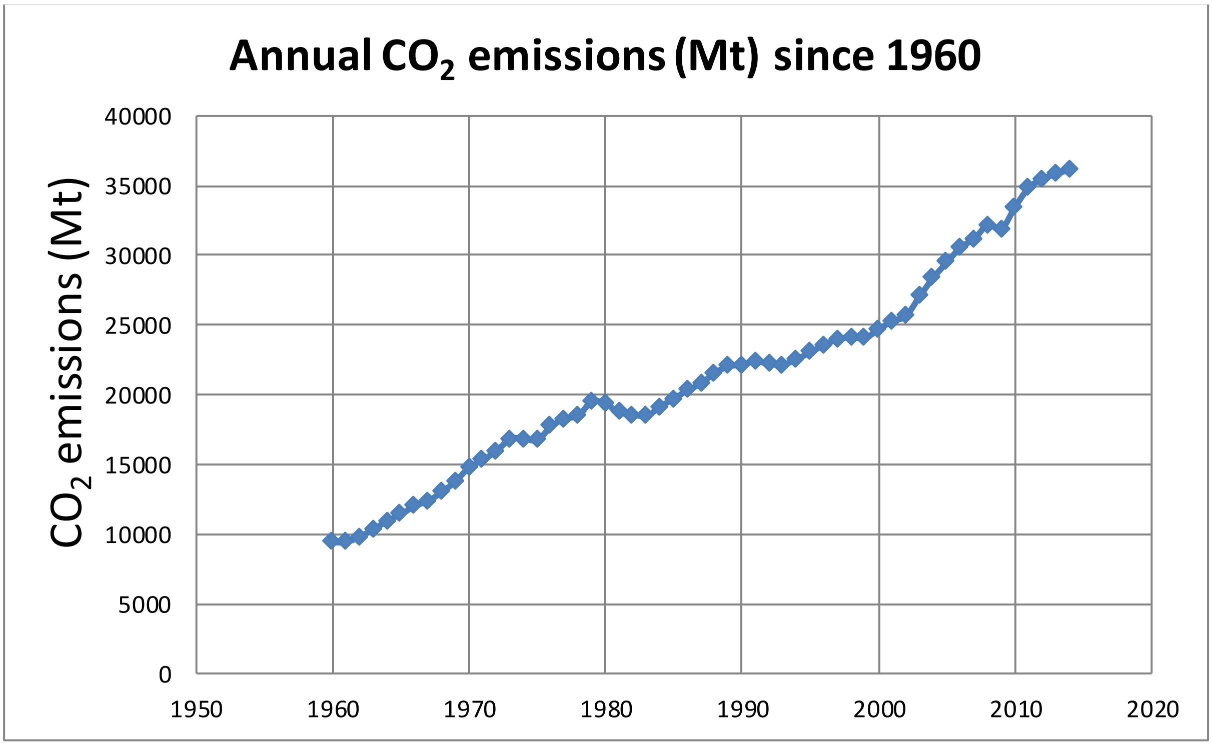


***Figure 21****. Although our population doubled between 1960 and 2000, our emissions more than doubled. Note the increased rate of growth in emissions from the year 2000. These data exclude emissions from land use.* (*Source*: World Bank)

Turning to emissions, we can see that our growing population is emitting more $CO_2$ than ever before (figure 21). It is not just $CO_2$ that is rising; emissions of methane, nitrous oxide and other greenhouse gases are also rising collectively more than ever before, almost doubling in my lifetime. Often these are converted into 'equivalent $CO_2$ molecules' ($CO_2e$) in order to standardise to a common unit of global warming potential. Globally, per capita, this seems to have levelled off over the last few years (though at an all-time high), but it is important to remember that the total figure is still increasing due to population growth and that underneath the aggregate emissions picture, different economic regions of the world have different patterns of growth or attrition in emissions profiles.

It is unsurprising that much of these $CO_2$ emissions in one way or another is due to demand for energy, whether that is for food or for fuel.

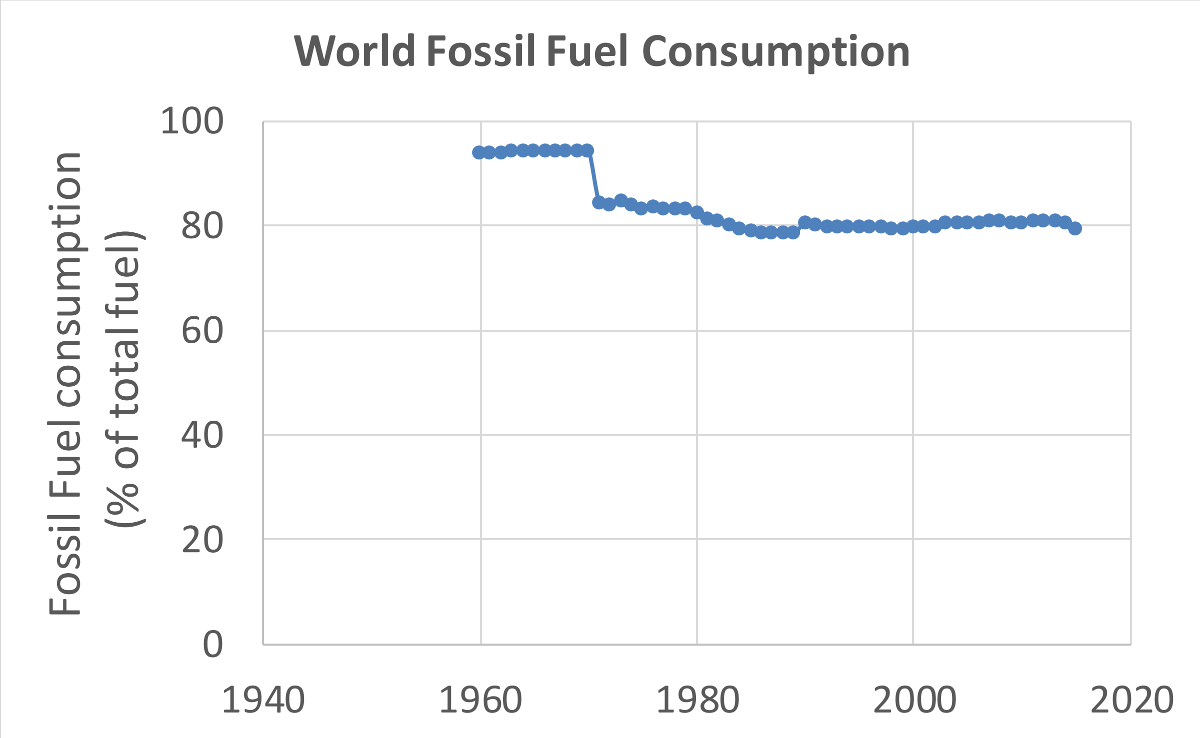


***Figure 22.*** *World fossil fuel consumption since 1990 as a percentage of all energy. The global penetrance of renewable fuel sources has hovered at 20% since the mid-1980s despite the rapid growth of renewables in electricity. Despite a downward trend in Europe, the global picture remains one of high overall consumptions.*

It is therefore logical to observe that as a global population we have stubbornly hovered around the 80% mark of our global energy derived from fossil fuels, for the last thirty years (figure 22).

## Climate change

There is an unambiguous link between atmospheric levels of greenhouse gases (GHGs) and the level of warming due to heat-trapping and the reduction in radiative heat loss to space, commonly known as the greenhouse effect. This is known to be a primary driver of global warming. Burning fossil fuels releases greenhouse gases in varying amounts, which in turn contribute to the greenhouse effect.
It is important to note that many other things, themselves dependent (though not wholly) upon fossil fuels, lead to greenhouse gas release. This is touched on briefly later in this report.

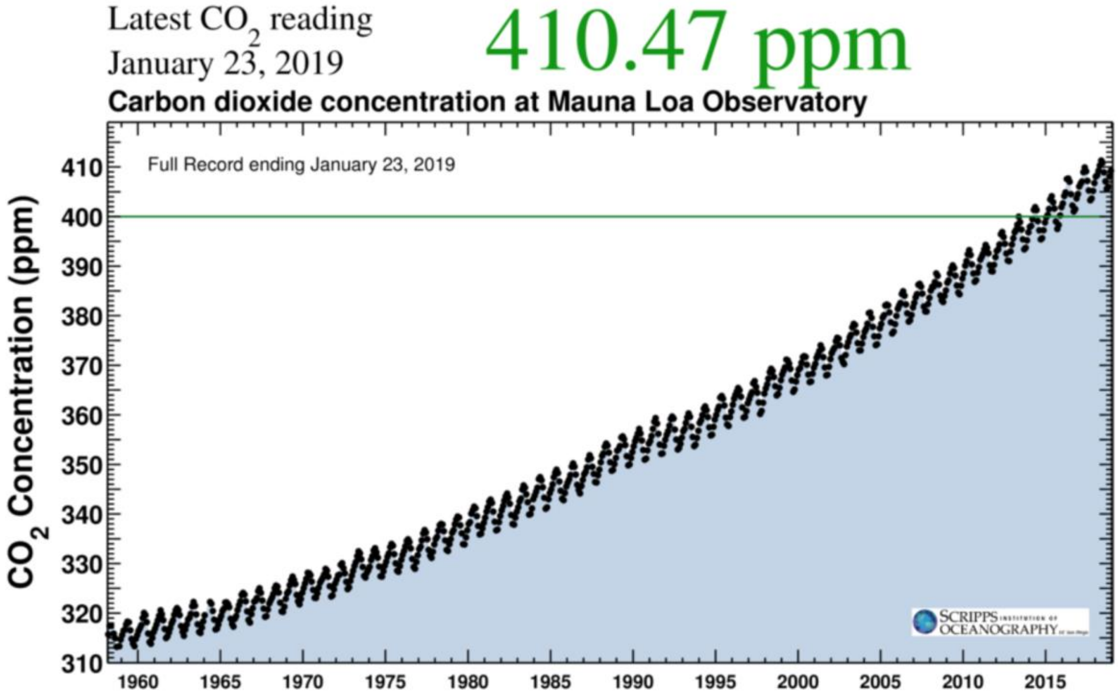


***Figure 23****. The Mauna Loa observatory in Hawaii has measured $CO_2$ levels in the atmosphere for nearly 70 years. Note the inexorable rise in $CO_2$ levels (measured in parts per million). If this seems infinitesimally small to make a difference to anything, for comparison the human nose is able to detect the smell of geosmin (which contributes to the petrichor smell when it rains after a dry spell) at 5 parts per trillion, which is 0.000005 parts per million). $CO_2$ levels reached a record high in May of this year (at the maximum of the seasonal cycle) reaching 415.7ppm on May 15$^{th}$. Source*: https://scripps.ucsd.edu/programs/keelingcurve/

For context, $CO_2$ levels at the current concentration (figure 23) have not been seen for millennia, probably around 3 million years ago At this point in earth's history it is thought that sea levels were around 25 metres higher than the present day and global temperatures around 4 degrees higher (Csank et al., 2011; Dwyer & Chandler, 2009). This shows that the earth's systems are dynamic and that life can be sustained at higher levels of $CO_2$. However, taking sea level rises alone, this would mean significant alterations to our landscape, especially, for the UK in some of our most fertile regions of the country (figure 24).


***Figure 24****. Using the sea level rise simulator, a rise of 25m in sea level would see a large proportion of the East of England under water. Source:* www.flood.firetree.net

Earth has of course seen far higher $CO_2$ levels than 415ppm in the past, but it must be remembered that the ecosystem was a very different place. 500 million years ago when $CO_2$ was at 3000ppm, there were no land plants (and no soil), 50 million years ago, when $CO_2$ levels were around 1000ppm and globally temperature around 8-18C higher, most of the plants we use for food today had not yet evolved.

Recent $CO_2$ levels in our atmosphere have rapidly spiked due to fossil fuel consumption, probably faster than any other natural process. The speed of this release may have consequences that have not been observed in earth's history (figure 25). It is therefore extremely difficult to know how much of an effect and how rapid the consequences of our actions. Recent modelling suggests that the ecosystem is exceptionally sensitive to $CO_2$ and therefore the climate sensitivity (the amount of warming that will occur due to a doubling of atmospheric $CO_2$) may be greater than previously thought (Zhu, Poulsen, & Tierney, 2019).

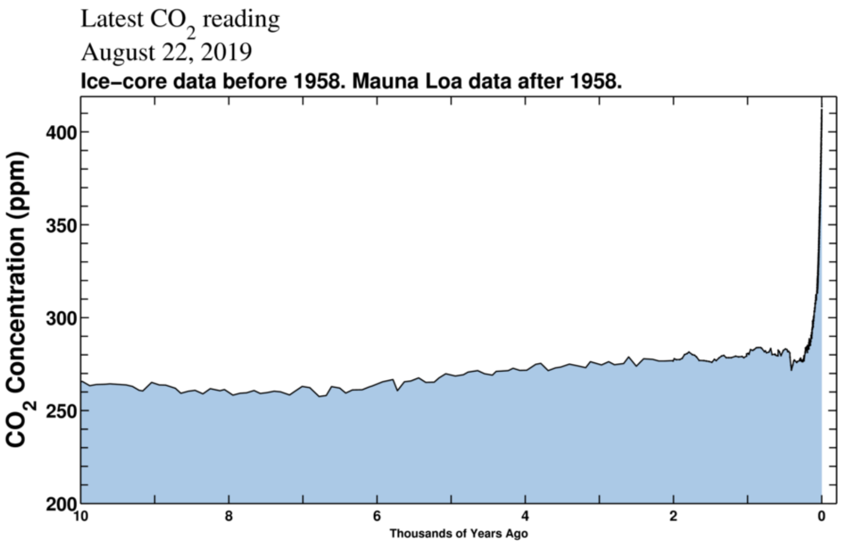


*Figure 25. The increase in atmospheric $CO_2$ on a thousand-year timescale is extremely rapid, at a rate that the world's ecosystem has never previously experienced.*
*Source*: https://scripps.ucsd.edu/programs/keelingcurve/

## Weather and climate

One of the most contentious areas of climate science at present is the linkage between the weather and the climate. One of the key predictions of climate scientists is that against a backdrop of a warming climate, extremes of weather will become more frequent. This is a complex area of scientific enquiry. However, there are some key observations that suggest that the recent trend of 'record breakers' in weather can be at least in part attributed to man-made climate change. What is incontrovertible is the fact that the top ten warmest years in the UK have been since 2002 (data collected since 1884), six of the ten wettest years have occurred since 1998 (data since 1862), and that the 21st century (so far) has been warmer than any of the previous three centuries (Kendon, McCarthy, Jevrejeva, Matthews, & Legg, 2019).

## Emissions sources

Emissions vary by sector, with transport (surface and air) now making up the largest source of emissions in most level 4 income nations. Direct agricultural emissions, which are mostly non-$CO_2$ in origin (nitrous oxide and methane being two major sources), are low at around 7-9% in many developed countries (figure 26).

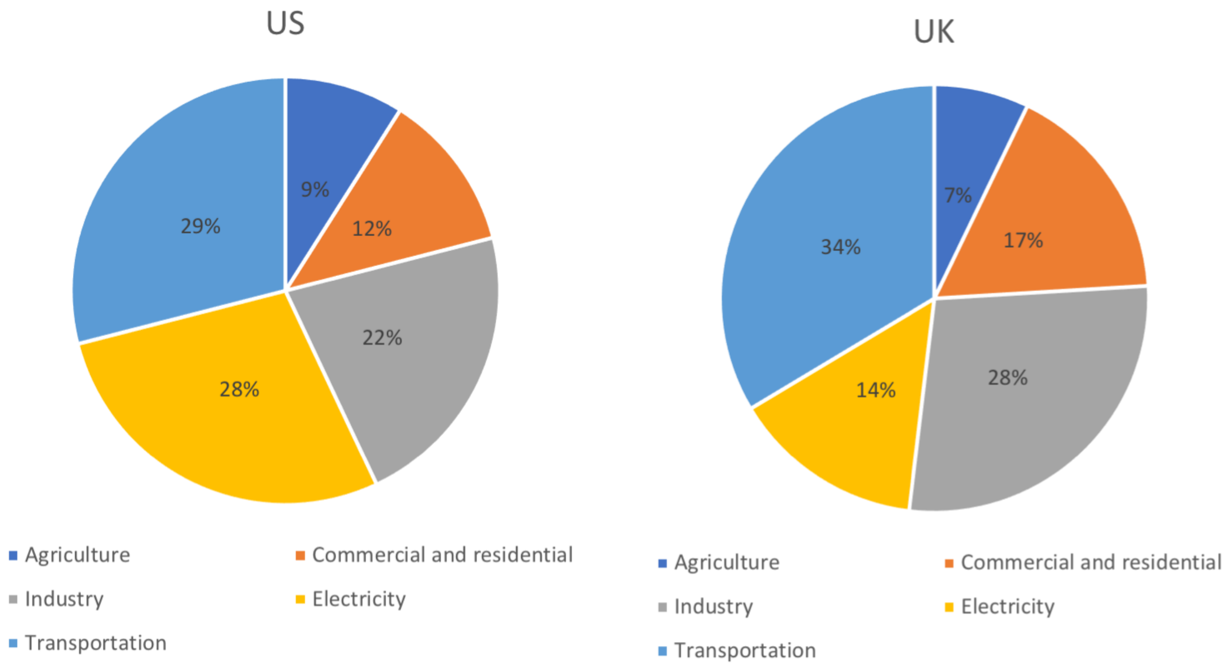


***Figure 26**. Comparison of emissions percentages between the US and the UK in 2017*
*Sources*: EPA and UK CCC

**Table 6** – Greenhouse gas emissions

| **Fifteen top sources of greenhouse gas emissions** |
|---|
| Power plants |
| Residential buildings |
| Road transport |
| Deforestation and land use change |
| Energy industry processes |
| Commercial buildings |
| Cement, Ceramics and Glass |
| Livestock |
| Iron and steel |
| Agricultural soil |
| Chemical Petrochemical industries |
| Oil and gas production |
| Waste and waste water |
| Coal mining |
| Aviation |

Farming, soils and livestock, along with ammonium fertilisers from the chemical industry and phosphorus from mining are all in the top 15 greenhouse gas emitters (table 6). In contrast to most sectors, these emissions have remained high over the past 25 years. We must also be mindful when considering any change to farming practice, as we must count both the direct emissions and the indirect emissions throughout the supply chain, for example, freight and cool-chain energy costs.

## Future Energy demands

Looking to energy demand and forecasting the future, we see that our demand (per capita) is going to continue to rise, we therefore expect to see $CO_2$ emissions to continue to track fossil fuel usage as so much of our global energy demands are serviced by fossil fuel (figure 27).

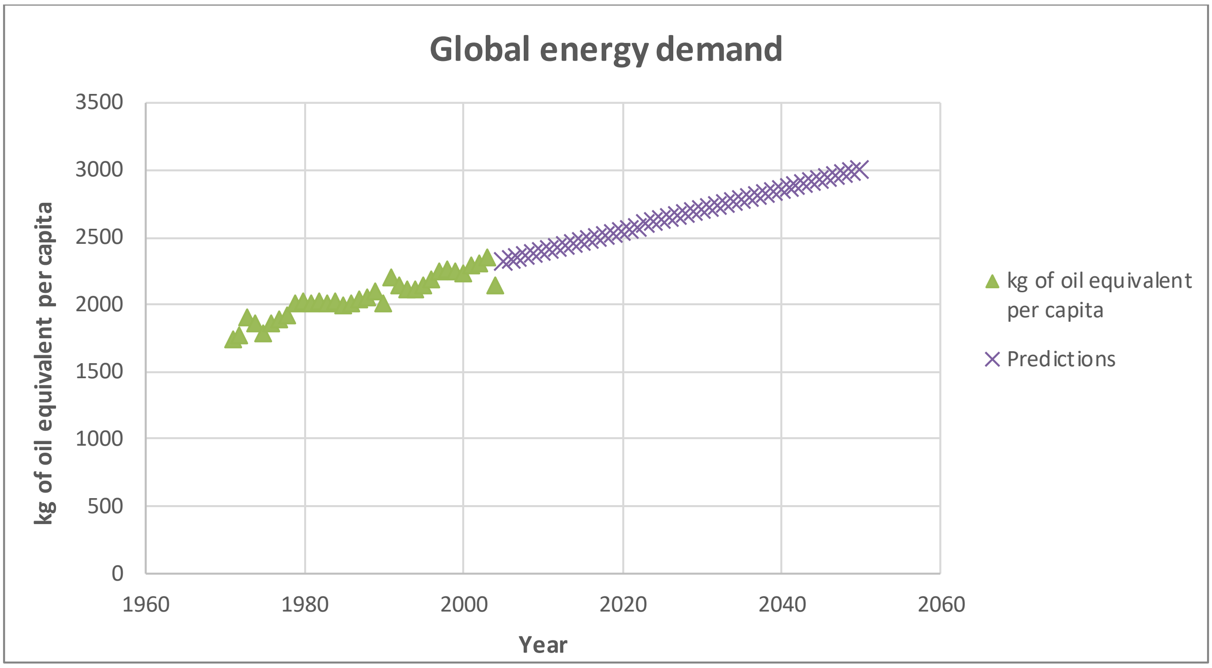


***Figure 27****. Projecting forward, based on the current rate of growth, global demand for energy will be approximately twice that of 1960 levels.* Source: World Bank

However, global trends are not the whole story. Looking at our own energy usage, we start to see the following patterns (figure 28). UK energy usage is falling. Indeed, if we take a trendline (which is always dangerous), by around 2035 we will be using per capita the same amount of energy as a typical Sub-Saharan African is using today; perhaps not.

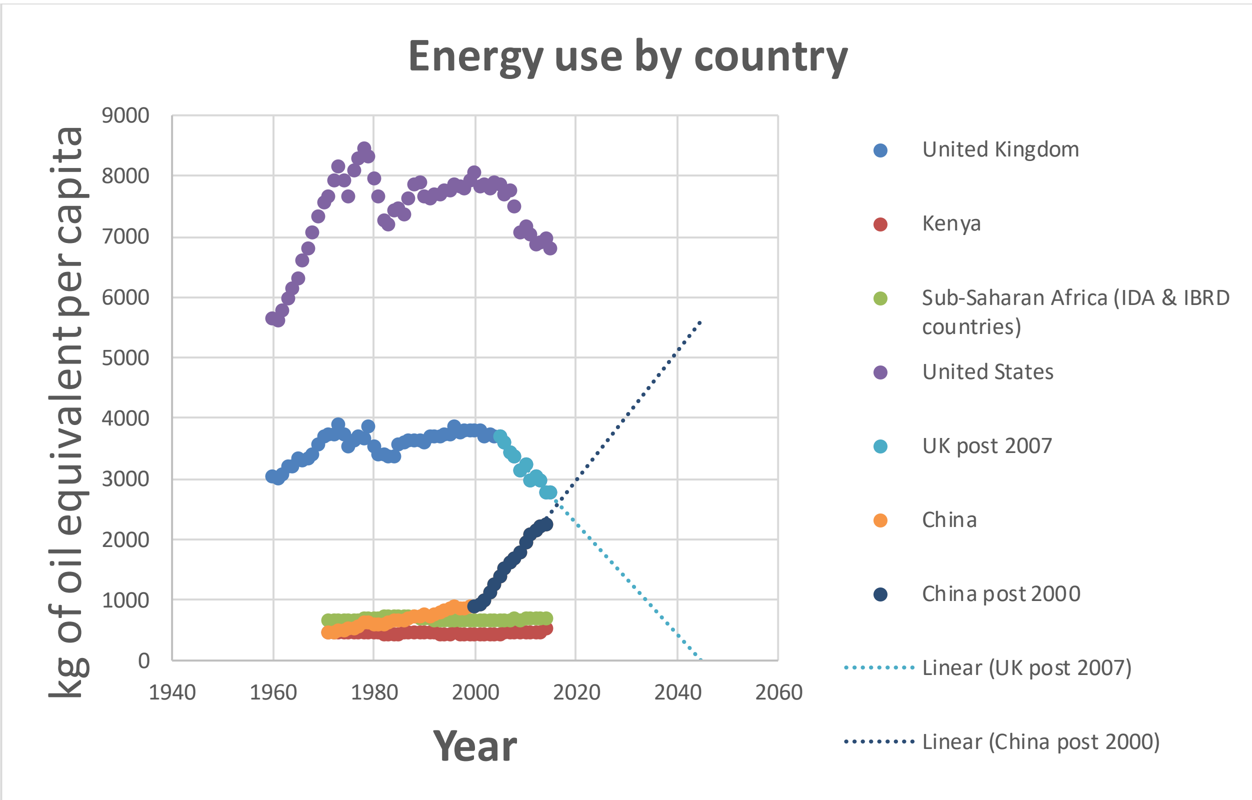


***Figure 28****. Per capita energy demands are variable between countries. Both the US and EU28- here represented by the UK have cut energy use, in the UK to below that of 1960. However, there is concern that in fact much of this per capita decline is due to the externalising of many heavy industries and manufacturing to China, therefore only giving the appearance of a national decline*. Source: World Bank

What we can see reasonably clearly is a pattern of other countries rapidly reaching and in fact overtaking us in terms of per-capita energy usage. China is a clear example of an energy hungry nation. After all, manufacturing all of those consumer goods for us requires a power source, infrastructure and transportation. This is where it becomes really difficult to interpret broad patterns without spending a lot more effort in building up data from the bottom up.

## Rapid global progress to income levels 3 & 4

Much of the global demand in energy is driven by the rapid progress developing nations are making towards higher income levels.

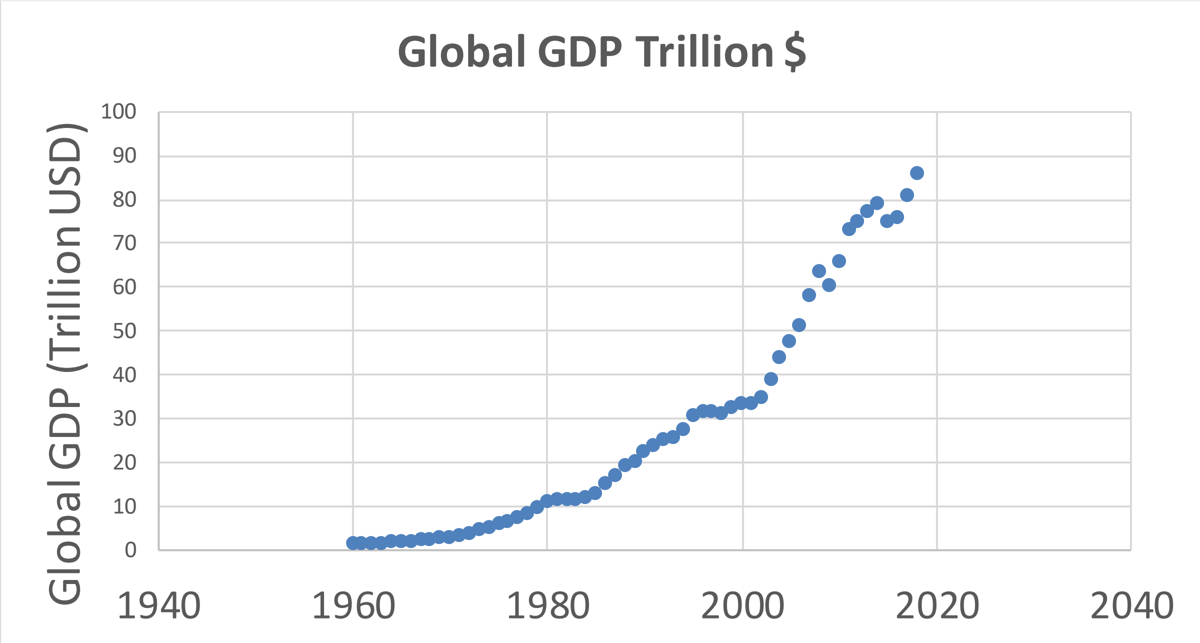


***Figure 29.*** *Global GDP levels have increased almost 100-fold over the past 60 years.* Source: World Bank

If we take a look at global Gross Domestic Product (GDP) (figure 29), we can see that this is currently on something of a non-linear path upwards, even if it did take a dip in 2010 due to the global financial crisis. Rising GDP, to a first approximation, is good. Rising GDP means that on the whole everyone is getting richer, though of course exactly what the metric is measuring can be questioned. However, people across the globe are moving up the income levels and with that comes many of the benefits that we currently enjoy.

This is fantastic news for development, as global growth is really happening. People are being lifted out of poverty, becoming more educated and living better lives. However, it also means that if we carry on as we are at level 4 and pass on our current ways of living, we will continue to exacerbate the problems of climate change, resource depletion and degradation of our precious natural resources. There is a very clear link between GDP and power consumption (figure 30), supporting the notion that as we improve as a global population, our energy problems and therefore, our emissions problems may get worse.

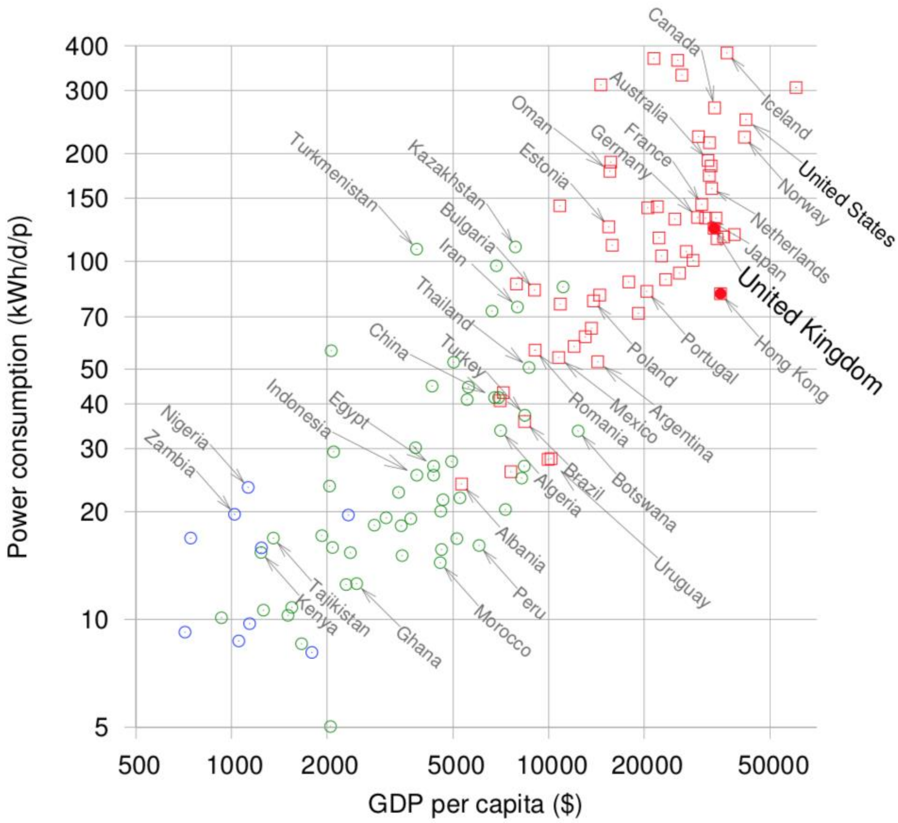


***Figure 30**. Power consumption versus GDP. All values are per capita in purchasing power parity US dollars.* This figure is reproduced from David Mackay's website and book *'Sustainable energy without the hot air'* (MacKay, 2009)

Take these advances together, and given that we are digging up, or sucking, drilling or fracking our way to these previously 'locked up' hydrocarbon sinks in ever more ingenious ways, it is easy to see how our demands for energy, our growing population and our lack of a truly sustainable energy transition form a serious and urgent problem for us all to tackle.

This is of course globally recognised as an issue and the UN sustainable development goals are in part focussed on this exact issue. The second goal to 'end hunger, achieve food security and promote sustainable agriculture' alongside goal 12, 'ensure sustainable consumption and production patterns' and goal 13, 'take urgent action to combat climate change and its impacts', all clearly articulate the challenges.

It is useful when reading this report to reflect on what the UN, for close to a decade now, has been proposing specifically for food, but until embarking upon this Nuffield study I had not heard about:

In 2011, as part of an FAO report, *Energy-smart food for people and climate*, the authors propose:

'An approach based on three pillars: (i) providing energy access for all with a focus on rural communities; (ii) improving energy efficiency at all stages of the food supply chain; and (iii) substituting fossil fuels with renewable energy systems in the food sector.'

At the time of this report, FAO Assistant Director-General for Environment and Natural Resources, Alexander Mueller, stated:

‘The global food sector needs to learn how to use energy more wisely. At each stage of the food supply chain, current practices can be adapted to become less energy intensive.’ [1]

[1] *Source* http://www.fao.org/news/story/en/item/95161/icode/

# Appendix 2 Developments in genetics and automation

As is expected with a Nuffield scholarship, the topic of study usually has some overlap with the existing career of the scholar. Until recently, as part of my day job I led the overall research and development of genetics, genomics and breeding at NIAB EMR and much of this research is focussed on soft fruit. I am therefore more familiar with this particular area than most. I therefore chose on my travels to include meetings with other researchers and breeders as part of my study, but not to prioritise this element of my study in the main body of this report. I include a short report on some of the key areas that are developing rapidly in this sector for completeness of the study and to reinforce the role of genetics in some of the wider systems changes that I propose within this report.

## Genomic selection – more rapid gain

Plant breeders are part scientist and part fortune teller. For tree crops it may be as many as twenty years before a variety achieves commercial release which nowadays is often far too slow to respond to market needs, leading to luck, rather than foresight, being the primary determinant of market success.

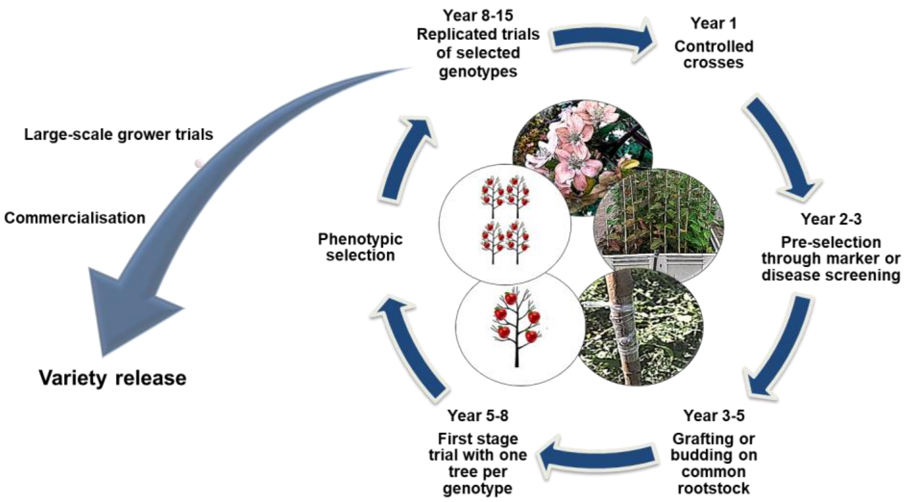


***Figure 31****. A selection cycle for a typical horticultural tree crop.* (Karlstrom, Cobo-Medina and Harrison 2018).

As can be seen from the diagram above (figure 31), even with the use of molecular markers for major gene traits (for example 'major gene' disease resistance) , the earliest time that a variety can be screened (in a tree crop) is around five years after crossing, also marking the first time that a variety can be used for crossing, setting an upper limit on the rate of genetic gain (the crossing of favourable combinations back into the breeding programme). This is then followed by further cycles of propagation for increasing cycles of trials. Speeding up this breeding and selection cycle is a problem that is particularly pronounced in tree crops, but extends out to most crop and animal breeding programmes. One of the solutions to this problem is genomic prediction, which dramatically alters both the efficiency of breeding programmes and also the speed at which they can be carried out.

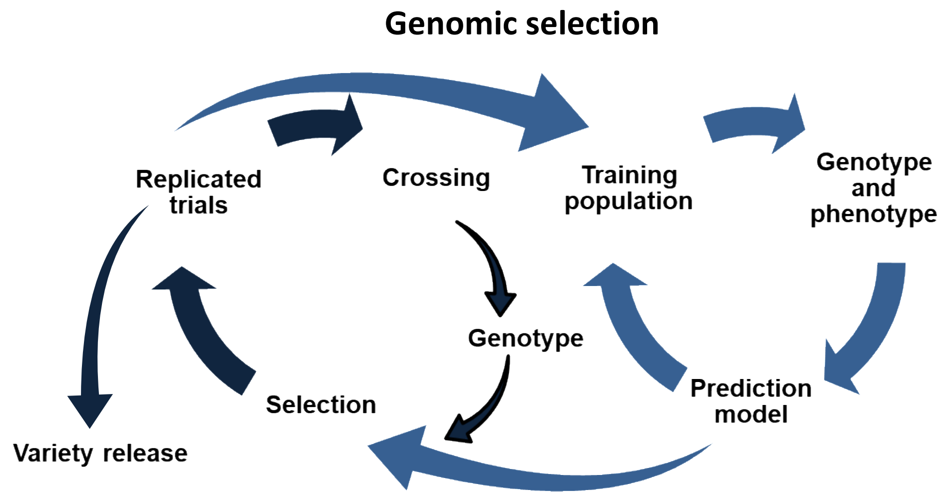


***Figure 32****. A schematic illustrating a typical genomic prediction approach to breeding:* (Karlstrom, Cobo-Medina and Harrison 2018).

Comparing the two breeding cycles (figures 31, 32) some fundamental differences can be observed. The first is that there are two separate parts to the programme, a 'training' population and a selection cycle. This is a difference to the traditional breeding cycle, as it allows the performance of the plant to be predicted at the seedling stage before the plant is mature enough to actually be measured for its performance. This is possible by measuring the relationship between plant performance and genetic variation in the training population and using that information as the basis for prediction in unmeasured derivatives (hybrids) of that training population. Coupled with techniques such as speed breeding, plant growth programmes that minimise generation time of plants through providing optimal light/temperature/vernalisation treatments, breeding cycles can be dramatically shortened and genomic gain per unit time enhanced. As a result, the application of genomic prediction is growing in size due to the recent developments in genome sequencing, the declining cost of genotyping (measuring a subset of variants within the genome) and the rapid advancement in statistical approaches to predicting plant performance.

Within the strawberry breeding field, I was pleased to learn that the efforts that we have been making in the UK over the past few years to move strawberry genetics to the forefront has paid off. Just three or four years ago I would have looked enviously at the developments in the US, France or the Netherlands. Having paid visits to U.C. Davis (California) and other worldwide breeding programmes, I am now confident that the UK is at least as good in the area of developing the underpinning genomic resources and deploying genomic selection directly into breeding efforts as our peers, albeit on a fraction of the budget! The same applies for gene editing approaches, in fact here the UK leads, certainly in gene editing efforts currently underway in strawberry (Wilson, Harrison, Armitage, Simkin, & Harrison, 2019).

## Massively parallel phenotyping – measuring (and understanding) everything

Hand in hand with developments in genomic selection are the advances being made in automated acquisition of crop data. This is equally important to drive down the cost of breeding programmes incorporating genomic selection, as rather than the relatively rapid evaluation of many tens of thousands of seedlings, detailed measurements of thousands of replicated plants need to be carried out to parameterise the genomic prediction model. This is extremely labour-intensive and so effective deployment most likely relies on objective measurements by automated systems.

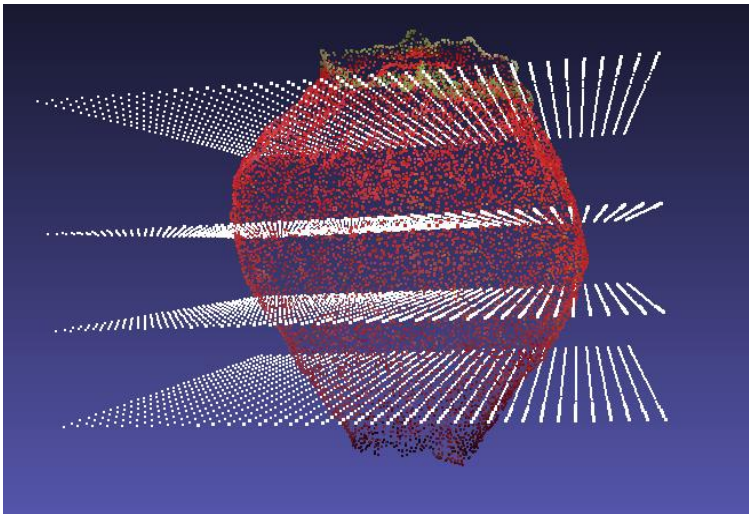

***Figure 33****. 3D imaging of strawberries allows automated characterisation of multiple shape and quality parameters.* (Li, Cockerton, Johnson, Stavridou and Harrison- unpublished data)

Again, I found that the work that we (at East Malling) were carrying out in this area was already comparable to that in most of the leading research facilities around the world. For example, for work imaging the 3D structure of fruit (figure 33). There is some way to go before automation can capture the subtleties of plant characterisation that our well-trained breeders can, but this is a field of extremely active research in the UK.

## Gene editing and new entrants to breeding

While gene editing is a pipe dream for European plant breeders, following the hugely disappointing Central Court for European Justice ruling on regulation of new gene editing techniques, for global markets, gene editing is a real possibility. As we move rapidly to a research capability where instead of genetic markers (which are genetically linked to a trait, but do not necessarily directly impact the trait themselves) we identify the exact genes and gene variants underpinning a trait, we move to a position where we can 'direct' evolution thorough targeted mutagenesis, rather than relying on chance to generate genetic variation. This does not fundamentally change the process of breeding and selection, it rather means that instead of having to screen through many seedlings for either chance mutations (as a result of natural errors in DNA replication) or for existing genetic variants that might be at very low frequencies within populations, we can direct the mutation process to a particular region of the genome. In simple applications this may mean taking an elite line of a crop and adding 'plus' traits, such as enhanced disease resistance, using the information gained from genetic characterisation of crop wild relatives, or landraces. This technology also means that previously impossible changes, such as transferring traits from one crop to another, become possible, not through the transfer of genes, but the engineering of the trait within the crop. These types of possibilities have led to new entrants into the plant breeding market. Although not feasible within our market, our collective failure to embrace these technologies means that the full range of tools are not available to us.

## A robotic future?

Finally, even during the course of researching and writing this report, the deployment to market of picking robots has begun (figure 34). These machines contain many of the characteristics needed for automated evaluation of fruit, as multiple quality assessments need to be undertaken before picking.

***Figure 34**. Robots from Dogtooth and Octinion respectively designed to pick soft fruit.*
Source: octinoin.com & dogtooth.tech

We are early in the development cycle of these instruments and it is likely that many iterations of both the technology and the business model will be needed before the technology is fully fit for purpose. The prevailing wisdom is that innovation in the packhouse and in less dextrous tasks, such as moving fruit around the farm, may give more affordable efficiency gains. I have been lucky enough to be involved in projects providing underpinning data and research approaches (for example the development of imaging and machine-learning approaches for non-destructive fruit characterisation), that I am confident enough that these technologies will reach market rapidly. I am also relatively confident that breeders will be able to respond with a combination of rapid phenotyping and genomic selection for the plant architecture traits required for the efficient automation of harvesting. However, in many horticultural crops this may take a long time. In strawberry the breeding cycle is a minimum of 7 years. This means that varieties with specifically-bred 'robot-enhanced' picking traits will only be on the market in 2027.

In terms of yield, data from the East Malling breeding programme (that I was involved with until May 2019) has shown that there are single lines that yield in excess of 2kg per plant, both 'June-bearer' types and the everbearing 'day-neutral' types. These offer large opportunities for genetic improvement within breeding programmes.

Having said this, a step change is still needed within most breeding programmes to integrate technologies and traits together in a cost-effective manner to drive forward rapid improvements in crop productivity, and it is clear that the private sector alone lacks the investment funds at the moment to drive this forward, especially when considering breeding for completely new production systems, as is discussed in subsequent sections.

## Appendix 3- A little bit more on a green energy future.

### Farming fossil fuels – is it really true?

In Appendix 1, I reported the fact that agriculture was a significant emitter of greenhouse gas. A recent Freedom of information request has led to the publication of a breakdown of emissions from UK agriculture (table 7). What this reveals is a relatively small amount of direct $CO_2$ emissions, with methane and nitrous oxide providing the bulk of GHG emissions.

**Table 7**. Greenhouse gas emissions in the UK from agriculture, hunting and related services. Weight in thousand tonnes of carbon dioxide equivalent ($ktCO_2e$)

| | 2012 | 2013 | 2014 | 2015 |
|---|---|---|---|---|
| Total greenhouse gas emissions | 49,696.0 | 50,186.3 | 51,204.5 | 51,233.8 |
| Carbon dioxide (CO2) emissions | 6,754.8 | 7,090.2 | 7,055.3 | 7,219.5 |
| Methane (CH4) emissions | 27,078.0 | 27,045.9 | 27,556.1 | 27,653.5 |
| Nitrous oxide (N2O) emissions | 15,823.6 | 16,009.9 | 16,549.2 | 16,315.3 |
| Hydro-fluorocarbons (HFC) emissions | 39.6 | 40.3 | 43.9 | 45.5 |
| Perfluorocarbons (PFC) emissions | 0.0 | 0.0 | 0.0 | 0.0 |
| Nitrogen trifluoride (NF3) emissions | 0.0 | 0.0 | 0.0 | 0.0 |
| Sulphur hexaflouride (SF6) emissions | 0.0 | 0.0 | 0.0 | 0.0 |

*Notes
(Total greenhouse gas emissions include carbon dioxide, methane, nitrous oxide, hydro-fluorocarbons, perfluorocarbons, sulphur hexafluoride and nitrogen trifluoride and is expressed in thousand tonnes of carbon dioxide equivalent.)
*Source*: reproduced from
https://www.ons.gov.uk/aboutus/transparencyandgovernance/freedomofinformationfoi/energyandwaterconsumptionintheagriculturalsector

Energy usage is reported to be approximately 116,873 Terajoules, or 2.79 million tonnes of oil equivalent, in 2015. Notably only a small fraction of agricultural emissions are direct $CO_2$ emissions (7% of the total for agriculture). For comparisons later on, if converted into terawatt hours this is around 32.5TWh per annum (32,465 GWh).

It is important to note that GHG figures have remained stubbornly high for many years and therefore, as a percentage of total emissions, are increasing, a fact that has not escaped the attention of the Committee for Climate Change (CCC) in their recent *net zero* report.[1]

Looking further into what is classed within agricultural emission within the Climate Change Convention (table 8), it is clear that indoor production of horticultural crops is not included within this sector and are instead classed as 'industrial' emissions. This is important, as it highlights that as a percentage agricultural emissions *senso lato* are actually higher.

[1] https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/.

**Table 8** – Annual Greenhouse Gas Emissions as reported in Annex 1 of the UN Convention on Climate Change

**Annual greenhouse gas (GHG) emissions for United Kingdom of Great Britain and Northern Ireland, in kt $CO_2$ equivalent**

Query results for — Party: United Kingdom of Great Britain and Northern Ireland — Years: 1990, 1994, 1995, 1996, 2000, 2005, 2010 and last year — Category: 3. Agriculture — Gas: Aggregate GHGs — Unit: kt $CO_2$ equivalent

| Category | 1990 | 1994 | 1995 | 1996 | 2000 | 2005 | 2010 | Last Inventory Year (2017) |
|---|---|---|---|---|---|---|---|---|
| 3. Agriculture | 49,173.86 | 48,156.49 | 47,954.35 | 48,590.59 | 45,926.29 | 43,596.43 | 40,914.35 | 41,549.10 |
| 3.A Enteric Fermentation | 25,392.50 | 25,097.78 | 24,867.42 | 25,158.48 | 24,161.22 | 22,643.16 | 21,119.26 | 21,458.44 |
| 3.B Manure Management | 8,175.23 | 8,218.10 | 8,151.64 | 8,339.59 | 7,819.13 | 7,266.55 | 6,901.26 | 7,041.59 |
| 3.C Rice Cultivation | NO | NO | NO | NO | NO | NO | NO | NO |
| 3.D Agricultural Soils | 13,610.39 | 13,210.14 | 13,312.04 | 13,429.73 | 12,786.39 | 11,757.36 | 11,137.24 | 11,466.79 |
| 3.E Prescribed Burning of Savannas | NO | NO | NO | NO | NO | NO | NO | NO |
| 3.F Field Burning of Agricultural Residues | 244.23 | NO | NO | NO | NO | NO | NO | NO |
| 3.G Liming | 1,012.43 | 1,012.88 | 1,070.22 | 1,136.22 | 629.90 | 1,405.34 | 1,175.09 | 936.67 |
| 3.H Urea Application | 327.60 | 211.85 | 148.92 | 135.41 | 133.02 | 203.76 | 269.90 | 343.95 |
| 3.I Other Carbon-containing Fertilizers | NO | NO | NO | NO | NO | NO | NO | NO |
| 3.J Other | 411.48 | 405.74 | 404.11 | 391.17 | 396.64 | 320.26 | 311.59 | 301.66 |

*Source*: Reproduced from: https://unfccc.int/process-and-meetings/transparency-and-reporting/greenhouse-gas-data/ghg-data-unfccc/ghg-data-from-unfccc

A 2012 EU project *agrEE* conducted a study of energy efficiency in Dutch tomato production, among other crops. In intensive production systems, yields of around 640 t $ha^{-1}$ were achievable with a total energy input of around 15,110 GJ $ha^{-1}$ (Consortium, 2012). That figure includes, fertilizer, pesticides, irrigation, materials, diesel and other energy usage (e.g. gas) but excludes sunlight. Converted into gigawatt hours (GWh) that is approximately 4.2 GWh per hectare. As total area of production in 2012 was around 1676 ha, this equates to a total energy usage of 7035 GWh per annum; this area of cropping produced around 1,072,640 tonnes of tomatoes, each tonne requiring 0.007 GWh to produce. For comparison, this is roughly the same amount of energy as boiling 44,438,057,135 (44.4 billion) kettles per year, or the same levels of emissions as roughly 840,000 cars (based upon CO2e emissions of 549 t/GWh from burning natural gas and the average emissions from a standard petrol car of around 4t/annum) (see table 5).

If we calculate a conversion efficiency - that is the amount of energy input into the system (excluding sunlight), compared to the amount of energy (in joules/Calories) recovered from the system - we arrive at an efficiency of approximately 3%. This is shockingly low. From the same dataset there is information about low input production in Portugal. Per hectare the yields of the Dutch system are roughly five times higher than the low input system and require approximately 4.25 times less land to achieve the same total tonnage. However, the energy usage of the Dutch system is roughly 177 times greater than the Portuguese system (table 9). In fact, the Portuguese low input system actually achieves a conversion efficiency of 114%, meaning that more energy is recovered in the crop than is put in from direct and indirect energy sources (excluding sunlight). This highlights the difficulty of estimating the true environmental cost of a production system, as both systems are presumably economically viable (or were in 2012).

**Table 9**- comparisons of emissions between tomato growing systems

| | ***hectares*** | ***t/ha*** | ***Total annual tonnage*** | ***kg/person (UK population)*** | ***GWh/ha per annum*** | ***Total GWh per annum*** | ***GWh / tonne*** | ***Total kWh per annum*** | ***Boiled kettles/ year*** | ***GJ*** | ***GJ/t*** | ***Conversion efficiency %*** | ***Emissions if electrified tonnes of CO2e*** | ***Emissions if gas tonnes of CO2e*** | ***Annual cars on the road (2018 UK elec mix)*** | ***Annual cars on the road (gas)*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Dutch tomatoes (2012 hectarage)* | 1,676 | 640 | 1,072,640 | 16 | 4 | 7,035 | 0.0066 | 7,034,544,444 | 44,438,057,135 | 25,324,360 | 24 | 3 | 1,266,218 | 3,861,965 | 275,265 | 839,558 |
| *Low input Portuguese tomatoes (2012 hectarage)* | 1,440 | 150 | 216,000 | 3 | 0 | 40 | 0.0002 | 39,600,000 | 250,157,928 | 142,560 | 1 | 115 | 7,128 | 21,740 | 1,550 | 4,726 |

***Assumptions:**
1kg tomatoes – kCal= 180
Average $CO_2$e emissions UK power 2018- 180t/GWh
Gas $CO_2$e emissions 540t/GWh
Annual $CO_2$e emissions from a family car 4t per annum
Kettle 0.15kWh to boil a 1.7L, 2.2kW kettle

Note that in the UK annual tomato consumption is approximately 8.3kg per person, per annum. This means that we consume approximately 550 thousand tonnes of tomatoes per year, roughly half of the total produced in the Netherlands in 2012.

**Table 10.** *Emissions and energy use of UK annual tomato consumption based upon 2012 Dutch production statistics*

| UK emissions | If all ELECTRIC | If all GAS |
|---|---|---|
| **t $CO_2$e** | 633,109.00 | 1,930,982.45 |
| **kt $CO_2$e** | 633.11 | 1930.98 |
| **Emissions (compared to total ag emissions) %** | 0.6 | 1.9 |
| **Energy use (compared to total ag usage) %** | 10.83 | |

Placing this into the broader context, if we were to assume that all tomatoes produced for the UK used the same amount of energy as we estimated for the Dutch system, we can calculate that the emissions from tomatoes (using the same figures as before for carbon intensity of electricity and gas $CO_2$e emissions) would range between 0.6-1.9% of the total of agricultural emissions and around 11% of the total energy usage of UK agriculture (table 10). However, it is also extremely important to note that where CHP systems are used, rather than just gas boilers, heat and $CO_2$ are by-products of energy generation and therefore the emissions should not necessarily be apportioned directly to tomatoes.

For completeness, if we assume that the average adult consumes 2000kCal per day and that the 8.32kg of tomatoes that we consume on average yields ~1500 kCal, then tomatoes make up approximately 0.19% of our annual calorific intake.

## Indoor production- the desire to control

There are many good reasons why there is a rising interest in indoor production, the more efficient use of water, the ability to produce year-round, 24/7, the opportunities for automation and the potential for greater yields are all valid proposals. There is also a growing argument that with growing climatic instability and variance in environmental conditions supply chains will be negatively impacted. Some evidence suggests that horticultural supply chains will be particularly negatively impacted, leading many to propose that permanent indoor structures are the way forward.

Again, drawing upon the study of tomatoes, less than 1% of the energy used came from the deployment or production of fertiliser, pesticides, irrigation and materials. The vast majority came from the energy used to heat the glasshouse. However, if we consider the fact that no vertical farming system to date, where light replaces sunlight, is able to economically substitute for glasshouse tomato growing, the scale of the issue is realised. Using the 2012 Dutch data the approximate electricity cost per kilo of tomatoes, if production were fully electrified, would be approximately 80 pence per kilo. Based on current domestic gas rates per kWh, this cost is approximately 10p per kilo. The average price of 1kg of tomatoes is currently £2.20, making the energy cost for gas 6%, while for electricity 36% of the total retail price.

This suggests that a total system redesign is required to make production economical. Either, electricity prices need to fall by a factor of about 6, or efficiency needs to increase by a factor of 6. This would mean reducing Dutch tomato production to roughly 0.0012 GWh per tonne (from the

2012 level of 0.007). This could involve the design of super-insulated structures and the use of artificial LED light with excellent heat recovery. Economical systems are not likely to be old sheds or industrial units, disused tube tunnels or railway arches or single-pane polycarbonate/glass houses.

During my visit to the Joint Centre for Artificial Photosynthesis at the LBL I met Dr. Frances Houle, the deputy director. She told me about California's ambitions to be 100% renewable by 2040 for electricity generation. She believes that this will be mostly achieved through the widespread deployment of PVs (photovoltaics), with local storage solutions and smoothing of demand through smart grid technologies. However, JCAP's projections show that the electricity grid cannot cope with the energy demands placed on it by a future with 100% electric vehicles.

JCAP believes that using a system called electrolysis, the conversion of water into hydrogen and oxygen gas for storage, may be one way to solve the electric vehicle problem, as large electrolysis plants could provide hydrogen for fuel cells for transport. However, cogeneration of hydrogen and oxygen over 4% is explosive and the focus at JCAP is separation at the source to enable economic and efficient production. JCAP is working on a system of renewable hydrogen generation using solar panels that would have a minimum life 10 years, an efficiency >10%, an energy payback 2-4 years and 40 years total lifespan.

The most striking thing that Francis said was that by 2040 it was her belief that "electricity will be free" given the rapid expansion of low-cost renewables sources. If true, this would certainly change many of the current pinch points in indoor production.

## The lack of robust lifecycle analysis – quantifying the externalities

Energy systems are just one piece of the puzzle when asking if production is truly sustainable. Throughout my reading and discussions, I learned about a technique known as Life Cycle Assessment (or Analysis- the two are used interchangeably). LCA tries to take account of the full process required to make an object (be it a television or a strawberry). This can then be used to ask many questions about the effect a production process has on the environment, in terms of emissions, water footprint etc.

I tried extremely hard to find up-to-date LCAs for soft fruit crops and was unable to do so. Many of the analyses that I found were 12+ years old, had multiple assumptions that no longer held in modern production systems and therefore were lacking. This was a great surprise to me, though I suspect that many analyses have been done, but have failed to reach the public domain.

This formed part of a conversation that I had with Prof Sir Ian Boyd, at the time the Defra Chief Scientist. I had arranged to discuss an article that he had written on his blog about a visit to a new vertical farm in Dundee[1]. He had remarked on the energy efficiency of the growing system. I was sceptical about whether this system was truly sustainable, or economic. He had prefaced his article by stating that he had read a report saying that for every 1 Calorie of food produced 10 Calories of energy were expended of fossil fuel. My tomato calculations suggested that was more like 31 Calories, so I couldn't understand how removing sunlight would make the situation better, not worse. We had a useful and (for me at least) stimulating discussion where I outlined my studies to date and he shared his thoughts. On many things we found that we were in complete agreement, especially on the lack of up to date LCAs. He challenged me to go and have a shot at calculating what might be possible if a 'redesign' of the system were undertaken. In the next section I detail my

[1] *Source*: https://ianlboyd.wordpress.com/2018/02/

attempts at this. In doing this I also realised that current LCAs are not necessarily fit for purpose and require further granularity if they are to help the individual grower. I also realised that used in isolation, they do not help improve things where system redesign is needed.

## Projections for strawberry

It took me a significant amount of research during my Nuffield scholarship to find data that I could use in order to calculate various scenarios for future strawberry production. These calculations are underpinned by some dated information which is derived from a very small amount of literature and are therefore only presented as a stimulus for discussion.

I started by attempting to calculate the amount of energy expended in the production of strawberries. This was hard, due to a lack of literature, but I did find a single estimate, which I used to calculate the values in table 11.

**Table 11**. Intensification of strawberries under varying assumptions - note the lower bound for intensive production is lower than current estimated energy use

| ***Scenario (yield gains)*** | ***hectares*** | ***GWh / tonne*** |
|---|---|---|
| UK strawberries 2012* | 4272 | 0.003 |
| Dutch tomatoes (2012) | 1676 | 0.007 |
| Intensive strawberry 500 t/ha** | 277 | 0.002-0.009 |

*Data taken from (Swain & Hardy, 2017) ,Defra Horticultural statistics (ONS & Defra, 2018), UK Energy Statistics, 2018 & Q4 2018, the agree consortium (Consortium, 2012) and Williams et al (Williams, Pell, Webb, Moorhouse, & Audsley, 2008)
**estimate based on maintaining current (2017-18) domestic supply levels

In 2012 strawberry production (based primarily on soil production), on a typical yield of around 20t/ha (based on Defra hort statistics) used about 3.1 MWh/ tonne. This used approximately 300 GWh in total based in the total tonnage of ~94kt. In contrast, Dutch tomato production used around 7000GWh to produce over 1000,000kt of crop, using around 6.5MWh / tonne. From a 2017 report from FEC energy, they estimate around 280GWh of energy is used for the 225 ha of strawberry glass that they surveyed. This leads to an energy figure of around 20MWh/tonne, much higher than Dutch tomato production.

Taking our present-day levels of self-sufficiency (we now produce around 138,000t) we would need around 2300 ha of glass (assuming 60t/ha yield), consuming a whopping 2872 GWh of energy per annum. However, if yields could be increased to 500t/ha then this would fall to 346GWh across an area of 277 ha. This most optimistic scenario would use 2.5MWh/tonne, lower than both 2012 production levels and 2012 tomato levels.

However, if scaled with either current strawberry energy use (as stated earlier), or if the 2012 Dutch tomato model of production was used, this would range between 20MWh and 70MWh/tonne (table 12).

**Table 12.** Yield intensification using current varieties and growing systems dramatically increases energy usage

| ***Scenario (no yield gains)*** | ***hectares*** | ***GWh / tonne*** |
|---|---|---|
| UK strawberries (2012) | 4272 | 0.004 |
| Dutch tomatoes (2012) | 1676 | 0.007 |
| Intensive strawberry current systems | 2300 | 0.021 |
| Intensive strawberry (2012 tomato model) | 2300 | 0.073 |

*Data taken from (Swain & Hardy, 2017) ,Defra Horticultural statistics (ONS & Defra, 2018), UK Energy Statistics, 2018 & Q4 2018, the agree consortium (Consortium, 2012) and Williams et al (Williams et al., 2008)

What these calculations illustrate is that depending upon how intensification is carried out, the consequences on land and energy use could vary by several orders of magnitude. Although a highly unlikely (and uneconomic scenario) shifting all current strawberry production to high intensity 'Dutch-style' glass house production could lead to the equivalent emissions of an extra 2.4 million cars for one year. Under the most optimistic scenarios, realising large yield increases in a largely electrified glasshouse production system, the UK could maintain its current level of self-sufficiency (around 70%) and only increase its current glass footprint by 52ha and hardly increasing emissions from current levels at all. This would liberate around 4367ha of land. In terms of direct $CO_2e$ emissions, this could even be lower than present levels, if our energy mix continues to shift towards renewables.

**Table 13**. Assumptions for energy yield from solar and biomass

| | ***Solar kWh/m2/y*** | ***Efficiency of light conversion to energy*** | ***kwh/y/m2*** | ***W/m2*** |
|---|---|---|---|---|
| *Solar panels (E/W- 60 degree tilt)* | 776 | 0.15 | 116.4 | 13.28 |
| *Biomass (Smil/Mackay estimates)* | 961 | 0.005 | 4.805 | 0.55 |

*Assuming typical UK figures of annual solar radiation (and interception). Conversion factor of 0.1140796 used for kWh/y/$m^2$ to W/$m^2$ Source: https://en.wikipedia.org/wiki/Solar_irradiance

If we assume that in terms of our energy needs, we require around 350 GWh/annum of energy to produce our current level of strawberries, what then would we need in terms of land to generate this energy renewably? If we modify our thinking rather than to what is currently practical or economic (which is likely some composite of solar and anaerobic digestion) to one where we consider the on-farm implications of biomass and solar and think purely in terms of land area and energy requirements.

Taking the UK average solar insolation (table 13) we would require around 297ha of solar panels (delivering around 13 W/m2) to support our strawberry farming operation if we could boost yields to 500t/ha (table 14). However, based on our current yields of 60t/ha (under glass) this would increase to 2467 ha.

**Table 14**. Area of land needed to produce energy for indoor strawberry production

| | ***ha energy*** | ***Total area (ha)*** | ***% of 2012 total*** | ***Yield Scenario*** | ***Energy area vs crop area (x difference)*** |
|---|---|---|---|---|---|
| ***Area of power (biomass)*** | 7,200 | 7,477 | 175 | 500t/ha | 26.0 |
| ***Area of power (solar)*** | 297 | 574 | 13 | | 1.1 |
| ***Area of power (biomass)*** | 59,771 | 62,071 | 1,453 | 60t/ha | 26.0 |
| ***Area of power (solar)*** | 2,467 | 4,767 | 112 | | 1.1 |

Turning to biomass, due to the much lower power density, we would need an area between 7,477 ha and 62,071 ha, for the 500t/ha and 60t/ha scenarios.

This very clearly serves to highlight how different choices can lead to dramatically different outcomes. Our most optimistic scenario leads to a land area 13% of the 2012 level being used for berry and energy production, while our least optimistic expands the areas by around 14x that of 2012 levels.

## Conclusions

Although very rough and ready, this analysis highlights the fact that if we wish to have intensive production of year-round horticultural goods close to the point of consumption, we need to think carefully about the design of the system. Could it be that new growing systems with high yielding varieties in them could be designed to utilise solely renewable resources and improve their efficiency? Could we even imagine a situation where we adapt the crop to grow in that new environment? My intuition would say yes, as our current systems have never fully looked to the challenges of use of renewables in their design brief. In order to achieve this, we need to link models of crop architecture, growing system design, energy system design and accurately parameterised improved lifecycle assessment methods to model out the optimum scenarios. An equally important question is whether this is worthwhile to do. I would argue that this may be the most efficient way of reducing absolute levels of fossil fuel use in the short-medium term as there are virtually no decent solutions for long distance transport that are low carbon, whereas a local solution in which all processes are renewable and/or electrified is likely within our immediate grasp. The local solution may require more energy and therefore be relatively less efficient, but may be lower in absolute emissions. Thinking back to Francis Houle's comments, I wonder what kind of world would it be, where 'clean' energy is effectively free?

9 781912 059140

Published by Nuffield Farming Scholarships Trust
Southhill Farm, Staple Fitzpaine, Taunton, TA3 5SH
T: 01460 234012 | E: director@nuffieldscholar.org