Economic policy, "alternative data" and global agriculture: from the trans-Atlantic slave trade to agroecology

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Abstract

We use heterogeneous public datasets and information (re)sources to aid the task of identifying technical, legal, financial, policy and other mechanisms capable of serving the diverse needs of practitioners of agroecology (primarily small scale farmers) and advocates of food sovereignty. Disparate material in the public domain and open source software tools are utilised to tell a story of interest to audiences ranging from the general public to policy and decision makers. A variety of financial and non-financial ("alternative") datasets are employed to explore the past, present and future of agriculture. Historical macroeconomic data released by the Bank of England in conjunction with other freely available data are utilised to paint a broad brush strokes picture of the impacts of Britain on the lands, agricultures, and economies of peoples and regions across the globe over five centuries. The overarching and interconnected topics considered are (a) the trans-Atlantic slave trade and European Empires, (b) 21st century large-scale land acquisitions, and (c) traditional farming systems, agricultural biodiversity, and climate change. The three sets of background notes and data-driven visualisations – cartograms and timelines overlaid with event data – are autonomous yet interlinked and complemenary. By weaving together historical, geographical, political, economic, and social threads, this triptych illustrates how the Bank has been and remains integral to agriculture, nationally, regionally and globally. Finally, we discuss how data science could contribute to specific problems in three poorly-studied areas of agricultural policy, (a) whole food systems policy: the Community-led London Plan through the lens of food, (b) research and development policy: public funds allocated to basic and applied studies in agroecology, and (c) small scale farmer-scientist collaborations.

Keywords: Bank of England; Trans-Atlantic slave trade; European Empires; Global large-scale land acquisitions; Agroecology

1 Introduction

Fiscal policy refers to government actions regarding taxation and spending whilst monetary policy refers to central banking actions regarding the money supply and interest rates. These two main strands of economic policy determine and influence agricultural policy: laws and activities relating to domestic agriculture and imports of foreign agricultural products. An increasingly important objective of policy makers and central bankers is preventing or mitigating the triggers of financial crises: greater monetary and financial stablity (as embodied in issues such as income inequality) are emerging as much more prominent aspects of the work of the Bank of England and the central banks of other countries [1, 2, 3]. Since its establishment in 1694 [4] in the age of mercantilism through the industrial revolution and beyond, the history of the Bank of England is intertwined with that of the trans-Atlantic slave trade [5, 6] and the British Empire [7], times when societies were treated as parts of economies rather than economies being considered parts of societies.

In February 2015, the Bank of England launched its *One Bank Research Agenda*, a wide-ranging and ambitious framework aimed at transforming and guiding its future research and as part of a committment to forging closer ties between policy makers and researchers, published a selection of its datasets [8]. The Agenda theme "Central bank response to fundamental technological, institutional, societal and environmental change" posed the question "What is the role of central banks in addressing risks from climate change?" [1]. Seven months later, Bank of England Governor Mark Carney delivered a speech at Lloyd's of London, an institution that was founded in 1688 at a time when "London's importance as a trade centre led to an increasing demand for ship and cargo insurance" and that "develops the essential, complex and critical insurance needed to underwrite human progress" [9]. He warned that "climate change is the tragedy of the horizon," noting that insurers are "anticipating broader global impacts on property, migration and political stability, as well as food and water security" [10].

A June 2017 publication by the Bank of England states "Climate change, and society's responses to it, present financial risks which impact upon the Banks objectives. These risks arise through two primary channels: the physical effects of climate change and the impact of changes associated with the transition to a lower-carbon economy" [11]. Given the Bank's mission is to "deliver monetary and financial stability for the British people" [12], the economic health of whole food systems [13] as well as the (re)building of rural and urban agricultural economies at home [14] and abroad [15] – including across the Atlantic [16] – are of more than passing interest.

Here, our specific aim is to illuminate the evolving relationship between fiscal policy, monetary policy and agricultural policy by painting a general picture of the impacts of Britain on the lands, agricultures and economies of peoples and regions across the globe over five centuries. Our overall objective is to highlight "agroecology" as defined and described in the 2015 Report of the International Forum for Agroecology: not just agriculture but the full diversity of food production, gathering and consumption – knowledge that is the outcome of diverse historical experiences and practices [17, 18]. That is, a transdisciplinary, participatory applied science embedded in a social context [19, 20, 21, 22, 23, 24, 25, 26, 27, 28]. Agroecology's multiple benefits include ensuring food sovereignty [29], sustaining and improving human health [30, 31], providing meaningful livelihoods [32], sustaining resilient communities [33], mitigating the effects of climate change [34, 35, 36, 37], and promoting local and stable economies [38, 39].

We propose that agroecology [18, 19, 21, 40] – undergirded by food sovereignty [29], land sovereignty [41], the right to water [42], agricultural biodiversity [43], and environmental health [44] – provides a shared, direct and cost-effective response to issues of concern to society writ large as well as the Bank of England: fundamental technological, institutional, societal and environmental change in general and climate change in particular [1].

Although not our focus, trade, labour, accumulated wealth, and land were of concern domestically during the period we consider – notably the Scottish clearances and Parliamentary Enclosures [45]. As elsewhere in the world, land and its ownership remains a pressing issue: farms in England under 50 hectares are in danger of vanishing by 2050 even though they "create greater diversity in food production and conservation, both of which shape rural heritage and rural economies" [46]. In Britain, a policy of increasing access to land would support new entrants to farming [47]. Indeed, a significant increase in the number of small agroecological market gardens (including those less than 5 hectares) could deliver environmental and social benefits such as reducing the trade gap for fruit and vegetables, providing year-round employment and rejuvenating communities [48]. Clearly, agroecology- and whole food systems-related policies and issues are critical today as well as tomorrow in the post-Brexit era [49, 50].

This paper is organised as follows. Section 2 is an overview of the trans-Atlantic slave trade and European Empires. Section 3 considers 21^{st} century large-scale land acquisitions. Section 4 explores traditional farming systems, agricultural biodiversity, and climate change. Each section contains background notes and visualisations of publicly available (macro)economic and alternative datasets. With respect to the timelines and events chart and cartograms, our aim is not that each one be interpreted, inspected and analysed in minute detail. Rather, these visual surveys of diverse information (re)sources are designed to highlight broad trends and to illustrate points and/or themes discussed in one or more of the aforementioned sections. Whether locally, nationally, regionally and internationally, evidence-informed policy for agrocology and whole food systems requires not just data but also ideas and arguments (the human element) [51]. In large part, this is because predictions arising from the application of machine learning methods to data are necessary but not sufficient when making decisions for policy problems: data have limits [52] and the "era of blind faith in big data must end" [53]. Bearing this caveat in mind, Section 5 identifies three under-investigated but critical aspects of agricultural policy and discusses how and when data science could contribute to addressing specific problems (a) whole food systems policy: the Community-led London Plan through the lens of food (a grassroot efforts to transform the policy of a large and complex city), (b) research and development policy: public funds allocated to basic and applied studies in agroecology (the public infrastructure pertinent to the science, development, financing, and practice of agroecology), and (c) small scale farmer-scientist collaborations. Finally, Section 6 provides practical information about how to access the code and data needed to recreate the visualisations (reproducible research).

2 The trans-Atlantic slave trade and European Empires

2.1 Background notes

The 1494 Treaty of Tordesillas [54] and the 1529 Treaty of Zaragoza [55] defined a pattern for exploration and conquest of non-Christian worlds outside Europe by Iberian colonial interests. Whereas the former treaty granted lands to the east and west of the Cape Verde Islands to Spain and Portugal respectively (essentially the Americas and Africa), the latter employed the Moluccan Islands as the basis for recognising Spain's dominion over the Americas and most of the Pacific whilst solidifying Portugal's claim to the Indian Ocean and all of Asia. Although other European maritime powers contested the commercial arrangement [56] in the "New World", irrespective of whether the traders were British, French, Spanish, Portuguese, Dutch, Norwegian, Swedish or Danish in origin [57], humans [58] remained the most attractive commodity in trans-Atlantic trade crossings [59, 60].

Europe, Africa and the Americas were the geographic pillars of the trans-Atlantic slave trade [61] that took place from the 16^{th} through to the 19^{th} century, a network of routes and an economic system lubricated by humans. Manufactured and luxury goods such as textiles, guns, knives, copper kettles, mirrors and beads from Europe were exported to the west African coast where they were exchanged for enslaved Africans. The slaves were sent forcibly to the New World where their labour underpinned the production of agricultural commodities such as sugar, tobacco, rice, cotton, mahogony and indigo: raw goods whose import by Britain fuelled the country's Industrial Revolution [62] and satisfied its lifestyle [63]. During 35,000 slave voyages, over 12 million Africans were transported forcibly to the Americas [60]. More slaves were imported from Africa into Haiti (Saint Domingue) than into North America [64]. By 1789, the latter was producing 60% of Britain and France's coffee and 75% of the world's sugar – Saint Domingue owed its profitability entirely to slavery [65].

During the 16^{th} and 17^{th} centuries, financial, commercial, legal, and insurance institutions emerged to buttress Britain's overseas trade and imperial ambitions [4]. Banks and banking were essential in making capital available to and securing profits from the transnational business of enslavement [66] and empire [67]. When set up in 1694, the Bank of England braced the entire system of commercial credit [7] needed for the trans-Atlantic slave trade. Acknowledging the centrality of slave-grown cotton to the economy of north west England [68] and recognising the importance of Manchester as a commercial centre, the Bank of England established a branch [69] there in 1826. The plantation slave economy – from slave-trading through slave-ownership to the shipping, trading, finance, and insurance of slave produce – contributed materially to the foundations of 19^{th}-century London [70]. In the early 19^{th} century, cotton was a commodity that determined the wealth of nations [71].

Governors of the Bank of England [72] were well-placed to facilitate creation of the political and regulatory milieu necessary to (re)orient the performance, structure, behaviour and decision-making of national, regional, and global economies. For instance, Sir John Houblon (1694 –1697) [73], Sir William Scawen (1697 – 1699) [74], and Sir Francis Eyles (1707 – 1709) [75] were also directors of the East India Company [76], a firm chartered in 1600 that rose to have a near monopoly of the world's trade, particularly in agricultural commodities such as cotton, silk, indigo dye, salt, saltpetre, tea, and opium [77]. After the hundred year military and administrative rule of large swathes of the Indian subcontinent by this corporation by the "original corporate raiders" [78], the British Crown assumed direct control of India in the mid-19^{th} century. Governors turned their gaze not only East but also West: Sir Humphrey Morice (1727 – 1729) [79] was both a trans-Atlantic slave trader and a Member of Parliament.

British slave-ownership was instrumental in transmitting the fruits of colonial slavery [80] to metropolitan Britain, shaping the country and bequething a commercial, cultural, historical, imperial, physical, social, economic and political legacy [81, 82] that reaches into the present [83, 84]. Although Parliament finally abolished slavery in the British Caribbean, Mauritius and the Cape in 1833, "in place of slavery the negotiated settlement established a system of apprenticeship, tying the newly freed men and women into another form of unfree labour for fixed terms. It also granted £20 million in compensation, to be paid by British taxpayers to the former slave-owners" [82]. That sum constituted 40% of the British state's expenditure in 1834 – the modern equivalent of £17 billion [85], the largest government pay-out prior to the bailout of the banks in 2009. The recipients of compensation, clustered overwhelmingly in the southern strongholds of high society, included 100 Members of Parliament (over and above the West India lobby) and 150 Anglican clergymen – "thus did mammon assert its priority over humanity and religion" [86]. Whereas British taxpayers subsidised the British Empire's scheme for abolition, the slaves in Saint Domingue who emancipated themselves from the French were forced to compensate their former slave owners: payments in service of the Independence Debt imposed by France on Haiti in 1825 continued until 1947 – an amount estimated to be $21 billion [65, 86].

Consider the Neave Baronetcy [87] created in 1795 for Richard Neave [88], a London Jamaica merchant whose wife, seven children (such as son Sir Thomas Neave [89] and daughter Harriet Trevelyn [90]) and their descendants were claimants and/or financial beneficaries of slave ownership. Sir Richard Neave was a Director of the Bank of England for 48 years as well as its Governor (1783 – 1785), a position held later by his son-in-law Beeston Long (1806 – 1808) [91] and grandson Sheffield Neave (1857 – 1859) [92], the latter also a Director for 27 years. Assisted by representatives of the colonial assemblies, the London Society of West India Planters and Merchants (whose chairmen included Sir Richard Neave and Beeston Long) formed the West India Interests which "through publications, depositions before parliament, and direct lobbying of government ministers . . . defended their self-proclaimed right to import African slaves based on constitutional precedent and a right to enjoy the fruits of their fixed property in the colonies" [93]. Founded in 1735, "ten out of fifteen members of one of the most important committees of the Society of Planters and Merchants held seats in the English Parliament" [94, page 94]. Today, the Society exists as the West India Committee [95], a registered charity promoting agriculture, trade and manufacturing in the Caribbean and providing services to corporations, institutions, government and other organisations.

Two other examples illustrate the transmission of the benefits of slave ownership across generations. Established six years before the Bank of England, "when Lloyd's was a coffee house and nothing more, many advertisements in the London Gazette about runaway slaves listed Lloyd's as the place where they should be returned. . . . Lloyd's, like other insurance companies, insured slaves and slave ships, and was vitally interested in legal decisions as to what constituted 'natural death' and 'perils of the sea.' . . . One of the most distinguished chairmen of Lloyd's in its long history was Joseph Marryat, a West Indian planter, who successfully and brilliantly fought to maintain Lloyd's monopoly of maritime insurance against a rival company in the House of Commons in 1810" [94, page 121]. Joseph Marryat (1757 – 1824) was a member of the House of Commons (1808 – 1824), chairman of Lloyd's (1811 – 1824), an Agent for Trinidad (1805 – 1812), an Agent for Grenada (1815 – 1824), and an important figure in the defence of slavery [96, 97]. Likewise, his son Joseph Marryat II (1790 – 1876) was a member of the House of Commons (1826 – 1834), an Agent for Grenada (1831 – 1851), and an individual who resisted moves towards emancipation [98, 99]. Yet, a major recipient of compensation by the British taxpayer was Joseph Marryat & Co, a firm whose partners were Joseph Marryat II and his brother Charles Marryat (1803 – 1884) [100]. The ancestors of David Cameron, U.K. Prime Minister (2010 – 2016), "were among the wealthy families who received generous reparation payments that would be worth millions of pounds in today's money" [101].

The system of plantations pioneered by the Spanish, perfected by the Dutch and adopted eagerly by the English were key to the internationally integrated trading network encouraged, approved, regulated and monitored by Parliament and lubricated by the Bank for England. Amongst those that thrived within this legal and financial infrastructure were the City of London's Corporation, Lloyd's, a host of banking facilities, and (domestic) industries which provided goods for exchange in Africa, equipped the slave plantations of the Americas, and processed and sold the imported slave grown produce [102]. Many of the financial, arts, cultural, religious, educational and other institutions in London [103], Greater Manchester [104], Oxford [105], and elsewhere were founded on the wealth gained from the trans-Atlantic slave trade. That profits trickled back to all levels and sections of British society – government, companies and households – is illustrated by "Dividend Day at the Bank of England" [106], an 1859 painting depicting investors from a broad range of social classes receiving their dividends. In contemporary life, the Empire's legacy is evident in social structures, public monuments, and art [107]. Echoing Britain, "the slave-based economy generated the profits that allowed the US to industrialize, and also enabled these processes to happen much quicker and much more extensively than could have been done without slavery. The factories and industrial-related employment provided allowed the US to absorb the millions of people immigrating from especially Europe in the late 1800s-early 1900s. Without this capability, emigration from

Europe would have been much more limited" [108].

The late 16^{th} and early 17^{th} century settlement of islands and regions in the Carribean and North American mainland formed the basis of the British Empire [109]. By 1922, this "empire on which the sun never sets" [110] held sway over one-fifth of the world's population and covered almost a quarter of the Earth's total land area. In the mid 20^{th}, the collapse of the formal British empire gave birth to a financial empire where the U.K. managed to retain a significant degree of influence over global flows of money [111, 112]. "Britain structured its economy not around manufacturing and productive sectors, but around finance. City of London banks provided the financing for the Empire and the colonies would pay interest to the City. Britain would create trade agreements with its colonies that would allow them to export a certain amount of their goods to the UK, thus enabling them to pay the interest on their loans. The Empire allowed the financial sector in the UK to take on a role and importance, which financial sectors did not have in other countries" [113].

2.2 Visualisations: what data can tell us about ...

For the following visualisations, the principle resources utilised are (1) a broad set of historical macroeconomic data from the Bank of England such as the contribution of different parts of the industrial and agricultural sectors to Gross Domestic Product (GDP) [114], (2) a collection of geographic, imputed voyage and other data drawn from libraries and archives around the Atlantic world on the trans-Atlantic slave trade [60], and (3) various entries in Wikipedia related to possessions and colonies of European countries.

Our first goal is to illuminate British economic growth (1270 – 1870) from the perspective of two distinct labour forces, (a) the internal workforce consisting of the population of England (1086 – 1870) and Great Britain (1700 – 1870) and (b) the external workforce consisting of slaves and individuals from the dominions, colonies, protectorates, mandates and other territories ruled or administered by Britain. Our second goal is to show the geographic extent of European empires and the global reach of the British Empire.

... British economic growth (1270 – 1870) and the population of England (1086 – 1870) and Great Britain (1700 – 1870)

English and British population plus English and British agricultural production (crops) This interactive timelines chart shows (a) English and British population (million). (b) English and British agricultural production (1270 – 1870): total arable output – wheat, rye, barley, oats, and pulses (million bushels). Data sources: [(a) A2; (b) A3 Table 3.06]

English and British population plus English and British agricultural production (livestock) This interactive timelines chart shows (a) English and British population (million). (b) English and British agricultural production (1270 – 1870): total output of livestock products – milk (million gals), beef (million lb), veal (million lb), mutton (million lb), port (million lb), wool (million lb), hides (million lb) and hay (milllion tons). Data sources: [(a) A2; (b) A3-Table 3.04]

English and British population plus English and British industrial production This interactive timelines chart shows (a) English and British population (million). (b) English and British industrial production (1270 – 1870): output of key industries – tin, iron, coal, wool/textiles, leather, foodstuffs, construction and printed books. Data sources: [(a) A2; (b) A4-Table 4.02]

English and British population plus English and British GDP(O) This interactive timelines chart shows (a) English and British population (million). (b) English and British GDP(O) (1271 – 1700): Real GDP – agriculture, industry, services, and GDP. Data sources: [(a) A2; (b) A6, A7]

English and British population plus regional trade This interactive timelines chart shows (a) English and British population (million). (b) Regional trade shares (1665 – 2015): export of goods to Europe, Africa, Asia, North Americal including West Indies to 1972, South and Central America and Australia; import of goods from these same regions. Data sources: [(a) A2; (b) A42]

... British economic growth (1270 – 1870), the number of captives transported, and the year a former British colony or dominion gained its independence

Number of captives transported plus English and British agricultural production (crops) This interactive timelines and events chart shows (a) Estimates of the number of captives embarked and disembarked at major sites in the Atlantic rim (1501 – 1866). (b) English and British agricultural production (1270 – 1870): total arable output – wheat, rye, barley, oats, and pulses (million bushels). (c) The year a colony or dominion gained its independence from Britain. Data sources: [(a)] [(b) A3-Table 3.06] [(c)]

Number of captives transported plus English and British agricultural production (livestock) This interactive timelines and events chart shows (a) Estimates of the number of captives embarked and disembarked at major sites in the Atlantic rim (1501 – 1866). (b) English and British agricultural production (1270 – 1870): total output of livestock products – milk (million gals), beef (million lb), veal (million lb), mutton (million lb), port (million lb), wool (million lb), hides (million lb) and hay (milllion tons). (c) The year a colony or dominion gained its independence from Britain. Data sources: [(a)] [(b) A3-Table 3.04] [(c)]

Number of captives transported plus English and British industrial production This interactive timelines and events chart shows (a) Estimates of the number of captives embarked and disembarked at major sites in the Atlantic rim (1501 – 1866). (b) English and British industrial production (1270 – 1870): output of key industries – tin, iron, coal, wool/textiles, leather, foodstuffs, construction and printed books. (c) The year a colony or dominion gained its independence from Britain. Data sources: [(a)] [(b) A4-Table 4.02] [(c)]

Number of captives transported plus English and British GDP(O) This interactive timelines and events chart shows (a) Estimates of the number of captives embarked and disembarked at major sites in the Atlantic rim (1501 – 1866). (b) English and British GDP(O) (1271 – 1700): Real GDP – agriculture, industry, services, and GDP. (c) The year a colony or dominion gained its independence from Britain. Data sources: [(a)] [(b) A6, A7] [(c)]

Number of captives transported plus regional trade This interactive timelines and events chart shows (a) Estimates of the number of captives embarked and disembarked at major sites in the Atlantic rim (1501 – 1866). (b) Regional trade shares (1665 – 2015): export of goods to Europe, Africa, Asia, North Americal including West Indies to 1972, South and Central America and Australia; import of goods from these same regions. (c) The year a colony or dominion gained its independence from Britain. Data sources: [(a)] [(b) A42] [(c)]

. . . The maximum extent of European Empires and major coastal regions involved in the trans-Atlantic slave trade

European Empires and the trans-Atlantic slave trade This interactive cartogram shows (a) The countries and territories ruled or administered formerly by Belgium, France, Italy, Portugal, Spain, the Netherlands, Britain, or another country. The colour of a region indicates the last colonial ruler, for example, Guyana is shown as a former British Colony even though it was colonised first by the Netherlands. Like other visualisations, this cartogram is for illustrative purposes only and is by no means a definitive history of European colonialism and imperialism. (b) Major sites in the Atlantic Rim from which captives embarked and disembarked; the size of the circle indicates the number of slaves involved. Data sources: [BE] [FR] [IT] [PT] [ES] [NL] [GB] [Other] [Captives transported]

3 21^{st} century large-scale land acquisitions and their consequences

3.1 Background notes

Since the turn of the century, estimates of the land acquired globally by international entities range from ~ 48 million [115] to ~ 67 million [116] hectares – concentrated mostly in middle and low income countries. Concommitant to the land, this massive and growing phenomenon appropriates the freshwater [117, 118] available therein plus any associated soil, mineral, and hydrocarbon resources [119]. The appropriation of green water (precipitation stored in soils and consumed by plants through evapotranspiration) and blue water (water extracted from rivers, lakes, aquifers, and dams) poses socioenvironmental and political challenges [120]. Two major events in 2005 contributed to this global land rush: launch of the European Union Emissions Trading System (carbon trading or "cap and trade") [121] and passage of the U.S.A. Energy Policy Act that contained provisions promoting biofuels and setting targets [115].

"21^{st} century colonialism" [122] and "land grabbing" [123] are terms that have been applied to the transfer of the right to own or use the land from local communities to foreign investors through large-scale land acquisitions intended primarily, though not exclusively, for agriculture, forestry, conservation, biofuels and tourism [124, 125, 126]. Although enabled by investment de-regulation and trade liberalisation of the present, particularly international free trade agreements and laws [127], the corporate land rush is bolstered by history [117], notably the seizures of lands by colonial rulers. In essence, today's economic dispossessions are co-mingled with the forced dispossessions of the trans-Atlantic slave trade and European empires.

The concentration of lands under increasingly larger holdings controlled by fewer people is affecting adversely the lives and livelihoods of small scale farmers and communities in Africa, Asia and Latin America [128] as well as in Europe [129]. Analysis of the geospatial and socio-ecological contexts of 139 transnational land acquisitions (>200 hectare per deal) in the Global South found that 35% of the deals targetted densely populated and easily accessible croplands, 34% remote forests with lower populations, and 26% moderately populated and accessible shrub- or grasslands [130]. In the 28 countries most affected by the global land rush from 2000 to 2014, one potential impact of transactions involving agricultural areas is loss of income and employment opportunities for over 12 million people in rural communities [131].

Green grabbing [132] is land appropriation for environmental purposes such as carbon trading initiatives. Acquisition of forests and lands to establish forestry plantations intended to offset carbon emissions elsewhere in the world can take away local communities' access to land [133] and hurt Africa's rural poor [134]. Small scale farmers everywhere face the serious challenges of land ownership, access to land, and water rights: from Africa [135] (particularly the sub-Saharan region [136]) through Haiti [137] to India [138] and Europe [139].

Particularly since the financial crisis of 2007 – 2009, farmland has come to be seen as a safe investment, a precious global commodity: "like gold with yield" [140]. It is an attractive alternative economic asset [116] for (global) investors [141] casting around for greater returns with low risk in a time of volatile markets for publicly traded securities and in a near zero interest rate environment for money-market and cash investments. Many investors have diversified their portfolios by reducing their exposure to equities whilst reallocating funds to "real" or "hard" assets overseas such as farmland [142]. The "financialisation of farmland" means that decisions to buy or sell this "fictitious capital" is governed as much by the wider financial environment as by the agricultural use value of land: the appeal of land as a financial asset is highly dependent on interest rates [140].

Central banks use the interest rate to shape monetary policy, control the country's economy. Perhaps the most influential lever the Bank of England [143] and the Federal Reserve [144] have under their control, shifting this crucial rate has a drastic effect on the building blocks of macroeconomics, including the behaviour of investors in the U.K. and U.S.A. with respect to land internationally, regionally, and domestically. As Britain's farmland becomes a tax haven [145], prices outstripping even prime central London real estate [146], an increasing proportion of land purchases are being undertaken by lifestyle buyers rather than farmers [147]. Private investors view (English) farms both as safe assets in which to store wealth and highly-prized places to live [148]. Increases in the Bank of England base rate place pressure on farmers reliant on loans [149], especially those used to support cash flow.

Marrying transnational commodity chains and global circuits of capital with agriculture and medicine is vital for understanding the financial and physical well-being of humans and communities as well as disease emergence in plants and animals. The field of Structural One Health [150] integrates the global political economy and multispecies biology (notably wildlife, livestock, crop, and human ecology) leading to, for example, propositions such as neoliberal economics and land use providing the broader context in which Ebola emerged in West Africa [151].

3.2 Visualisations: what data can tell us about . . .

For the following visualisations, the principle resources utilised are (1) interest rates from the central banks [152] of Britain and the U.S.A., (2) the contribution of the agricultural sector to the GDP of countries that are (major) targets of large-scale land acquistions, (3) international free trade agreements, and (4) the land acquired in a country and the countries targetted by investors from Britain and the U.S.A.

Our first goal is to illuminate the increasing role played by financial actors, institutions, markets, and motives in the operation of international and domestic economies by highlighting the connection between monetary policy (banks' lending practices) and the financialisation of land and agriculture – for example, rich investors tend to target (poorer) economies with abundant land and water resources [126].

Our second goal is to highlight how the growing interlinkages between the financial and agrifood sectors are shaping the latter in areas ranging from food retail to land ownership [153]. For example, "private equity players and asset managers that acquire land or corporate farms, do not see food production as a complex ecological process, do not consider starvation, obesity and malnutrition as challenges that they have to address and, more importantly, do not recognize the role and existence of small scale farmers. On the contrary, they see food production as any other industrial operation, based on efficiency and satisfaction of the global demand, a matter of competition on the global market rather than a matter of socially and culturally embedded practices that can satisfy the needs and rights of the communities. Massive amounts of resources have thus been invested, and will be invested, in production and distribution of food not on the basis of what is ecological, socially acceptable, healthy or capable of guaranteeing the long-term resilience of land and the ecosystem" [154].

. . . The interest rates of the central banks of Britain and the U.S.A., the economic contribution of agriculture to the GDP of countries that are the targets of global land acquisition and international free trade agreements

Central bank interest rates and agricultural production in targets of land acquisition This interactive timelines and events chart shows (a) Interest rates from the Bank of England (1694 – present) [114] and the Federal Reserve System (1919 – present) [155]. (b) The economic contribution of the agricultural sector to the GDP (average percent) for 28 countries that have been the targets of significant large-scale land acquisitions and all other countries (1980 – 2010) [131]. The significantly grabbed countries are Angola, Argentia, Benin, Brazil, Cameroon, Colombia, Congo, DRC, Ethiopia, Gabon, Ghana, Guatemala, Indonesia, Liberia, Madagascar, Malaysia, Morocco, Mozambique, Nigeria, Papua New Guinea, Peru, Philippines, Russia, Sierra Leone, South Sudan and Sudan, Tanzania, Uganda, and Uruguay. (c) International trade agreements: multilateral free trade agreements in operation [156] and Asian-African Conference of Bandung [157]. Data sources: [(a) UK, A31] [(a) U.S.A. Federal Funds rate] [(b) Figure 1 from [131]] [(c)]

. . . The targets of global large-scale land acquisitions and major investor countries

Global large-scale land acquisition: target countries and investor countries This interactive cartogram shows countries that are targets of the land grabbing phenomenon [158]. The shading is proportional to the percent of the land area of a country that has been acquired in. As of October 2017, the top two investor countries involved in transnational land acquisitions in terms of the number of deals are the U.S.A. (143 deals) and the U.K. (129 deals) [159]; the top investor country in terms of the area of land acquired is the U.S.A. (9,979,713) [160]. Flags mark countries where investors from the U.S.A. [161] and the U.K. [162] have acquired land. Data source: [Land Matrix]

4 Traditional farming systems, agricultural biodiversity and climate change

4.1 Background notes

In 2015, representatives of diverse constituencies from all continents that produce ~70% of the food consumed by humanity issued the Declaration of the International Forum for Agroecology [17, 18]. This joint vision of peasants, fish harvesters, fish workers, mobile indigenous peoples, and many others across the world [163, 164, 165, 166, 167, 168, 169, 170] identified land and territories as well as collective rights and access to the Commons as a fundamental pillar of agroecology. Agrarian reform is a common struggle for small scale farmers [171], a group who produce most of the world's food with less than a quarter of all farmland, a paltry share that is shrinking [172]. Despite the legacies of slavery and colonialism, threats to indigenous peoples' livelihoods from emerging technologies [173], attempts to replace natural products with products containing synthetic biology ingredients [174], disruptions caused by erratic weather patterns, and other many challenges, small scale farmers in the Southern U.S.A. [175, 176], Haiti [177, 178, 179], Honduras [175, 180, 181], Zimbabwe [182, 183], the Andean region [30], Brazil [184], Mexico [185, 186], Peru [187], Pakistan [188], India [189, 190], the Philippines [191], Tanzania [192], California [193], and elsewhere are feeding, healing, clothing, and fueling many parts of the world. Numerous success stories and multiple case studies [194] demonstrate the capacity of agroecological agriculture to mitigate the effects of climate change and address hunger and poverty whilst respecting farmers and the environment [195, 196, 19, 39].

Building on ancestral production systems developed over many millenia, the Declaration [17, 18] emphasized food sovereignty [29] as the framework offering a collective path forward from today's food, public health, climate, environmental, and other crises. Given the intimate connection between the ability to cope with (even prepare for) extreme climatic events and high levels of on-farm biodiversity, traditional farming systems and agroecological strategies – particularly biodiversification, soil management and water harvesting – represent the "only viable and robust path to increase the productivity, sustainability and resilience of peasant-based agricultural production under predicted climate scenarios" [197].

Agroecology has two interacting and complementary pillars [21]: soil quality (enhancing organic matter and biological activity) and plant health (enhancing the habitat for beneficial biota) – that is, improving below-ground as well as above-ground community biodiversity and function. Agrocological practices such as building soil, recycling nutrients, dynamically managing biodiversity, and conserving energy at all scales both lessen the adverse impacts of food systems on the climate (adaptation) and reduce green house gas emissions (mitigation). Innovations created and/or employed by small scale farmers include ones that provide effective control of pests and diseases [198, 199, 200], produce carbon-rich soil through sustainable grazing by ruminant animals [201], improve air quality through reduced nitrogen pollution [202], enhance livelihoods through sustainable food and fibre production [188], increase knowledge through farmer training [192], develop cultivars/breeds from traditional varieties and stock through farmer-scientist collaborative research [191], and explore the design and implementation of closed-loop plant-based indigo production systems [203].

The key attributes of the ideal food system are "offers adequate nutrition and health", "creates biodiversity and avoids negative ecological and environmental impacts", and "ensures livelihood for farmers, diverse landscapes, equitable access to land, water, seeds, and other inputs" [204]. Whilst the relationship between soil fertility and the health of humans and animals has been known for decades if not millenia [205, 206, 207, 208, 209], recent efforts in pursuit of yield may have compromised biodiversity and nutritional quality, one culprit being soil depletion. For example, analysis of historical data on the nutrient content of food in the U.K. (1940 – 2002) [210, 211] and in the U.S. (1950 – 1999) [212] revealed declines during the periods studied [213]. Possible reasons for this downward trend include changes in varieties/cultivars, farming practices, the environment, soil minerals and microbes, (whole) food systems, and the acquistion and/or evaluation of food composition data. Across a wide range of plant species – including food crops, elevated concentrations of atmospheric carbon dioxide appear to reduce the concentrations of vital minerals and elements such as nitrogen, phosphorus, potassium, calcium, sulphur, iron, zinc, copper, and manganese in the plant [214]. One protective response of a range of food crops to extreme weather such as drought conditions and increases in temperature is the synthesis of specific chemical compounds that could be harmful to human and animal health if consumed for a prolonged period of time [215]. Finally, external farming inputs such as fertilisers and pesticides affect the microbial communities in and around plants [216], an important issue given that the dynamic and reciprocal interactions at the soil-root interface influence root function and ultimately plant growth, production, and quality.

Agroecology is a way to design climate change-resilient farming systems [217] whose social, cultural, economic and environmental benefits include the provision of plant crops for human and/or animal consumption that meet consumer demand for nutritional quality and density. One explanation is that agroecological practices embody an understanding that each plant growing in field conditions is not a single individual but a community: the myriad connections between a plant and its (a)biotic environments are critical for meeting the challenges of food, fuel and fibre production. That is, the cornucopia of aerial- and soil-based associations and interactions amongst and between plants and microbes exert a strong influence on crop yield and economic viability [218] as well as nutrient value.

A keystone of agroecological practices is improving the well-being of the cornucopia of beneficial micro- and macro-organisms that reside in, on, and in the vicinity of plants and animals in general and crops and livestock in particular. The phyllosphere is the above-ground portions of plants inhabited by commensal and other microorganisms [219]. The rhizosphere is the narrow regions around a root where microorganisms and processes important for plant growth and health are located [220] and whose functions include helping plants to acquire nutrients from the environment (notably nitrogen, minerals and elements), improving water use efficiency, and protecting against pathogens [221]. A common mychorrhizal network is the system of fungal hyphae that link together the roots of most land plants [222]. Plants use this underground network to warn neighbouring plants of imminent attack from diseases and pests and to communicate unfavourable conditions such as drought whilst the services performed by the fungi include uptake of phosphate and mineral nutrients [223, 224]. Collectively, the phyllosphere, rhizosphere and common mycorrhizal network are key mediators and determinants of the dynamic, reciprocal, multifaceted and intimate relationship between agroecosystem health (crops as well as livestock) and human health.

In addition to food, feed, and medicines, tangible products of agroecosystems include fibre and dye plants and animals [225, 226, 227, 228, 229]. For materials such as cotton ("white gold"), new global and local perspectives on the entire value supply chain and the complete cycle of production, processing, consumption, and recycling include "From Farm to Fashion" [230] and "soil to soil" [231]. Regenerative and sustainable agricultures and community-driven textile systems consider issues ranging from classical plant breeding methods with hierloom naturally coloured cotton varieties [232] through indigo cultivation and processing [233] and community supported cloth [234] to garment design and construction [235] – local fibres, local dyes, and local labour.

These and other agroecological approaches to and economic frameworks for perhaps the most important natural fibre crop worldwide stand in stark contrast to those that existed during the trans-Atlantic slave trade and British colonialism [236]. At the turn of 1800, the lives and communities of skilled middle-class weavers and textile artisans in the English counties of Nottinghamshire, Yorkshire and Lancashire were being upended by low-skilled low-wage labourers toiling in dismal factories [237]. Between 1811 and 1813, a group of cotton and wool workers rebelled by smashing machines which were destroying their trades, undercutting wages and forcing them into unemployment and destitution. These "Luddites" resisting destruction of livelihoods by industrialisation were opposed only to technology "hurtful to Commonality", that is, whilst sceptics about the dogma of technology as progress, they did not deny the real benefits of some technologies [238, 239]. However, the "expansion of cotton manufacturing in Great Britain depended on violence across the Atlantic" [108] – the expansion of cotton production overseas.

"What distinguishes the United States from virtually every other cotton-growing area in the world was planters' command of nearly unlimited supplies of land, labor and capital, and their unparalleled political power ... The coercion and violence required to mobilize slave labor was matched only by the demands of an expansionist war against indigenous peoples" [240]. Plantation owners in the Southern states melded agricultural science and labour management to alter, simplify and (re)organise humans and nature to meet the needs of capital [241]. Indeed, "most of the cotton picked by Valley slaves was Petit Gulf (*Gossypium barbadense*), a hybrid strain developed in Rodney, Mississippi, patented in 1820, and prized for its 'pickability.' The hegemony of this single plant over the landscape of the Cotton Kingdom produced both a radical simplification of nature and a radical simplification of human being: the reduction of landscape to cotton plantation and of human being to 'hand.' Cotton mono-cropping stripped the land of vegetation, leached out its fertility, and rendered one of the richest agricultural regions of the earth dependent on upriver trade for food" [242]. Many of the four million black slaves tilling fields in 1860 were both workers and human capital: the commodities produced for sale by the American slave-breeding industry included not only agricultural items such as tobacco, rice, sugar, and cotton but also people [243]. Today, some prison industries have "ancestral roots in the black chattel slavery of the South" [244] where, for instance, "much of the work on the 18,000-acre former slave plantation consists of backbreaking labor in the cotton, corn, and soybean fields, presided over by armed guards on horseback" [245].

The Bank of England's new research agenda states "fundamental changes in the environment could affect economic and financial stability and the safety and soundness of financial firms, with clear potential implications for central banks" [1]. Thus, the formulation and implementation of Bank policies that directly and/or indirectly strengthen small scale farmers and build rural and urban agroecology provide a simple, shared, and cost-effective way to tackle one of the major challenges faced by today's national, regional, and global economies: systemic environmental risks such as climate change [35]. In part, this is because food sovereignty helps to weather economic crises plus the established link between public health and the economy [246] – the long term financial benefits of reduced mortality and morbidity flow to the state.

Agrocology-based strategies for addressing serious economic and financial risks include increasing the capacity of local communities to experiment, evaluate and scale-up innovations [247] through farmer-to-farmer and field-based research and education, nationally, regionally and internationally [248, 249, 250], and where "innovation" and "technology" are not necessarily synonyms. Crucial factors in the success of such endeavours are land sovereignty [41] (the "right of working peoples to have effective access to, use of, and control over, land and the benefits of its use and occupation, where land is understood as resource, territory, and landscape"), the right to water [251] (including in Europe [252]), and world's biodiversity for food and agriculture [253]. Ultimately, "we need to address the agricultural research agenda if it is to serve the interests of farmers, consumers and society as a whole, rather than narrow but powerful economic interests" [254].

4.2 Visualisations: what data can tell us about ...

For the following visualisations, the principle resources utilised are (1) atmospheric oxygen and carbon dioxide levels measured at nine locations around the world [255], (2) the warm (El Niño) and cold (La Niñap) phases of complex weather patterns [256] that result from fluctuations in temperature between the ocean and atmosphere in the east-central Equatorial Pacific and can last between 9 months to 2 years. El Niño produces below-average rains and high temperatures resulting in, for instance, reduced Asian monsoons and triggering potentially prolonged droughts, (3) organisations of small scale farmers and fisher folks around the world that helped to formulate the Declaration of the International Forum for Agroecology [17, 18], (4) diverse, complex, locally adapted agricultural systems developed over centuries and generations [206], and (5) centres of agricultural biodiversity.

Our first goal is to illuminate some of the weather- and climate-related conditions faced by the social, biological, economic, and political components of national, regional and global whole food systems in general and small scale food producers in particular. Our second goal is to highlight the global distribution of agroecosystems (heritage and current farming systems) rich in agricultural biodiversity and associated wildlife that are also repositories of indigenous knowledge and culture – especially *materia dietetica* and *materia medica*. Critical engagement with local and indigenous knowledge systems [257] provides a better understanding of the challenges posed by climate change and how to respond to it, agroecology being one example [258, 259].

. . . The global atmospheric oxygen (O_2) and carbon dioxide (CO_2) levels and El Niño and La Niña episodes

Average global oxygen and carbon dioxide levels and El Niño/Niña episodes This interactive timelines and events chart shows (a) Global atmospheric O_2 and CO_2 levels based on measurements from nine different stations around the world (1989 – 2016; parts per million, ppm). The values are the averages of O_2 and CO_2 levels monitored at Alert, Canada; Cold Bay, Alaska; Cape Kumukahi, Hawaii; La Jolla Pier, California; Mauna Loa Observatory, Hawaii; American Samoa; Cape Grim, Australia; Palmer Station, Antarctica; and the South Pole [255]. (b) El Niño (warm; red) and La Niña (cold; blue) episodes of the El Niño-Southern Oscillation cycle (1950 – present). Data sources: [(a) O_2] [(a) CO_2] [(b)]

. . . Groups representing peasants and fisher folk producing the majority of food consumed by humanity, globally important agricultural heritage systems and landscapes, and centres of agricultural biodiversity

Small scale food producers and agricultural biodiversity This interactive cartogram shows (a) Members of La Via Campesina (LVC), an international movement which brings together over 200 million small scale producers [163] – peasant small and medium-size farmers, landless people, women farmers, indigenous people, migrants and agricultural workers from around the world (including Europe [260]). (b) Members of the World Forum of Fish Harvesters and Fish Workers (WFF), an international body encompassing small scale fishers' organisations [167]. (c) Globally Important Agricultural Heritage Systems (GIAHS), sites that have been created, shaped and maintained by generations of farmers and herders, are based on diverse natural resources, and use locally adapted management practices [206]. (d) Centres of diversity of agricultural crops and livestock – geographical areas where groups of organisms, either domesticated or wild, first developed their distinctive properties [261]. Data sources: [(a)] [(b)] [(c)] [(d)]

5 Data science and agricultural policy

5.1 Whole food systems policy: Community-led London Plan through the lens of food

Over the centuries, London-based financial, commercial, legal, insurance and other institutions buttressed Britain's overseas trade and imperial ambitions. One legacy of these entities and their actions is today's global agriculture. That is, whole food systems are strategic sites for understanding everyday finance, law, economics, ethics, equity, ecosystems, environment, society, politics and history. Food integrates place, people and pedagogy across multiple time scales and levels of organisation. Since it play critical roles in diverse areas, food falls under the remit of disparate local, regional, national and international bodies and departments – transport, housing, public health, education, environent, employment, local economy and so on.

As the top-tier administrative body, the Greater London Authority (GLA) is responsible for coordinating land use planning in the 1579 km^2 (610 square miles) that make up Greater London, England. The individual London Borough Councils are bound legally to comply with the strategic plan, the "London Plan", produced by the Mayor of London. Just Space is "a network of local and London-wide metropolitan groups campaigning on planning issues – housing, transport, services, environment, rights of minorities but especially of working class and low-income groups. Activists and groups support each other in influencing formal plans and policies at scales ranging from metropolitan, through municipal to local" [262]. Its main work is "developing ideas about what a London Plan would be like if it were to prioritise – or at least protect – the interests of its citizens, its environment and the real economies in which we meet each others needs." That is, to shape research and policy development by the GLA planning teams working on the London Plan and the Mayor's other strategies.

In August 2016, Just Space and its member groups released the document *Towards a community-led London Plan: policy directions and proposals* [263] and a year later additional material [264]. Inspired by the increasing interest in developing urban food policy around the world [265], the main aims of the newly proposed project, *Community-led London Plan through the lens of food*, are to increase human and environmental health and wellbeing [266], support fundamental and applied studies which result in innovations that are not "hurtful to commonality" [238], and reflect a genuine "people's control of the research agenda, objectives and methodology" [17, 18]. This new project provides a vehicle for grass-roots and underrepresented groups such as the working class, universities and policy makers to transform the whole food system of a large and complex city whenever and wherever possible: to chart a roadmap for London to agroecology and food sovereignty.

Like other evidence-informed policy areas [51], ideas, arguments and data are three sources of useful information for creating policies for whole food systems. An important challenge for the Just Space Network and its collaborators – individuals or organisations at different levels in the planning hierarchy (neighbourhood, borough, city, government) – is identifying (possibly generating) and analysing heterogenous public data to support the decision making process, enable the development of guidelines and facilitate the formulation of policies for the roadmap. However, it is worth bearing in mind the limits of using Big Data for prediction and addressing policy problems [52, 53].

5.2 Research and development policy: public funds allocated to basic and applied studies in agroecology

A poorly investigated but critical aspect of agricultural policy is the public infrastructure pertinent to the science, development, financing, and practice of agroecology. One type investment made by governments has particularly long term consequences: research projects supported by awards from national, supranational and/or international agencies in the U.K., E.U. and U.S.A. Public data on successful research proposals could be used to study the allocation of public funds for research in agroecology within and between countries and regions as well as the social, cultural, economic, and political factors producing such text corpora. Statistical analysis of awards from U.S. agencies [267] (for example, [268, 269, 270]), U.K. research councils [271], the European Research Council [272], and other organisations using tools and techniques from natural language processing and machine learning provide a foundation for domain experts to elucidate, enumerate, compare, contrast, and understand the research and development landscapes and priorities of public agencies in the global north. The insights gained from such investigations will be of interest to parties preparing a report on The State of the World's Biodiversity for Food and Agriculture for the Sixteenth Regular Session (2017) of the Food and Agriculture Organisation [253]. These approaches and overall strategy are sufficiently general that they could be adapted easily by those wishing to study publicly funded research in other fields of science, techology, engineering, mathematics and medicine. This framework is of potential utility to researchers, policy makers and others interested in microeconomics and macroeconomics at regional, national, transnational and international levels.

The following observations from a 2017 examination of increasing agricultural sustainability by applying plant ecological knowledge [254] are noteworthy. "The modern 'hypothetico-deductive' scientific method tells us how to test hypotheses, but it says nothing about how hypotheses are generated. We can test hypotheses about how to increase yields with high inputs, or hypotheses about increasing sustainability. Which we choose is the research agenda. European agriculture is developing in two very different and fundamentally incompatible directions: (i) Industrial agriculture: high intensity, high input, unsustainable industrial farming, driven by large international agrochemical corporations. (ii) A movement, usually referred to as Agroecology, which promotes lower intensity, lower input, more sustainable farming, driven by consumers, environmentalists, public health professionals and some farmers. . . . The good news is that the science of ecology has advanced to a level where we have much of the knowledge necessary to build highly sustainable food production systems that can produce enough food to feed the world's population. More research will enable us to do this much better, but, to borrow a metaphor from ecological science, the 'limiting factor' for the development of sustainable agricultural systems is not our scientific knowledge, but the political and economic structures within which agriculture is practised" [254].

5.3 Small scale farmer-scientist collaborations

The well-being of current and future generations requires (re)invigorating and (re)engaging agroecology by linking ecologists and traditional farmers [273]. Whilst necessary, this is likely insufficient because additional inter-, multi- and transdisciplinary partnerships will need to be forged. For instance, "from grains to rains" [274] embodies the notion that growing plants contribute to making rainfall via the ice nucleation-active microorganisms they harbour ("bioprecipitation") [275].

Active microorganisms thrive among extremely diverse communities in cloud water [276]. A study of large areas of southern Australia [277] observed a correlation between the dynamics of ice nuclei concentrations and patterns of positive rainfall feedback and suggested that wheat-growing areas, irrigated regions, and metropolitan areas provide more suitable habitats for ice nucleating microorganisms than natural vegetation. The decline in precipitation observed in southwestern Australia during the twentieth century is believed to be caused by three factors effective on different spatial and temporal scales: changing atmospheric circulations, deforestation, and anthropogenic aerosol emissions [278]. An open access tool for mapping rainfall feedback on a planetary scale from historical daily rainfall data and maps has been developed [279]. A framework to assess the contribution of bioaerosols to the outcome of meteorological contexts favourable for rainfall has been proposed [280]. This tool and framework could be applied to map the intensity and patterns of rainfall feedback at GIAHS, the farmlands of LVC members and similar sites plus that at suitable "control" sites. Theoretical and computational advances in the underlying methdology – for example, the feedback index and its calculation from fragmented time series data [279, Supplementary file] – would improve the ability to identify trends within and between these field sites and to generate hypotheses amenable to further investigation.

As landscapes and systems where the biosphere, lithosphere, atmosphere and hydrosphere have coevolved over millenia, agricultural heritage sites and indigenous cultivation practices are propitious fora for investigating questions at the intersection of agroecology, geography, aerobiology, climatology, machine learning, and communication theory. For example, do these diverse areas have a high propensity for bioprecipitation and can the locally-adapted networks of intercommunicating plants, animals and microbes both induce and tailor weather patterns to satisfy their growth and development needs? Spatiotemporal analysis of (historical) rainfall data, direct field measurements of ice nucleation active particles and other biogeographic variables such as land use and biodiversity could illuminate whether the microbiomes of GIAHS, the farmlands of LVC members and similar sites are particularly adept at, for instance, influencing rainfall – seeding clouds to enhance rain on a local or regional scale. Do the cultivation practices, cultivars and rhizospheres/common mycorrhizal networks at these sites and farms influence the nutrient content of the food crops they produce? Free-air carbon dioxide enrichment technology [281] could be used to understand the impacts of elevated levels of atmospheric carbon dioxide on the macro- and micronutrient concentrations of crops from heritage and modern-day agroecological farming systems. Such studies are necessary and important because current concerns about increasing levels of carbon dioxide leading to less nutritious crop plants [214] tend to be based on analysis of crops that are the products of conventional farming systems [281]. Thus, small scale farmer-scientist collaborations have the potential to generate fundamental new knowledge about biogeochemical processes and simultaneously, identify novel research directions for achieving food, feed, medicine, fibre and dye sovereignty.

6 Supplementary Material

All visualisations were produced using the R Project for Statistical Computing, a free software environment for statistical computing and graphics. Reproducing this research requires the following resources.

6.1 Files: details and availability

The files used to produce the visualisations can be downloaded as follows

- R code
- Datasets

6.2 Software: details and availability

The R libraries and packages used to create the timelines and events charts are

- xts: eXtensible Time Series "Provide for uniform handling of R's different time-based data classes by extending zoo, maximizing native format information preservation and allowing for user level customization and extension, while simplifying cross-class interoperability".
- dygraphs "The dygraphs package is an R interface to the dygraphs JavaScript charting library. It provides rich facilities for charting time-series data in R".

The R libraries and packages used to create the cartograms are

- Leaflet "Leaflet is one of the most popular open-source JavaScript libraries for interactive maps".
- rworldmap: Mapping global data, vector and raster "Enables mapping of country level and gridded user datasets".
- RColorBrewer: ColorBrewer Palette "Provides color schemes for maps (and other graphics) designed by Cynthia Brewer".
- Classes and Methods for Spatial Data "Classes and methods for spatial data; the classes document where the spatial location information resides, for 2D or 3D data. Utility functions are provided, e.g. for plotting data as maps, spatial selection, as well as methods for retrieving coordinates, for subsetting, print, summary, etc."
- maptools: Tools for Reading and Handling Spatial Objects "Set of tools for manipulating and reading geographic data, in particular ESRI shapefiles; C code used from shapelib. It includes binary access to GSHHG shoreline files. The package also provides interface wrappers for exchanging spatial objects with packages such as PBSmapping, spatstat, maps, RArcInfo, Stata tmap, WinBUGS, Mondrian, and others."

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