The Role of Crop Science in Opening Commodity Frontiers

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March 2017

Supported by The British Academy
THE NATIONAL ACADEMY FOR THE HUMANITIES AND SOCIAL SCIENCES

Commodities of Empire Working Paper No.27

ISSN: 1756-0098

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Technology can be a critical determinant of the place and pace of the expansion of commodity frontiers – defined as the exploitation of natural resources to provision global markets. This is because agricultural technology generally does not travel well and must be adapted to the local agro-ecological, socio-economic and institutional contexts, especially for new crops in new areas. In the discourse on contemporary land-use changes, science and technology are often given a central role in frontier expansion since well-adapted technology can reduce risks to entrepreneurs and raise returns to land thereby making it profitable to expand.[2] However, the historical discourse on commodity frontiers has generally given little attention to the sources of technology and the role of science in extending the frontier.[3] To be sure, scientific organisations, especially the imperial botanic gardens, played an important role in extending commodity frontiers in the nineteenth century, but this usually involved collection and distribution of seeds with little science in the modern sense.[4] The lack of science and the consequent critical role of disease epidemics in shifting frontiers has also been recognised most notably by McCook for coffee rust disease, *Hemileia vastatrix*.[5]

The historical literature appears to assume either that suitable technology is available or that it is endogenously generated by frontier investors. There are good examples of both. The development of the edible oils frontier in Nigeria described by Byerlee is an example of the first case.[6] There, smallholders already successfully grew oil palm (in the south) and groundnuts (in the north) for local consumption, and with the opening of railways and waterways to provide access to foreign markets, farmers were able to quickly expand production using available land and labour to produce and process for global markets. By contrast, the banana industry in Latin America based on large-scale plantations was developed from scratch by American companies that invested not only in the infrastructure and logistics, but also in their own research stations

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[1] Paper prepared for a workshop on ‘Global Commodity Frontiers in Comparative Context’, University of London, 9-10 December 2016. I greatly appreciate the helpful comments of Tony Fischer, Ulbe Bosma, William Clarence-Smith, and participants in the workshop.

[2] A. Angelsen & D. Kaimowitz (eds), *Agricultural technologies and tropical deforestation*, Wallingford: CABI Pub, 2001.

[3] See, for example, J. W. Moore, ‘Sugar and the expansion of the early modern world-economy: Commodity frontiers, ecological transformation, and industrialization’, *Review (Fernand Braudel Center)* (2000), pp.409-33; and A. R. Hochschild, ‘The commodity frontier’, in Jeffrey C. Alexander et al. (eds), *Self, Social Structure, and Beliefs: Explorations in Sociology*, Oakland: University of California Press, 2004, pp.38-56.

[4] L. H. Brockway, ‘Science and colonial expansion: the role of the British Royal Botanic Gardens’, *American Ethnologist*, 6:3 (1979), pp.449-65.

[5] S. McCook, ‘Global rust belt: *Hemileia vastatrix* and the ecological integration of world coffee production since 1850’, *Journal of Global History*, 1:2 (2006), pp.177-95.

[6] D. Byerlee, ‘Shifting frontiers for exports of tropical oils: Roles of markets, technology and agrarian policies’, Paper presented at the Workshop on *Commodity Frontiers: A research agenda*, IISH, Amsterdam, 4-5 December 2015.

to develop suitable varieties and management practices.[7] Likewise, sugar companies collectively funded the research on sugarcane varieties at Pasuruan Experimental Station in East Java that enabled Java to become a major player in world sugar markets around 1900.[8]

In this paper, I will argue that after 1900, when investments in public research to support agriculture became mainstream, crop science has often played an important and sometimes decisive role in influencing when, where and at what speed commodity expansion takes place.[9] To do this, I selected three hypothesised scenarios. In the first case, I sought cases where state and private interests seemed to have fixed on a particular commodity considered strategic (at least to the imperial powers) and then analysed the role of science in that expansion. For this case, I use rubber (*Hevea brasiliensis*) in Malaya around 1900.[10] In the second scenario, I sought cases where official policy was to expand the frontier for settlement, or for economic or political aims, but the specific commodities to drive this expansion were not pre-identified. For this case, I use livestock feed in Thailand (maize, *Zea mays,* and cassava, *Manihot esculenta*) in the 1950s and 60s and in central-west Brazil (soybeans, *Glycine max*) from the 1970s. Finally, I sought cases where the main impetus for frontier expansion appeared to come from scientific discoveries themselves. I use the case of the breeding of dryland wheat (*Triticum aestivum*) in south-eastern Australia around 1900 and the discovery of 'trace element' soil deficiencies in South Australia to expand wool and wheat production in the 1930s and 1940s. As a subsidiary hypothesis, I also posit that public investments in science are more likely to serve the public interest and drive a more egalitarian agrarian structure on the commodity frontier. This is because public science makes its discoveries freely available to all, although the political economy may distort research priorities toward certain groups.

In each case, I reviewed the main drivers of frontier expansion paying special attention to the sources of technology and the role of public science. I also reviewed the original scientific discoveries published in the literature at the time to understand the motivations and methods for undertaking the research.

Pioneering Plantation Rubber in Malaya

The popular history of rubber romanticises the role of the British Kew Botanic Gardens in contracting Henry Wickham to collect seeds of the Brazilian rubber species of the *Hevea* genus, and smuggle them out to Britain in 1876 and eventually to the British colonies of Asia. The reputed imperial motive was to establish a plantation industry that could supply the growing appetite of British industry for rubber and forgo dependence on wild rubber harvests from

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[7] See, for example, John Soluri, *Banana cultures: agriculture, consumption, and environmental change in Honduras and the United States*, Austin: University of Texas Press, 2005; and D. Southgate & L. Roberts, *Globalized Fruit, Local Entrepreneurs: How One Banana-Exporting Country Achieved Worldwide Reach*, Philadelphia: University of Pennsylvania Press, 2016.

[8] U. Bosma & J. Curry-Machado, 'Turning Javanese: The Domination of Cuba's Sugar Industry by Java Cane Varieties', *Itinerario*, 37 (2013), pp.101-20.

[9] Modern crop science involves plant breeding using Mendelian principles, and research on crop, pest and resource management involving scientific methods of randomisation and replication. This paper does not analyse post-harvest and processing technologies, which may be equally important.

[10] The Malay Peninsular at the time consisted of the Federated States of Malaya and the Straits Settlements of Malacca, Penang, and Singapore. For brevity, I will refer to these collectively as Malaya.

Brazil, Congo and elsewhere.[11] In fact, while there were several seed shipments in the late nineteenth century, there is no evidence that the seeds were taken out of Brazil illegally. The seeds were shared with other colonial empires, such as the Dutch in the East Indies and later the Belgians, Germans and Portuguese in Africa, and the huge surge in the demand for rubber for the nascent automobile industry after 1900 was unanticipated at the time of Wickham's shipment.[12]

Rather than the seeds themselves, the major contribution of science was on developing the management practices for rubber under plantation conditions, since up to 1900 rubber was collected from several species of wild trees and vines in the tropics of the Americas, Africa and Asia. This research was initiated from the 1870s in the botanic gardens in Ceylon and in Malaya linked to Kew. The Singapore Gardens, under the direction of Henry Ridley, soon took the lead and focused its efforts on the management of rubber cultivated in plantations from 1888 to 1905. Although there were several genera and species of rubber being tested, Ridley settled on *Hevea brasiliensis* from Brazil.[13] His most important contribution was the development of sustainable and efficient methods for tapping rubber, in terms of the tapping tool, the frequency, depth and shape of the incisions, and the initial age of trees to begin tapping. This work was critical given that methods used for tapping wild *Hevea* rubber in Brazil were not known to Ridley; and in any event, were highly destructive.[14] He and his staff also undertook research on density and spacing of trees, weeding, disease control and green manuring. By 1900 the basic knowledge for managing *Hevea brasiliensis* had been established, but there was still considerable uncertainty on 'best practices'.[15]

The research on rubber management in plantations was carried out over twenty years through careful observation and measurement, although the research was done before more rigorous statistical methods became mainstream.[16] Even so, the work of Ridley and his team was considered by colonial officials as being 'too scientific'.[17] However, after the initial success was demonstrated, rubber research was mainstreamed through the establishment of the Department of Agriculture in 1905, which quickly expanded to 8 scientists and officials by 1909 and to 28 by 1914 (to cover all crops). However, it was not until 1926 that the Rubber Research

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[11] See, for example, John A. Tully, *The devil's milk: a social history of rubber,* New York: Monthly Review Press, 2011; and Joe Jackson, *The thief at the end of the world: rubber, power, and the seeds of empire,* New York: Viking, 2008.

[12] W. Dean, *Brazil and the struggle for rubber: a study in environmental history,* Cambridge: Cambridge University Press, 1987; M. R. Dove, 'Hybrid histories and indigenous knowledge among Asian rubber smallholders', *International Social Science Journal*, 54:173 (2002), pp.349-59.

[13] H. N. Ridley, 'Rubber cultivation', *Agricultural Bulletin of the Malay Peninsular,* 7 (1897), pp.132-40.

[14] H. N. Ridley & R. Derry, 'The second annual report on the experimental tapping of para rubber trees in the Botanic Gardens, Singapore, for the year 1905', *Agricultural Bulletin of the Straits and Federated Malay States,* 5 (1906), pp.439-68; John H. Drabble, *Rubber in Malaya, 1876-1922; the genesis of the industry,* Kuala Lumpur: Oxford University Press, 1973; O. F. Cook, 'Beginnings of rubber culture: Special Characters of the Hevea Tree Determine Method of Tapping', *Journal of Heredity,* 19:5 (1928), pp.204-15.

[15] Drabble (1973)

[16] Ridley and Derry (1906); H. Wright, *Hevea brasiliensis: or, Para rubber, its botany, cultivation, chemistry and diseases,* Colombo: A. M. & J. Ferguson, 1908; Howard Wolf & Ralph F. Wolf, *Rubber: a story of glory and greed.* Shrewsbury: Smithers, 1936; P. R. Wycherley, *The Singapore Botanic Gardens and rubber in Malaya,* Singapore: Government Printing Office, 1959.

[17] D. J. M. Tate, *The RGA history of the plantation industry in the Malay Peninsula,* Kuala Lumpur: Oxford University Press, 1996.

Institute of Malaya was created with 22 scientists. This institute would prove to be decisive in maintaining Malaya's lead in rubber for the first half of the century.[18]

Meanwhile rubber growers through the Rubber Growers' Association of Malaya also supported research, especially on processing, and eventually instituted a levy to fund the Rubber Research Institute. Scientists in Ceylon also contributed by developing methods for processing to coagulate rubber and surveying diseases.[19] In terms of breeding, the Dutch took the lead in the East Indies from 1912 and pioneered the development of high yielding clonal rubber at Buitzenborg Botanic Gardens and Deli.[20]

Of course, the major factor causing the rubber industry to take off (see Figure 1) was the surge in demand and rising prices after 1900 with the advent of the automobile-tyre industry and the concomitant decline in prices of other commodities, especially for coffee. Initially the colonial authorities in Malaya did not support the rubber industry, but this quickly changed with the surge in demand and prices, when the state provided subsidised loans and cheap land concessions, and facilitated labour migration from India and China.[21]

Smallholders also quickly entered the industry throughout the region despite active discouragement by colonial officials. By 1914 they accounted for over 40 percent of the rubber area in Malaya and by the late 1990s almost all rubber in the region.[22] However, public science initially ignored the needs of smallholders who developed their own systems based on indigenous knowledge of wild rubber harvesting and adaptation of plantation tapping practices from the estates.[23] In the Dutch East Indies, in particular, 'jungle rubber' with rubber planted at high density into swidden agricultural systems was the norm and "the only attention that the [colonial government] gave to the smallholder sector was punitive in nature".[24] Some smallholder practices, such as denser planting of rubber and maintenance of ground cover, were eventually adopted on estates, although with a long delay due to cultural, racial and modernist prejudices at the time.

Even so the investment by Malaya, especially the Singapore Botanic Gardens, in developing management techniques for plantation rubber and the energy and enthusiasm of Ridley – sometimes known as 'Mad Ridley' – were major factors in explaining the initial leadership role in the industry of Malaya some years ahead of Ceylon and the Dutch East Indies. Rubber area in Malaya reached 1,000 acres by 1898, by 1900 in Ceylon, by 1903 in the Dutch East Indies and by 1908 in Indochina.[25] Thus, Malaya was able to reap pioneering profits from plantation rubber, which as quickly as 1914 equalled the supply of wild rubber – a lead that

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[18] Colin Barlow, *The natural rubber industry, its development, technology, and economy in Malaysia*, Kuala Lumpur: Oxford University Press, 1978.
[19] Drabble (1973); Wycherley (1959).
[20] W. J. Baulkwill, 'The history of natural rubber production', in C. C. Webster & W. J. Baulkwill (eds), *Rubber*, Harlow: Longman Scientific and Technical, 1989, pp.1-56.
[21] Barlow (1978); James C. Jackson, *Planters and speculators; Chinese and European agricultural enterprise in Malaya, 1786-1921*, Kuala Lumpur: University of Malaya Press, 1968.
[22] Barlow (1978); D. Byerlee, 'The Fall and Rise Again of Plantations in Tropical Asia: History Repeated?' *Land*, 3 (2014), pp.574-97.
[23] Barlow (1978); Michael Dove, *The banana tree at the gate: a history of marginal peoples and global markets in Borneo*, New Haven: Yale University Press, 2011.
[24] Dove (2011), p.7.
[25] Drabble (1973).

Malaya was to maintain until the 1960s when it was overtaken by Thailand and Indonesia (Figure 1).

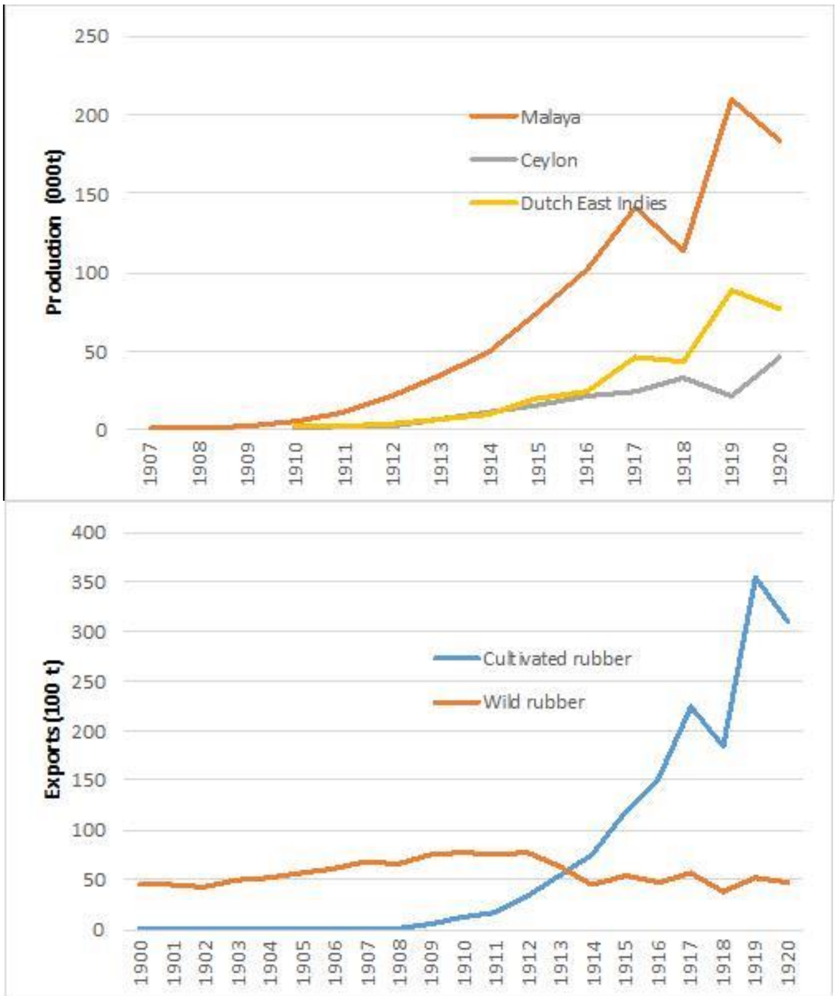

Figure 1: *Top panel*. Rubber production in southeast Asia, 1907-20. *Bottom panel.* World exports of cultivated and wild rubber, 1900-20
Source: Drabble (1973)

Other studies have identified a lack of investment in science as one factor in the failure of Brazil and West Africa to develop a plantation industry.[26] The plantation industry in Brazil was highly constrained by the incidence of rubber-leaf blight, *Microcyclus ulei*, which is indigenous to the region. Despite increased global communication, Asian nations have successfully kept out the leaf-blight disease for over a century. This is a major achievement of modern quarantine systems, but still leaves the region at grave risk of disaster from future transmission of the disease.[27]

[26] Dean (1987); Dove (2002); J. Fenske, '"Rubber will not keep in this country": Failed development in Benin, 1897-1921', *Explorations in Economic History*, 50:2 (2013), pp.316-33.
[27] B. T. de Hora Junior et al., 'Erasing the past: a new identity for the Damoclean pathogen causing South American leaf blight of rubber', *PloS one*, 9:8 (2014), p.e104750. Seed imports from the Americas to Asia were banned from 1920 (Dean 1987)

As an epilogue, in the late twentieth century, the rubber frontier in Southeast Asia expanded decisively to the north outside of its comfort zone in the tropical latitude band within ten degrees of the equator, where yields are seriously affected by a long dry season and cool temperatures. The Chinese in particular invested heavily in research on management techniques to produce rubber under the much cooler conditions of Yunnan Province, and bred clones to withstand drought and cold.[28] Motivated by the burgeoning demand for rubber for industrialisation, China through investment in science has become the world's fourth largest producer of rubber (and its largest consumer).

Livestock Feed Frontiers in Thailand and Brazil

Post WWII exports of maize and cassava from Thailand

After the Second World War Thailand instituted an explicit national policy to open the forest frontier toward its north and northeast to settlement, motivated in part by high population pressure in the south and central regions, but also by security concerns from a communist insurgency and takeovers in its northern Indochina neighbours.[29] The major mechanism to open the frontier was through construction of roads – particularly the Friendship Highway opened in 1958 – and malaria control, both largely funded by the US government (also concerned by the communist threat). Some settlements were planned and supported by the government, but most were spontaneous. With improved transport systems, cropland expanded threefold from 1940 to 1970 and then doubled again to 1990.[30] Much of this was at the expense of forests area that fell by 28% from 1955-75.[31]

The newly opened upland areas on the Thai frontier had the potential to produce a range of crops including rice, the major export at the time. However, state policy was to diversify its agriculture away from rice, which covered 89 percent of land area in 1950, and together with rubber accounted for over three quarters of agricultural exports.[32] Starting around 1950, a large US Operations Mission (the US foreign assistance programme) strongly supported crop diversification through a combination of investment in research, extension, seed production and university education on a wide range of crops (e.g. sorghum, soybeans, groundnuts, maize, cassava, pasture grasses and legumes). A total of 12 American agronomists worked on the programme, and 43 Thais were sent abroad for training between 1950 and 1960.[33]

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[28] E. C. Chapman, 'The expansion of rubber in southern Yunnan, China', *Geographical Journal* (1991), pp.36-44; L. Zhang et al., 'The expansion of smallholder rubber farming in Xishuangbanna, China: A case study of two Dai villages', *Land Use Policy*, 42 (2015), pp.628-34. Some rubber had been produced in more tropical Hainan Province since the 1930s

[29] D. Feeny, *The political economy of productivity: Thai agricultural development*, 1880-1975, Vancouver: University of British Columbia Press, 1982.

[30] R. De Koninck & S. Déry, 'Agricultural expansion as a tool of population redistribution in Southeast Asia', *Journal of Southeast Asian Studies*, 28:1 (1997), pp.1-26.

[31] D. Feeny, *Agricultural expansion and forest depletion in Thailand, 1900-1975, Economic Growth Center Discussion Paper* 458, New Haven: Yale University, 1984.

[32] Robert J.Muscat, *Development strategy in Thailand; a study of economic growth*, New York: Praeger, 1966.

[33] C. A. Breitenbach, 'The Thai-USOM cooperation in the promotion of corn production in Thailand', Bangkok, 1961, at http://pdf.usaid.gov/pdf_docs/Pnadx191.pdf.

Through a combination of technology and markets, the four upland crops that emerged on the new frontier were maize, cassava, kenaf (*Hibiscus cannabinus,* a type of jute) and sugarcane (*Saccharum officinarum),* with Thailand quickly becoming the largest exporter of dry cassava, the second largest sugar exporter and the fourth largest maize exporter in the world. The maize and cassava (locally known as tapioca) were destined for livestock feed in Japan and the European Economic Community (EEC), respectively.[34]

Both maize and cassava had a long presence in Thailand after being introduced into Southeast Asia and had spread fairly widely in the region. However, in Thailand both were very minor crops in 1950, with maize largely confined to a small area of 84,000 hectares in the hills while about 34,000 hectares of cassava were grown in the northeast.

The rapid expansion of maize beginning in the late 1950s represented a new commodity frontier. The technology was provided by the US programme to the Thai Department of Agriculture in the form of a well-adapted variety Tequisate Golden Flint that had been developed at Iowa State College's (now University) Tropical Research Center in Guatemala. This variety, along with many poorly adapted US materials, reached Thailand via Indonesia through the US assistance programme in 1950.[35] Irving Melhus, after leaving his post as director of the Tropical Research Center, took a six-month consultancy in Indonesia in 1949 and introduced Tequisate Golden Flint there. Since nearly all maize improvement work in the tropics at the time was focused on white dent maizes that were used for food in most of Latin America and Africa, there was very little improved yellow flint maize for the tropics. However, the Golden Flint variety was ideal for the Japanese livestock feed market.[36]

At the time, maize area in Thailand was negligible. But after the release of Guatemala variety (locally known as Gotemara), and a large extension programme, production surged to one-million tons by 1965 and maize yields doubled (Figure 2).[37] "Without the work of the agronomist who sought out, tested and established a well-adapted variety, …the crop could not have prospered."[38]

Under a trade agreement signed in 1959, almost all Thai maize was exported to Japan, which was seeking to diversify its sources of livestock feed to provision its rapidly growing appetite for meat. Ironically, the USA government by supporting the Thai maize programme undermined the near monopoly that USA maize exports had enjoyed in the Japanese feed market.

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[34] The rapid expansion of sugarcane appears to be due more to strong farmer organisations and state support than to technology (A. Ramsay, 'The political economy of sugar in Thailand', *Pacific Affairs,* 60 (1987), pp.248-70).
[35] Breitenbach (1961). Iowa State College had established its Tropical Research Center in 1945 with support from an Iowa seed company, partly to improve maize in Guatemala but also to collect and supply diversified tropical germplasm to US seed companies (Irving E. Melhus & E. E. May, *Plant research in the tropics,* Ames: Agricultural Experiment Station, Iowa State College, 1949). The centre developed Tequisate Golden Flint from a cross of Cuban and Guatemalan materials probably to serve the Iowa companies rather than Guatemalan consumers since the latter strongly prefer white maize.
[36] Breitenbach (1961).
[37] M. Yanagisawa & E. Nawata, 'Development of commercial cultivation of field crops in Thailand: A case study in Saraburi and Lopburi provinces', *Southeast Asian Studies,* 33:4 (1996), pp.588-608.
[38] Breitenbach (1961), p. 13.

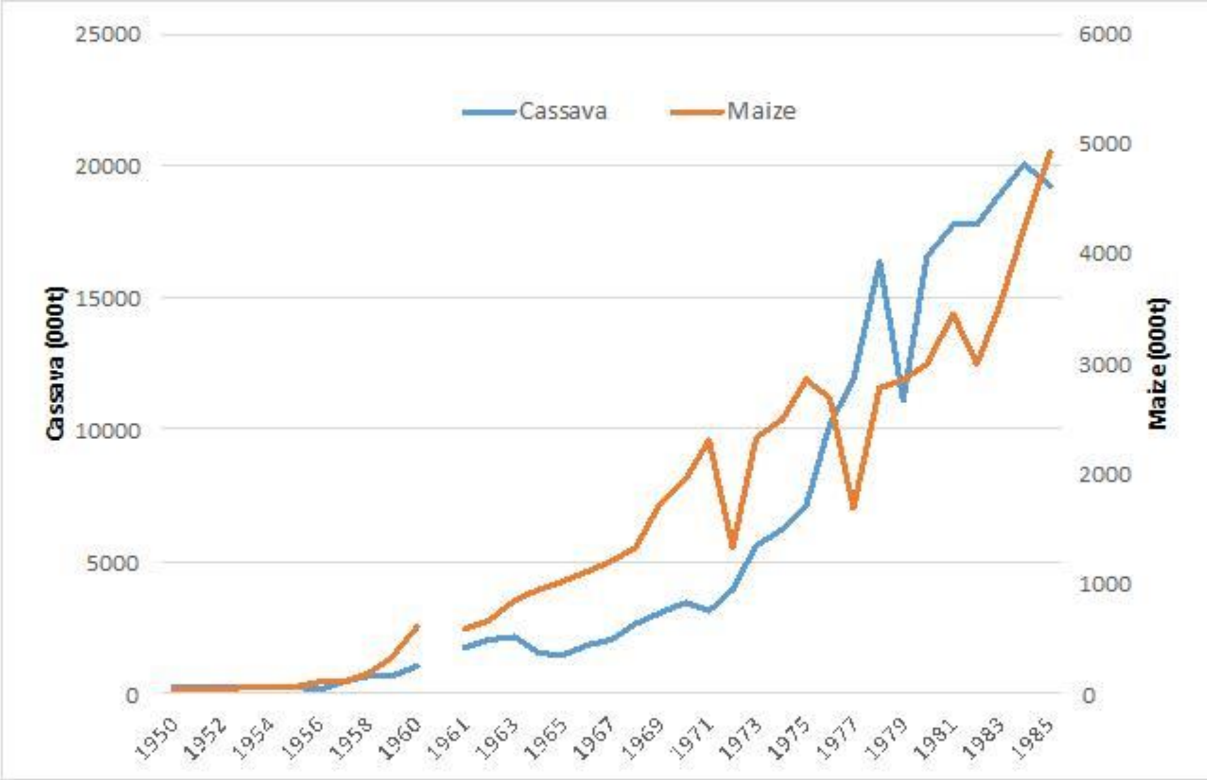

Figure 2: Cassava and maize production, Thailand, 1950-85.

Notes: 1950-60 data are from L. R. Brown, 'Agricultural diversification and economic development in Thailand: a case study', *Foreign Agricultural Economics Report* 8, Washington: USDA, 1963; and data from 1961-85 are from FAOSTAT http://faostat3.fao.org/. Note that cassava data are fresh weight that converts to about 38% dried chips or pellets.

Science played a further major role in maintaining the growth of the industry when the Gotemara variety was hit by a devastating attack of downy mildew disease in the 1960s – a disease that was endemic in Southeast Asia but not found in Guatemala. The Rockefeller Foundation, from its base in India, had started supporting a national maize-improvement programme at Kasetsart University around 1960 and moved its Inter-Asian Corn Program there in 1966.[39] Including highly motivated Thai scientists at the University who had been trained at the Foundation's Mexican Agricultural Program, the University became one of the strongest maize-breeding hubs in Asia. A new downy mildew-resistant variety, Suwan 1, was released in 1973 and was quickly adopted in Thailand as well as many other countries in the region.[40]

Maize exports expanded to four-million tons by 1985 making Thailand a major player in world markets. Exports then declined as Thailand established its own feed-mill and intensive livestock industry. The main driver of this transformation was the Charoen Pokphand (CP) company owned by a Chinese-Thai family that had started marketing vegetable seed prior to the Second World War, but in the 1950s and 1960s built their own feed mills and a poultry industry based on the increasing supply of maize. These CP investments led to the export of poultry rather than feed to Japan and elsewhere. CP was also a major producer of maize seed and in the 1980s led the development of the hybrid maize-seed industry and the establishment

[39] D. Byerlee, *The Birth of CIMMYT: Pioneering the idea and the ideals of international agricultural research.* Mexico DF: CIMMYT, 2016.

[40] S. Sriwatanapongse et al., *Suwan-1: Maize from Thailand to the world*, Mexico DF: CIMMYT, 1993.

of secondary frontiers in the early twenty-first century in neighbouring countries based on CP hybrid seed. Today CP is one of the world's largest agribusiness companies and a leader in livestock feed, poultry and pig meat in Asia, in part due to the successful opening of the maize frontier in the 1950s.[41]

The livestock-feed frontier moved into the drier and poorer northeast in the early 1960s, when Thailand started exporting dried cassava and pellets to the EEC market exploiting a loophole in EC protection that provided an advantage to cassava over maize imports from the USA. As in the case of maize, cassava was a very minor crop in Thailand, but with the opening of the EEC market, the Rayong Agricultural Research Centre established in 1956 selected Rayong 1 variety from locally available materials.[42] Local processors developed a drying, chipping and pelleting technology of fresh cassava for shipment to Europe. Rayong 1 became the most widely grown cassava variety in the world with over one-million hectares planted in the 1960s; and Thailand accounted for over 80 percent of the world exports of cassava between 1960 and 1980.[43]

Cassava yields, starch content and disease resistance were given another impetus starting in 1971 through collaboration with the International Centre for Tropical Agriculture (*Centro Internacional de Agricultura Tropical*, CIAT) that had recently been created from a Rockefeller Foundation programme in Colombia.[44] CIAT established a research program in Thailand in the early 1980s that led the release of KU 50 using Latin American germplasm that resulted in a 30 percent yield increase.[45] The EEC eventually instituted import duties and quotas on Thai cassava, and the area plateaued (Figure 2) and exports peaked around nine-million tons in the late 1980s. However, Thailand was able to revamp its export market by diverting sales to the emerging market in China.[46]

These examples demonstrate not only the role of science in helping create new commodity frontiers, but also in establishing commodity exports led entirely by smallholders. Initially Thailand exported the raw materials, but especially in the case of maize, it added value through establishing a feed industry and then became the world's largest poultry exporter. Partly as a result of the smallholder-based livestock-feed frontier, Thailand has had one of the best records anywhere of reducing rural poverty and in the poorest region, the Northeast, poverty fell sharply.[47]

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[41] In Thailand maize area has declined from 1985 due to competition with other higher value crops

[42] C. Rodjanaridpiched et al., 'Recent progress in cassava varietal improvement in Thailand', in Reinhardt H. Howeler, (ed.), *Regional Workshop Cassava Breeding, Agronomy Research and Technology Transfer in Asia 1993*, Kerala: Trivandrum, 1993.

[43] CIAT, *CIAT Report 1981: Highlights of Activities in 1980*, Cali: CIAT, Cali, 1981.

[44] Rodjanaridpiched et al. (1993).

[45] Jonathan Robinson & C. S. Srinivasan, 'Case studies on the impact of germplasm collection, conservation, characterization and evaluation in the CGIAR', Standing Panel on Impact Assessment, Rome, 2013.

[46] R. H. Howeler & C. H. Hershey, *Cassava in Asia: Research and development to increase its potential use in food, feed and industry: a Thai example*, Bangkok: CIAT, 2002.

[47] B. Ekasingh et al., 'Competitive commercial agriculture in the Northeast of Thailand', *World Bank Working Paper*, Washington DC: World Bank, 2007.

Soybeans in the Cerrados of Brazil

Like Thailand, Brazil had for a long time aspired to settle its vast interior, and as early as 1937 announced an official policy of '*Marcha para o Oeste*' (Move to the West). The first step in this movement was expected to be the Cerrado, a huge area of over two-hundred million hectares (about one quarter of Brazil) in the centre-west of the country, of reasonable if not always reliable rainfall covered by savannah and woodlands. However, productivity was extremely low – extensive grazing with about one cow per five hectares – due to the infertile and highly acid soils. By 1950 only 3 percent of Brazil's population lived in the area.

This situation began to change around 1961 when a new federal capital city, Brasilia, was constructed in the Cerrado and new highways were built to link the capital to the south and east. In 1958 too, path-breaking research by the International Basic Economy Corporation Research Institute (IIR) funded by the Rockefeller Brothers, in collaboration with the Brazilian Instituto Agronomico Campinas, was published that indicated that the application of heavy doses of lime and superphosphate could increase the productivity of Cerrado soils two- or threefold and make them suitable for crop agriculture.[48]

Starting in the early 1970s, improvements in infrastructure and the emerging science led the Brazilian government to begin to actively support settlement in the area through large colonisation and credit programmes such as POLOCENTRO.[49] The initial emphasis was on rice production and pastures that could be moderately productive with limited investments in soil amendments.[50]

In 1973 scientific research received a big impetus with the establishment of the Brazilian Agricultural Research Corporation (EMBRAPA), which had a strong focus on the Cerrado through its Centre for Agricultural Research on the Cerrado. EMBRAPA quickly grew to employ a thousand scientists within four years and went on to become a premier research centre on tropical agriculture. Its soils-research programme carried out pioneering work on soils mapping and fertility leading to detailed recommendations on soil amendments in 1980.[51] EMBRAPA's chief soil scientist, Edson Lobato and Colin McClung of the 1950s IRR program went on to win the prestigious World Food Prize in 2006 for outstanding scientific contribution to world agriculture.[52]

A second critical scientific front was opened in the 1970s to develop soybean varieties suited for the Cerrado. The US embargo on soybean exports in the 1970s had opened the soy market to Brazilian farmers in the south, and many of these farmers migrated north to the

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[48] L. M. M. Freitas et al., 'Field Studies on Fertility Problems of Two Brazilian Campos Cerrados, 1958-1959', *IRI Research Bulletin* 21, New York: IBEC, 1960; Ryan L. Nehring & Wendy W. Wolford, 'Yield of Dreams: Marching West and the Politics of Scientific Knowledge in the Brazilian Agricultural Research Corporation (Embrapa)', MSc Thesis, Cornell University, 2016.

[49] Akio Hosono et al., *Development for sustainable agriculture: the Brazilian cerrado.* Basingstoke: Palgrave Macmillan, 2016.

[50] G. S. A. D. C. Barros et al., 'The Brazilian Cerrado experience with competitive commercial agriculture: a critical review', Background paper for the Competitive Commercial Agriculture Africa (CCAA) Study, Washington DC: World Bank, 2007.

[51] Hosono et al. (2016).

[52] The third person in the World Food Prize award was Alysson Paolinelli, who as Secretary of Agriculture for Minas Gerais and later Minister of Agriculture for Brazil provided key policy support.

Cerrado in search of larger farms.[53] The Japanese government also strongly supported research and investment programmes to cultivate soybeans to serve Japan's feed industry. As was the case of maize in Thailand, Japan sought to diversify its heavy dependence on US exports.[54]

Soybeans originated in the higher latitudes of northern China, and in fact Manchuria under Japanese occupation was the world's dominant soybean exporter prior to the Second World War. EMBRAPA achieved a major breakthrough in producing varieties suited to the tropical latitudes but also with tolerance to aluminium toxicity and low calcium, features of the Cerrado soils.[55] The first such variety, Doko, was released in 1981 and became the world's most widely grown soybean variety. The programme also included development of *Bradyrhizobium* nodulation strains to fix nitrogen and minimise the use of nitrogenous fertiliser. These breakthroughs increased the yield of soybeans in the region by about threefold and encouraged the expansion of soybeans as the preferred crop.[56]

The third and most recent element of the technological package was zero or conservation tillage to make production systems more sustainable. This was introduced from southern Brazil by networks of farmers, the private sector and researchers, and was aided by the release of genetically modified varieties tolerant to herbicides in the early twenty-first century.

Soybean area in the Cerrado increased from virtually nothing to become the premier soy basket of the world, particularly after China opened its market to imports in the 1990s (Figure 3). Led by Brazil, soybeans quickly rose to become the worlds most valued agricultural commodity in world trade. In short, "the weapons used to conquer the 'Brazilian wilderness' were scientific research".[57] However, heavy credit subsidies through the 1980s amounting to as much as 20 percent of agricultural GDP were also a major driver of the investments in land clearing and soil amendments.[58]

The settlement of the Cerrado was initially based on family farms, albeit quite large averaging about one-thousand hectares, aided by strong state support. However, withdrawal of the state in the 1990s led to large private companies opening the frontier, including some of the largest arable farms in the world. Soybeans remain the major commodity export from the region today, but many studies conclude that the expansion of the Cerrado frontier was a missed opportunity in terms of promoting an equitable agrarian structure with more positive social outcomes.[59]

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[53] W. Jepson, 'Private Agricultural Colonization on a Brazilian Frontier, 1970–1980', *Journal of Historical Geography* 32:4 (2006): 839-63.
[54] Nehring & Wolford (2016).
[55] C. R. Spehar, 'Impact of strategic genes in soybean on agricultural development in the Brazilian tropical savannahs', *Field Crops Research*, 41:3 (1995), pp.141-46.
[56] Spehar (1995); D. Kaimowitz & J. Smith, 'Soybean technology and the loss of natural vegetation in Brazil and Bolivia', in Angelsen & Kaimowitz (2001).
[57] C. M. da Silva, 'Science, Agriculture and Nation Building: IRI Research Institute (IRI) and the Conquest of the "Campos Cerrados" in Brazil (1946-1980), 2012, at http://rockarch.org/publications/resrep/dasilva.pdf., p.13.
[58] D. Byerlee et al., *The Tropical Oil Crop Revolution: Food, Feed, Fuel, and Forests*, New York: Oxford University Press, 2017.
[59] See, for example, World Bank, *Awakening Africa's sleeping giant: prospects for commercial agriculture in the Guinea Savannah zone and beyond*, Washington, DC: World Bank, 2009.

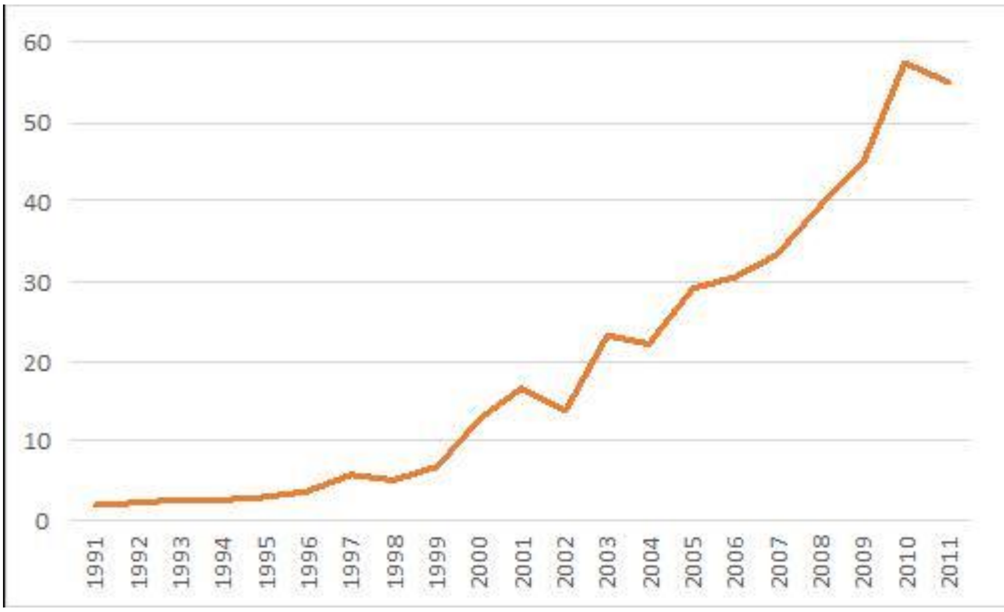

Figure 3. Production (Mt) of soybeans in the Cerrado, Brazil, 1991-2011
Source: http://www.conab.gov.br/conteudos.php?a=1252&

Scientists as the Lead in the 20th Century Australian Frontier

Dryland wheat varieties

The pioneering wheat-breeding research of William Farrer in Australia is often credited with extending the wheat frontier to drier areas in the early twentieth century.[60] Until the late nineteenth century wheat varieties in Australia were selected from introductions, often from areas with quite different agro-climatic conditions. Disease losses, especially to the wheat rusts (various *Puccinia* species), were high and most varieties were unsuited to the hotter and drier climate of Australia. Farrer, who had graduated from Cambridge University and migrated to Australia, experienced these problems first hand in his job as a land surveyor and set up his own cross-breeding programme in 1889 – one of the first and largest in the world.[61] For the first few years he operated with his own resources motivated by the scientific challenge rather than profit. As it grew into a very large programme and its benefits were increasingly appreciated, the state employed Farrer and funded the programme from 1898.

Although the initial focus was on rust resistance and milling quality, dry years in 1895 and 1896 turned Farrer's attention to breeding earlier and more heat-tolerant varieties, using Indian varieties as parents. He also set up an extensive testing network in the drier areas. By 1901, he had released his most famous variety, Federation, that became the most widely grown

[60] A. L. Olmstead & P. W. Rhode, 'Biological Globalization: The Other Grain Invasion', in Jeffrey G. Williamson et al. (eds), *The new comparative economic history: essays in honor of Jeffrey G. Williamson,* Cambridge: MIT Press, 2007; L. T. Evans, 'Response to challenge: William Farrer and the making of wheats', *Journal of the Australian Institute of Agricultural Science*, 46 (1980), pp.3-13. A parallel experience was the search for suitable winter wheat varieties to extend the frontier in the US Great Plains based on importing germplasm from Russia, although was based on germplasm collection rather than wheat breeding initially (David Moon, 'In the Russians' steppes: the introduction of Russian wheat on the Great Plains of the United States of America', *Journal of Global History* 3 (2008), pp.203-25; Olmstead & Rhode 2007).
[61] A. Russell, *William James Farrer. A biography*, Melbourne: Cheshire, 1949.

variety in Australia. During this period, the area of wheat in New South Wales expanded westward increasing the state wheat area tenfold from 1890 to 1930 (Figure 4), and Australian wheat exports went from 0.7 million tons in 1901 to over 3 million in 1930.

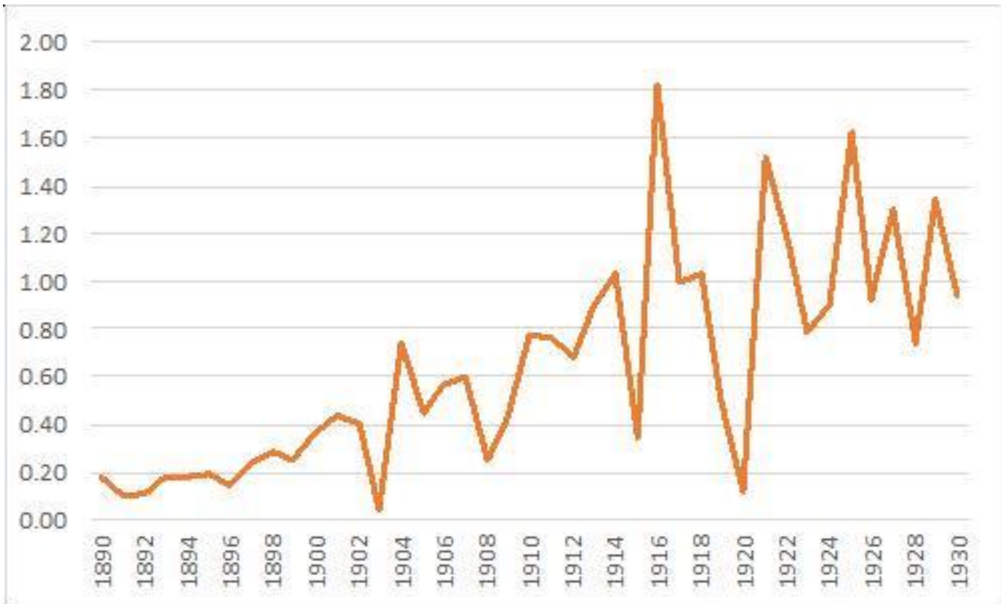

Figure 4. Area (Mha) of wheat in NSW, 1890-1930
Source: http://www.abs.gov.au/ausstats/abs@.nsf/mf/7124.0

How much of this expansion can be attributed to the new wheat varieties? The state government was clearly already supporting the westward movement of the frontier by revising land laws to break up large estates, investing in land surveys for closer settlement and constructing a dense railway network.[62] These investments, as well as the adoption of superphosphate from around 1900 to improve soil fertility, were no doubt critical, but the better adapted varieties were also an important factor in accelerating the expansion and ensuring its success.[63] As F. B. Guthrie, a wheat breeder and contemporary of Farrer, observed;

> Undoubtedly it is due to the capacity of varieties that he [Farrer] produced to resist dry conditions that wheat-growing has become profitable in western districts where formerly it was commercially unthinkable.[64]

Not surprisingly, Farrer is probably the only wheat scientist anywhere to be immortalised by placing his image on the nation’s currency (the 1966 two-dollar note).

[62] M. E. Robinson, *The New South Wales wheat frontier, 1851-1911 [history, development]*, Australian National University, Department of Human Geography, 1976.
[63] Olmstead (2007).
[64] F. B. Guthrie, ‘William J. Farrer and the results of his work’, *Scientific Bulletin* 22, Sydney: Department of Agriculture, 1922, p 19.

The Discovery of 'Trace Element' Deficiencies

By 1930, the wheat and intensive pasture frontier in the state of South Australia had essentially closed. However, a large strip of land of about 2.5 million hectares remained unsettled in the southeast of the state and across the border in the neighbouring state of Victoria, that included what were then known as the Ninety Mile Desert, the Big Desert and the Little Desert. This area of siliceous sands (also known as Laffer sands) and heath-like vegetation had good rainfall (at least by Australian standards), averaging about 450 millimetres, and lay to the south of drier land that had recently been settled using the Farrer wheat varieties.[65] Some of it was used for extensive grazing, but at extremely low productivity at one sheep to every five to fifteen hectares.[66] This was much lower even than the native Cerrado vegetation of Brazil. Prior to the Second World War all settlement in these soils had failed, and it was strongly suspected that it was a soil problem.[67]

The solution of the problem gradually emerged from 1938 to 1944. The Commonwealth Scientific and Industrial Research Organisation (CSIRO) had been established in 1926 to undertake 'fundamental research' and break the perceived British imperial hegemony over science in Australia.[68] One of its lines of research on animal nutrition led to investigation of 'Coast Disease' of sheep that identified a deficiency of cobalt as the cause in 1938 – a world first for animal nutrition. This stimulated research more generally on micronutrient or so called 'trace elements' in livestock, pastures and crops that uncovered a range of other micronutrient deficiencies in different locations in South Australia, including copper (also a world first), zinc, molybdenum and manganese.[69]

Building on this new knowledge base, CSIRO scientist, David Riceman carried out pioneering research in the Ninety Mile Desert in 1943-44, on a farm near Keith. Working with improved pastures he found that the application of copper and zinc together with superphosphate could increase pasture yield fourfold (Figure 5).[70] More informal research in the same area showed that cereal yields could be increased by between five- and tenfold by the application of the same nutrients.[71] These research discoveries "symbolized the growing power of biological sciences…and gave a new lease of life to the nineteenth-century frontier spirit".[72]

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[65] H. F. Bell, & W. H. Cairns, 'Notes on the A.M.P. Society's Land Development Scheme in South Australia', *Australian Journal of Agricultural and Resource Economics*, 2:2 (1958), pp.104-12.
[66] D. Fry, *The Story of Keith, 1851-1973: The Green Desert*, Adelaide: LPH, 1974; C. M. Donald & J. A. Prescott, 'Trace elements in Australian crop and pasture production 1924–1974', in *Trace elements in soil-plant-animal systems*, London: Academic Press, 1975, pp.7-34.
[67] A. Marshall, '"Desert" becomes "downs": the impact of a scientific discovery', *The Australian Geographer*, 12:1 (1972), pp.23-34.
[68] C. B. Schedvin, *haping science and industry: a history of Australia's Council for Scientific and Industrial Research, 1926-49*, Sydney: Allen & Unwin, 1987.
[69] Donald & Prescott (1975).
[70] D. S. Riceman, *Mineral deficiency in plants of the soils of the Ninety-mile Plain in South Australia*, Melbourne: J. J. Gourley, 1948.
[71] Marshall (1972); Schedvin (1987).
[72] Schedvin (1987), p.135.

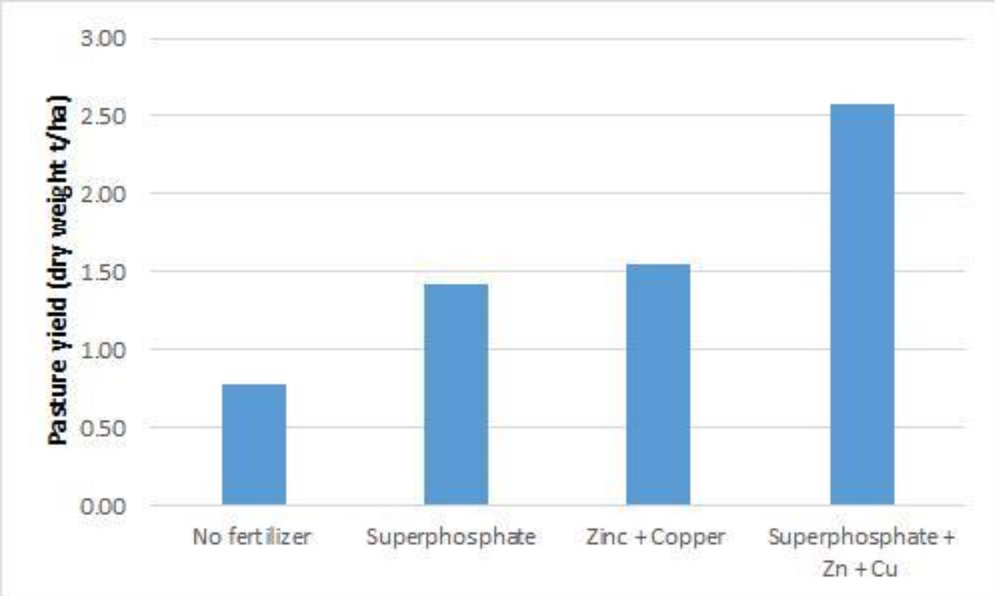

Figure 5. Pasture yield under different treatments in the second year of an onfarm experiment, Keith, South Australia, 1944
Source: Riceman (1948). Superphosphate applied at 125 kg/ha, and zinc sulphate and copper sulphate each at 7.9 kg/ha.

After the Second World War this discovery was quickly translated into practice. Hugh Robinson, an employee of the AMP Insurance Company who managed rural mortgages, was aware of Riceman's discoveries and persuaded the company to invest in land development in the area.[73] The company set up the AMP Land Development Scheme that pioneered large-scale mechanical clearing of land, application of soil amendments, sowing of improved pastures and construction of basic infrastructure.[74] After development, the land was turned over to pre-selected workers in the company who were expected to operate family farms with long-term loans from the company.

The state played only a minor role in this frontier development. The main Adelaide-Melbourne highway and railway had already passed through the area since 1886. The state did agree to the large land lease of 300,000 hectares for development, provided that it was turned over to family farms after the initial phase of land development.

Overall, the scheme was rated as highly successful in transforming an area of very low productivity – a "chemical desert" –[75] into one of the most productive areas in the state. The use of private capital greatly accelerated the land development, but always with the ultimate objective to create communities of family farms. Local historians appropriately ascribe much of this success to science.

[73] June Fergusson, *Bush Battalion: The AMP Society's Ninety Mile Desert Development in South Australia*, Sydney: Australian Mutual Provident Society, 1984.
[74] W. F. Edgerley, 'Thoughts on the A.M.P. Land Development Project', *Australian Quarterly* 25:4 (1953), pp.25-32.
[75] P. G. Pardey, *The diffusion of trace element technology: an economic analysis*, University of Minnesota, Department of Applied Economics, 1978.

When one looks at the phenomenal progress of the country in the past twenty years, it is amazing to put it down for the most part as due to the work of science.[76]

Discussion and Conclusions

Table 1 summarises the main findings of this review. It goes without saying that in all cases markets were essential to the commodity expansion; and in most cases, the new frontiers exploited new market opportunities. It is conceivable that science itself may sometimes open new market opportunities. For example, breeding of canola to reduce the erucic acid content changed rapeseed oil from largely suited for industrial use to a preferred food oil that drove its late twentieth century expansion in Canada and elsewhere. Investments in infrastructure were also essential in all cases to connect the new frontier producers to the emerging market opportunities.

Despite the obvious importance of markets, in most of the cases there were multiple market opportunities that could have allowed any one of a number of commodities to lead the frontier expansion. For example, in the case of livestock feed, in other circumstances soybeans might have led the Thai expansion and maize the Brazilian expansion.[77] Eventually, a diversified portfolio of commodities did emerge in these upland areas.

In nearly all cases, the commodity expansion took place within a national policy framework to push out the frontier even if the specific commodities had not been pre-identified by that policy. Strategic interests of the colonial power and/or importing country were also evident in some case studies. Once rubber cultivation had been successfully demonstrated in Malaya, the colonial authorities in Malaya strongly supported its expansion including increased investment in research. Similarly, Japanese aid agencies significantly invested in both the science and infrastructure to enable soybeans to expand in the Brazilian *Cerrado* and enable the Japanese feed industry to diversify it supplies away from the US.[78] By contrast, the US aid assistance to establish the maize industry in Thailand undermined the US's own maize exports to Japan.

In all cases, public science played a role in determining the success of specific commodities in a particular location. The nature of the science varied from quite applied, such as the development of tapping methods in rubber or selection of suitable varieties in Thailand, to quite fundamental research, such as the Brazilian development of soybeans for tropical latitudes and the Australian discoveries on the role of micronutrient deficiencies in plants. In most cases, the investment in science was long term, over ten to twenty years, and involved a range of disciplines from breeding new varieties to research on crop and soil management to develop a profitable and sustainable system. The long-term and risky nature of the research, underscores the key role of public investment in science, since private investors seek shorter term pay outs.

[76] Fry (1974), p 88.
[77] Maize in fact was the second crop in the Cerrados grown in rotation with soybeans
[78] Hosono et al. (2016).

However, the importance of science in driving the commodity frontier varied across the cases. In rubber, the research by the Singapore Botanic Gardens surely helped in facilitating the effective take off of cultivated rubber, but given the rubber shortage and rising prices experienced in the early twentieth century and the fact that several colonial governments in southeast Asia and Africa were working on cultivating rubber, the plantations would have eventually succeeded in replacing wild rubber. Even so the research by Ridley and his team allowed Malaya to benefit from being a 'first mover'. The role of public science in helping Thailand capture the world cassava market was also modest, involving only the selection of the best available local variety – in fact, the more important innovation was the drying and pelleting technology that was developed by the private sector. At the other extreme, the research on trace elements was decisive in opening the last frontier in the southern part of South Australia. In some of the cases, the individual scientist as well as the science were highly influential. Both Ridley in Malaya and Farrer in Australia were passionate about the value of their work and made every effort to extend their findings.

All the cases demonstrate strong international dimensions to the scientific discovery process with free flows of germplasm and knowledge across continents and empires.[79] These exchanges were largely informal. For example, Farrer in Australia maintained a prodigious correspondence and seed exchange with contacts around the world to the extent that he has been called a "one-man international centre".[80] There was also an element of serendipity, as demonstrated by the circuitous route by which a Guatemalan maize variety arrived in Thailand. Even so, scientific publication after 1900 was important in diffusing knowledge. The *Agricultural Bulletin of the Straits and Federated Malay States* published by the Singapore Botanic Gardens was a major source of information throughout Asia and the world on rubber-cultivation practices. Australian discoveries of trace elements were closely informed by related discoveries in Europe and North America through scientific journals.

The cases only weakly support the idea that investments in public science resulted in more favourable social outcomes and equitable agrarian structures. Broader institutional and policy factors relating to access to land and capital, and the political economy of public science, were much more important influences. This is seen in the cases of the livestock-feed frontier, where policies on land tenure and credit favoured smallholders in Thailand and made the outcomes strongly pro-poor relative to policies prevailing in Brazil. In some cases, the inherent efficiency of smallholders may override policy biases, as shown by the rapid takeover of the rubber market by smallholders in Asia despite lack of scientific support in the early years to address their needs.

The early investments in science may also profoundly influence the path dependency of an industry. The fact that Malaya was a first mover in experimentation on rubber and followed this with the establishment of the world's first rubber-research institute gave it a global leadership role in world rubber markets for nearly seventy years. Similarly, the early success of maize and cassava production in Thailand provided the foundation for a Thai company to

[79] See also Bosma & Curry-Machado (2013).
[80] Evans (1980).

become an Asian giant in the livestock-feed and poultry industries. In these cases, their pioneering status turned out to be transformative in the long run.

The findings also contribute to the controversy about the role of science and technology in contemporary frontier expansion. The historical cases strengthen evidence that improved technology may indeed accelerate commodity expansion in land-abundant regions. In most cases, this was at the expense of natural savannahs and forests, although at the time this was seen as a positive development in 'taming the wilderness'. Only in the later part of the twentieth century were the global values of these natural areas for biodiversity conservation and mitigation of climate change recognised. In fact, the development and settlement of the 'chemical deserts' in Australia was eventually halted in the 1960s in order to conserve significant areas in their natural state.

Finally, the findings from cases in this paper argue that studies of commodity frontiers, especially from 1900, give more attention to the role of science and technology as drivers of the choice of commodity and the place and pace of its frontier expansion. More in-depth cases are needed to confirm these findings. In this paper, I have focused on success stories only and further research should seek out investments in science designed to build new commodity frontiers that have failed – an entirely plausible and indeed likely scenario.

Table 1: Summary of results of case studies

Commodity frontier (critical research period)	Market opportunity	Policy framework	Role of science	Long-run social outcomes
Rubber, Malaya (1890-1905)	Rapid increase in demand and a price boom after 1900	Existing plantation economy. Rubber boom encouraged further state support to plantations	**Significant** in developing practices for plantations and for allowing Malaya to reap pioneering profits	Transformed Malaya into monocrop economy based initially on plantations. Smallholders developed rapidly despite negative support from the state
Maize and cassava, Thailand (1950-80)	Japan seeking to diversify sources of supply. Open EEC market for cassava due to loophole in protection	Explicit policy to open frontier, mainly through road construction	**Significant** for maize in initiating the export boom and maintaining competitiveness **Modest** for cassava initially but with significant contributions after 1980.	Smallholders led with strong support from the state and favourable land policies. Laid basis for development of Thailand as global leader in livestock feed and poultry.
Soybeans, Cerrado, Brazil (1955-80)	US embargo on export of soybeans and Japan seeking to diversify sources of supply.	Explicit state support to frontier expansion through roads and credit programs	**Significant** for soil research that encouraged heavy state investment in infrastructure and credit. **Decisive for s**oybean breeding for the tropics and conservation tillage and turning the Cerrado into the world's 'soy basket'	Original aim to settle family farmers. However, rent seeking in credit and land markets gave advantage to large farmers and after withdrawal of state, large farming companies emerged
Wheat varieties for drylands, Australia (1890-1905)	Existing global markets	Land and infrastructural investments to encourage frontier expansion	**Significant** in reducing risks and improving profitability in dryland areas	Family farming favoured by land policies.
Trace elements, South Australia, (1935-45)	Existing global markets	No explicit policy. Well-developed institutions and infrastructure already in place.	**Decisive** through. fundamental discoveries in crop and soil science	Family farming favoured by private capital with support from the state.

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The mutually reinforcing relationship between 'commodities' and 'empires' has long been recognised. Over the last six centuries the quest for profits has driven imperial expansion, with the global trade in commodities fuelling the ongoing industrial revolution. These 'commodities of empire', which became transnationally mobilised in ever larger quantities, included foodstuffs (wheat, rice, bananas); industrial crops (cotton, rubber, linseed and palm oils); stimulants (sugar, tea, coffee, cocoa, tobacco and opium); and ores (tin, copper, gold, diamonds). Their expanded production and global movements brought vast spatial, social, economic and cultural changes to both metropoles and colonies.

In the Commodities of Empire project we explore the networks through which such commodities circulated within, and in the spaces between, empires. We are particularly attentive to local processes – originating in Africa, Asia, the Caribbean and Latin America – which significantly influenced the outcome of the encounter between the world economy and regional societies, doing so through a comparative approach that explores the experiences of peoples subjected to different imperial hegemonies.

The following key research questions inform the work of project:

1) The networks through which commodities were produced and circulated within, between and beyond empires;
2) The interlinking 'systems' (political-military, agricultural labour, commercial, maritime, industrial production, social communication, technological knowledge) that were themselves evolving during the colonial period, and through which these commodity networks functioned;
3) The impact of agents in the periphery on the establishment and development of commodity networks: as instigators and promoters; through their social, cultural and technological resistance; or through the production of anti-commodities;
4) The impact of commodity circulation both on the periphery, and on the economic, social and cultural life of the metropoles;
5) The interrogation of the concept of 'globalisation' through the study of the historical movement and impact of commodities.

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