Humanities & Social Sciences Communications

ARTICLE

https://doi.org/10.1057/s41599-024-03310-z OPEN

Check for updates

Colonial policy, ecological transformations, and agricultural "improvement": comparing agricultural yields and expansion in the Spanish and U.S. Philippines, 1870–1925 CE

David Max Findley[1,2✉], Noel Amano[1,2], Ivana Biong[3], Greg Bankoff[4], Patricia Irene Dacudao[4], Francis Gealogo[4], Rebecca Hamilton[1,2,5], Ruel Pagunsan[6] & Patrick Roberts[1,2,3✉]

Burgeoning global trade and colonial policies promoted transformations in land use and agriculture throughout tropical regions in the 19th and 20th centuries, but the local and regional ecological consequences of landscape changes are still being identified and analysed. The Philippine Archipelago, which experienced successive colonial regimes across more than 7100 islands, exemplifies the multiplicity of ecological outcomes produced by these transformations. To better characterise diverse landscape change, we use colonial censuses and datasets to assess land use, production and agricultural yields in the Philippines during the late Spanish and early U.S. colonial periods (ca. 1870–1925). Our novel digital, quantitative analysis indicates that, at the national and provincial scales, agricultural production and land use increased for all major crops in both periods, while agricultural yields were mostly constant. Our results suggest that colonial investments to "improve" Philippine agriculture, specifically their efforts to increase production per hectare, were not effective. Our provincial-scale analysis also confirms the importance of distinct labour patterns, geographies and socio-political arrangements in defining this period's ecological consequences, and we provide quantified and historically contextualised data in a format amenable to ecologists to promote future, localised historic ecological research.

[1] isoTROPIC Research Group, Max Planck Institute of Geoanthropology, Jena, Germany. [2] Department of Archaeology, Max Planck Institute of Geoanthropology, Jena, Germany. [3] School of Archaeology, University of the Philippines Diliman Campus, Quezon City, Philippines. [4] Department of History, Ateneo de Manila University, Quezon City, Philippines. [5] School of Geosciences, the University of Sydney, Camperdown, Australia. [6] Department of History, University of the Philippines Diliman Campus, Quezon City, Philippines. ✉email: findley@gea.mpg.de; roberts@gea.mpg.de

Introduction

Four centuries of European colonial expansion transformed human-environment interactions at all scales, affecting land use, biodiversity, climates and ultimately the entire Earth System (Lewis and Maslin, 2015; Lenzner et al., 2022; Roberts et al., 2023). Colonial systems' impacts at large scales over ~400 years included: the substitution of native flora and fauna with newly imported species (Crosby, 1986); extensive deforestation (Grove, 1995; Tucker, 2000; Williams, 2006); and the replacement of Indigenous land use and food production with European-inspired systems of cultivation (Boserup, 1965; Cronon, 1983). Burgeoning global trade in the 19th and 20th centuries accelerated many of these alterations, including in tropical regions (i.e., regions located between the tropics of Cancer and Capricorn) that produced commodities like sugar, cotton, chocolate, rubber and lumber (Moore, 2003; Ross, 2017). Given that tropical landscapes, and tropical forests in particular, are hotbeds of biodiversity that strongly influence the atmosphere and Earth System (Malhi et al., 2014), colonial-inspired landscape transformations in these two centuries were likely globally significant and merit both scientific and historical investigation as potential components of the Anthropocene (Roberts et al., 2023).

Less well chronicled are the localised ecological consequences of growing commodity production in the tropics, which partially reflects the difficulties of detailing such varied changes. Whereas global impacts may be discerned through rigorous examination of commodity chains or inferred from prescribed agricultural practices, localised alterations were geographically and chronologically non-uniform (e.g., Ross, 2017). They were determined by the interplay between local factors—topography, agricultural practices, population and political status—and the aforementioned global market forces and colonial policies of various states (Boomgaard, 2007). Diverse historical ecological outcomes must thus be enumerated to fully comprehend past landscape transformations and their consequences for both local communities and the wider Earth System (Thomas et al., 2020; Roberts et al., 2023).

Precisely detailing local and regional ecological change in the past, and using that research to understand past human impacts on the Earth System, will ultimately require multi-disciplinary collaboration that integrates archival research into ecological sciences, including zoology, botany, geology and geochemistry (e.g., Amano et al., 2021; Hamilton et al., 2021). As a first step towards such collaboration, information on human-environment interactions contained in archival documents must be made compatible with the highly quantitative data that natural scientists use to study the Earth System. Historical data, in its many formats, must be translated and quantified (see Camenisch et al., 2022). In the context of 19th and 20th century commodities in the tropics, this means quantifying and characterising agricultural land use, agricultural production, and the ratio between them—the "productive yield" or "yield"—over time for different commodity crops. The Philippine Archipelago epitomises the challenges and benefits of this type of historic ecological research. Consisting of over 7100 geographically diverse islands, the Philippine Islands are home to many ethno-linguistic and cultural groups who had distinct experiences of two separate colonial regimes: the Spanish (1565–1898 CE) and the United States (U.S.; 1902–1941 and 1945–46). Of particular interest are the "late Spanish" (1870–1898) and the "early U.S." (1902–1925) periods (for more on periodisation, see Supplementary Notes). In those fifty-five years, both administrations expended great effort to fully incorporate the colonial Philippines into global markets for agricultural goods by encouraging or enforcing the production of rice, corn, sugar products, coconut products, abacá fibre ("Manila hemp"), tobacco, coffee, cacao and other commodities (de Jesus, 1980; McLennan, 1980; McCoy and de Jesus, 1982; Owen, 1984; Larkin, 1993; Legarda, 1999; Ventura, 2022; Dacudao, 2023).

While available data on commodity production suggests unprecedented agricultural changes took place in these two colonial periods, the pace and consequences of these changes were not uniform across provinces or islands (Larkin, 1993). Of the two colonial eras, the early U.S. period proved more transformative to landscapes. This occurred, in part, because the U.S. occupation was better funded, but also because the U.S. justified its presence in the archipelago through explicit efforts to "improve" Philippine agriculture (Owen, 1984; Larkin, 1993; Ventura, 2009 and 2016; Orquiza, 2020). It funded the construction of new irrigation channels, roads and railways (A. Corpuz, 1999; Tecson y Ocampo, 1908a and 1908b); redistributed land from Spanish friar estates to Philippine smallholders (Roth, 1977; Ventura 2009); and created agricultural banks and credit lines to finance farming expansions (McLennan, 1982; Ventura, 2009). Simultaneously, U.S. authorities endorsed "best agricultural practices," a.k.a. "scientific agriculture" (Ventura, 2022), through widely distributed journals and pamphlets including the *Farmers' Bulletin* and *Philippine Agricultural Review*; a newly established educational system; and agricultural research stations like the University of the Philippines's College of Agriculture at Los Baños (Miller, 1911; May, 1980). Late Spanish period policies were less well-financed but were still significant. The opening of various ports to international trade, the construction of overland infrastructure and the founding of the islands' first national bank in the latter half of the nineteenth century all catalysed agricultural expansion and facilitated increased international commerce (Legarda, 1999). Agricultural research centres and the Escuela de Botanica y Agricultura were also founded to promote best practices, and agricultural manuals were irregularly published through groups like the *Sociedad Económica de Amigos del País* (Patero, 1872; Gutierrez Creps, 1878; Copeland, 1908; Elena and Ordonez, 2000).

The similarities in both regimes' policies reflect a shared desire to increase the profitability of Philippine agricultural products (U.S. Bureau of the Census, 1905, hereafter the Census of 1903, 1905). From this goal was derived a consistent notion of "agricultural improvement" that was applicable in the Philippines and, seemingly, mirrored similar concepts across the world (International Institute of Agriculture, 1937; Boserup, 1965; Anker, 2001; Ventura, 2009; Jones, 2016) Throughout the nineteenth and twentieth centuries, incipient sciences including agronomy, forestry, ecology and conservation claimed their mediations could "improve" land management in supposedly "underutilized", "underperforming" or "wild" landscapes to generate greater profits and productive gains in agriculture, animal rearing and commercial logging (Krinks, 1975; Anker, 2001; von Ausdal, 2012; Orquiza, 2012; N. Roberts, 2014). Concurrently, the emergence of statistical accounting by states (Statistik) promoted the belief that effective management was derived from the ability to count people, their land use and their trade (Ileto, 1999; Jones, 2016). Lastly, how statisticians and states viewed and counted agricultural land was increasingly modelled on factory-inspired conceptualisations of production, time and value (Thompson, 1967; Pasquinelli, 2022). The intellectual convergence of these thoughts defined "agricultural improvement" in the late nineteenth and early twentieth centuries, resulting in policies designed to increase measurable production, minimise measurable "waste", and thereby achieve greater production per hectare, a.k.a. yield. In colonial contexts, this new definition also reinforced long-standing condemnations of tropical agriculture, which was derided as "indolent" and "wasteful" (Conklin, 1957; Conklin, 1961; Boserup, 1965; Spencer, 1966; Ross, 2017; Smith and Dressler, 2020). Numeration, then, provided the basis and impetus for "improvement," while also denigrating traditional techniques not intent on maximising profits.

The metrology—the system of measurement—inherent to this conceptualisation of improvement encouraged taking civic censuses (Cavada, 1876; Census of 1903, 1905; Census Office of the Philippine Islands, 1920, hereafter Census of 1918, 1920). The U.S. regime in particular was dependent upon routine national censuses as well as non-compulsory statistical reports to measure "agricultural improvement", a fact reflected in the immediate taking of a civic census, which included agricultural data, in 1903 upon the conclusion of U.S. military rule in the islands (Census of 1903, 1905). However, the first ecclesiastic and civic censuses in the Philippines were undertaken during the Spanish period. These censuses were taken semi-routinely and their agricultural data was often incomplete or unreliable (Cavada, 1876; Census of 1903, 1905; Gealogo, 1998 and 2011; Supplementary Notes). However, they did use the data gathered to calculate productive yields, characterise Philippine agriculture as "underperforming", and propose solutions (Cavada, 1876). Thus, both regimes increasingly understood Philippine agriculture through productive yields and the emerging metrology of commercial agriculture, and both relied on censuses to assess progress towards "improving" Philippine agriculture. While overlapping approaches to agriculture between the two regimes have been discussed in environmental, socio-economic and demographic histories (e.g. May, 1980; McCoy and de Jesus, 1982; Bankoff, 2007a and 2013), the recent proliferation of digitised copies of the censuses and open-access geo-analytical tools like QGIS permit novel and rapid analysis of voluminous datasets. This newly-utilisable data, in conjunction with qualitative archival material and historical scholarship, can now be used to quantify and compare changes in land use, production and yields associated with colonial policies throughout the Philippine Archipelago. Simultaneously, that same data can be integrated with ongoing ecological research to more precisely detail past human-environment interactions at scales ranging from small islands and provinces to the entire Earth System.

This paper analyses civic censuses, annual agricultural reports, and educational publications from both the late Spanish and early U.S. colonial periods to extract statistical information on the changing land use, production and yield of commodity crops in the Philippines between 1870 and 1925 CE. Using datasets from the 1903 and 1918 censuses, and internal governmental reports provided to Vice Governor Joseph Ralston Hayden (Hayden, n.d., hereafter the JRH papers) for the years 1903, 1910, 1915 and 1920–25, we establish how land use, production, and yields shifted throughout the early U.S period. Since the late Spanish period lacked comparably reliable and thorough statistical counts (see Supplementary Notes), we analyse agricultural manuals from both colonial periods to deduce how production and yields changed in the late Spanish period. This analysis serves two purposes. First, it provides an environment-centric and quantitative history that assesses whether colonial states' own censuses indicate progress towards the agricultural "improvement" they sought, complementing and building on the well-developed body of socio-economic research on this period. Second, it assembles historical agricultural data in a quantified format compatible with contemporary ecological and Earth System research, setting a framework for future collaborative work and indicating regions where further research is needed.

Methods

Censuses and the Joseph Ralston Hayden Papers. Agricultural data for the Philippine Archipelago in both colonial periods were gathered from the JRH papers located at the Bentley Historical Library in Ann Arbor, Michigan and the Censuses of 1903 and 1918, which were digitally available via HathiTrust. The JRH papers, official documents assembled by the Division of Farm Statistics of the Bureau of Agriculture, reported national land use and production for more than two dozen crops and agricultural products in the years 1903, 1910, 1915 and 1920–25, as well as provincial data for 1925. The censuses of 1903 and 1918 reported provincial and national-scale land use and production for their respective years.

Table 1 List of crops, their associated agricultural products, and the units in which products were reported in censuses and statistical reports in the U.S. and Spanish periods.

Crop	Product(s)	Reported units of production
Rice	*Palay*	Hectolitres, Cavanes, Kilograms
Sugarcane	Granulated Sugar	Kilograms
	Molasses	Litres
	Basi	Litres
Corn	Corn	Hectolitres, Cavanes, Kilograms
Abacá Plants	Abacá	Kilograms
Coconut trees	Nuts	Nuts
	Copra	Kilograms
	Coconut oil	Litres
	Tuba	Litres
Tobacco	Tobacco	Kilograms
Cacao	Cacao	Litres, Kilograms
Coffee	Coffee	Litres, Kilograms

Data transcription, selection and preparation. All quantitative datasets presented were transcribed in Microsoft Excel. This data is made available in the Supplementary Material. In both the Censuses of 1903 and 1918, there were occasional disagreements between provincial-scale tables, which are highlighted in our datasets. To minimise these discrepancies' impact, we only transcribed and analysed data found in tables in the 1918 Census that compared provincial land use and production in 1903 and 1918.

Due to scarcity of data, as well as the varying quality of the earliest census and statistical reports (Supplementary Notes), some crops were excluded from analysis. Crops that were not reported at all three timepoints—1903, 1918 and 1925—were not considered. Items whose production could not be expressed in kilograms based on available data were also excluded from consideration (Table 1). Further, items whose land use across the islands totalled <5000 hectares were not analysed, with the exception of coffee and cacao due to the emphasis placed on both items in the censuses and JRH papers. Ultimately, these criteria disqualified bananas, cotton, mandarins, oranges, cassava, *ube* (yams), *gabi* (taro), mango, maguey, lumbang, peanuts, castor bean, kapok, pomelo, pineapple, papaya, pili nuts, lanzones, tugui and rubber from analysis. *Kamote* (sweet potato) was also excluded because it was severely under-reported in 1903, despite meeting our other criteria (see "Sulu" in Supplementary Datasheets).

Because the aforementioned comparative tables in the 1918 Census presented data from the Census of 1903 in accordance with provincial boundaries in 1918, we were able to account for most historic changes to internal boundaries without adjusting transcribed data. To reconcile the 1918 Census's comparative tables with the JRH papers, small adjustments had to be made to both datasets. The 1918 Census reported land use and production in several sub-provinces and two cities not included in the JRH papers. In these instances, reconciliation required sub-provinces'

Abbreviation	Province
BTS	Batanes
ILN	Ilocos Norte
CAG	Cagayan
ILS	Ilocos Sur
ABR	Abra
MTN	Mountain
ISA	Isabela
LUN	La Union
NVI	Nueva Vizcaya
TAY	Tayabas
PAN	Pangasinan
NEC	Nueva Ecija
ZAM	Zambales
TAR	Tarlac
PAM	Pampanga
BUL	Bulacan
BAT	Bataan
RIZ	Rizal
CAV	Cavite
LAG	Laguna
BTG	Batangas
ACS	Ambos Camarines
MIN	Mindoro
MAR	Marinduque
ALB	Albay & Catanduanes
SOR	Sorsogon
ROM	Romblon
MAS	Masbate
SAM	Samar
PAL	Palawan
ANT	Antique
CAP	Capiz
ILO	Iloilo
NOC	Negros Occidental
NOR	Negros Oriental & Siquijor
CEB	Cebu
BOH	Bohol
LEY	Leyte
SUR	Surigao
ZMB	Zamboanga
MIS	Misamis
AGU	Agusan
LAN	Lanao
BUK	Bukidnon
COT	Cotabato
DAV	Davao
SUL	Sulu

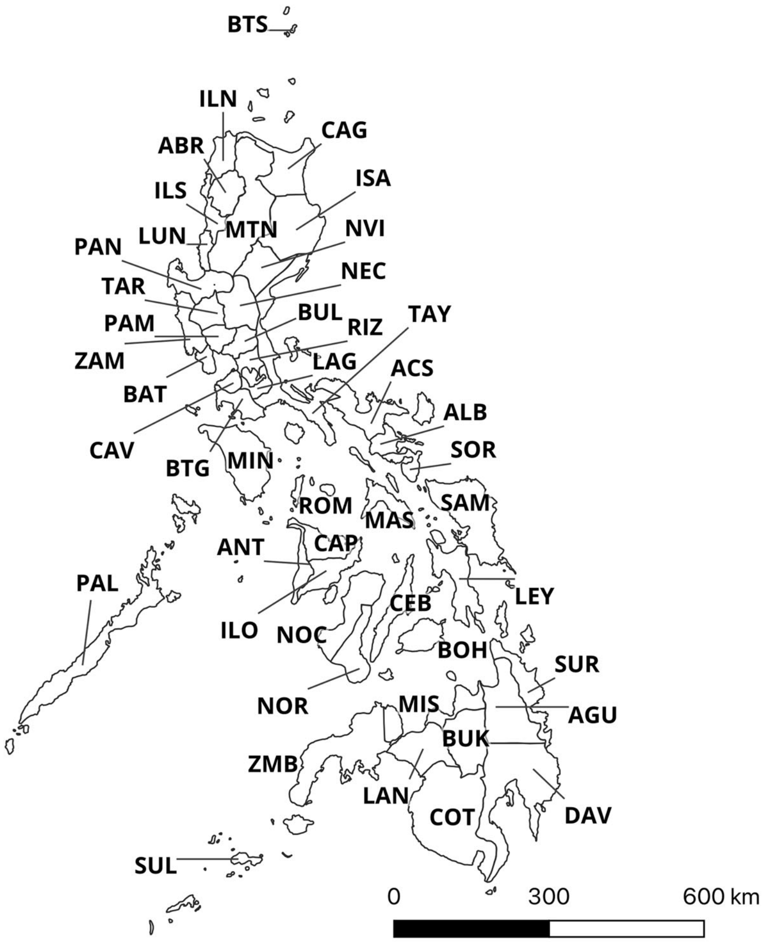

Fig. 1 Map of Philippine Provinces. *All provincial boundaries are drawn as described in the Census of 1918 (1920).*

reported land use and production be added to their provinces' data. Similarly, the JRH papers reported data for Camarines Norte and Sur, two provinces formed from splitting Ambos Camarines. Again, adding data for the two provinces together reconciled the JRH papers and 1918 tables. However, while relying on the comparative tables, we were unable to fully account for substantial changes to provincial boundaries in Mindanao and Luzon's Cordillera region. In Mindanao, the "Moro Province" that comprised nearly two-thirds of the island in the first decade of U.S. rule was separated into several smaller provinces, and no agricultural data from 1903 is available for three of these. Nonetheless, these provinces were included in our provincial-scale analysis (Fig. 1). Boundary changes in Luzon's Cordillera were too frequent and substantial to be addressed, and the region was therefore excluded from analysis at all timepoints. Lastly, we were unable to account for small adjustments to the provincial boundaries of Ilocos Sur, La Union, Cagayan, Pangasinan, Zambales, Nueva Vizcaya and Misamis made between 1903 and 1918. These changes, which mainly involved switching settlements between provinces, were insufficient to preclude comparison across timepoints (for additional detail, see Supplementary Notes).

Lastly, prior to analysis, all relevant production data were converted to kilograms. Products such as rice, cacao, coffee and corn were reported in hectolitres or litres in the censuses. The JRH papers reported all solid-form products in kilograms, including data gathered from the 1903 Census, which provided us with conversion factors for these products. For crops like coconut trees and sugarcane, which produce several saleable products such as molasses, *basi* (a sugar-based spirit), nuts, coconut oil and *tuba* (coconut wine), we only analysed data for solid-form products that were reported in kilograms: granulated sugar for sugar cane and copra for coconut trees (see Table 1).

Data analysis. Land use and production data for the entire archipelago as well as all provinces were used to calculate productive yield in kilograms per hectare at the national and provincial scale. Additionally, we calculated the average annual growth rate of each crop's land use and production in each province for the intervals 1903–1918 and 1918–1925.

Non-quantitative publications, reports and Farmers' Bulletins. Historical analysis is influenced by prevailing social, cultural, economic and intellectual currents. To minimise subjectivity, our analysis emphasises the arrangement of information in colonial-era documents, the problems they aim to redress, and their underlying rationale and justification, all of which is analogous to the scientific "paradigm" that informs each publication (Kuhn, 1996). Thus, when comparing documents from both colonial periods, we search for thematic and structural convergence or disagreement. This approach emphasises how knowledge is sought, created and presented rather than the technical advancements made between publications, and is therefore especially useful when comparing scientific documents published decades apart.

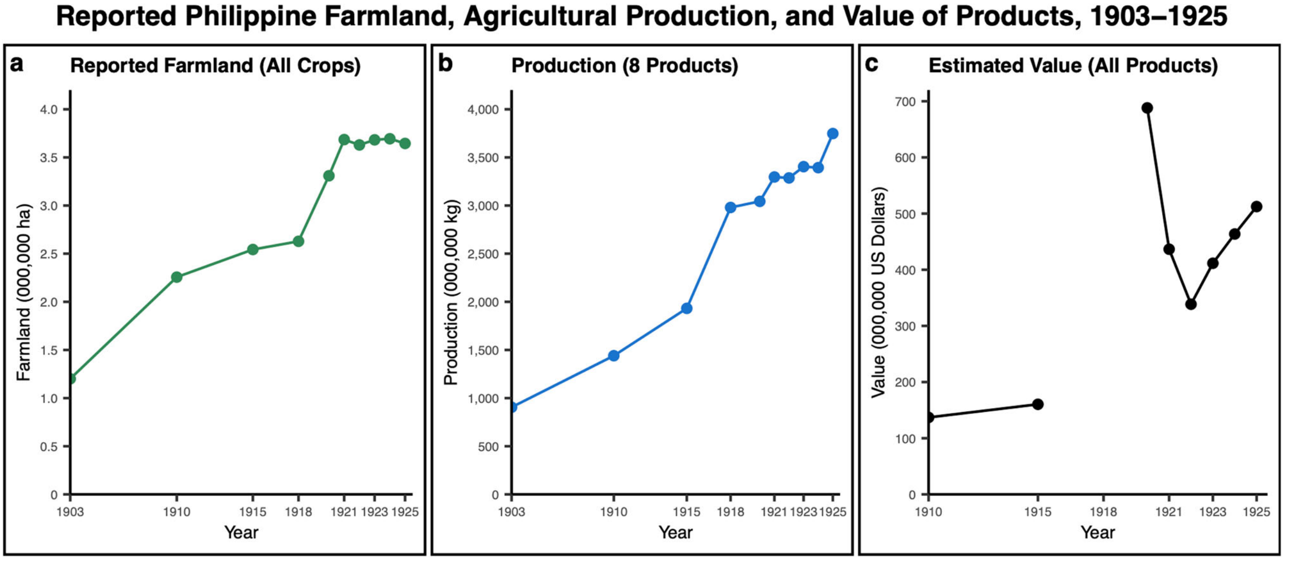

Fig. 2 Philippine Land Use, Agricultural Production, and the Estimated Value of Agricultural Products in the Early U.S. Period, 1903–1925. **a** Reported farmland planted to all crops in hectares. **b** Reported agricultural production for the eight items that could be measured in kilograms and are displayed in Table 1. **c** Estimated value of all agricultural products reported in the JRH Papers. Value estimates are not given in the 1903 or 1918 censuses and are not available for these years. All data presented was transcribed from the Censuses of 1903 and 1918 as well as the JRH Papers.

We apply this method to the first volume of the *Agricultural Review* as well as the first 16 volumes of the *Farmers' Bulletin* manuals, all of which were digitised by HathiTrust and were physically available at the Hatcher Graduate Library in Ann Arbor, Michigan. We also study the article-length Spanish period manuals *Cultivo del cacao y café* and *Memoría de la cultivación de azúcar*, both of which were available through the Worcester Collection at the Hatcher Graduate Library. These documents were either published directly through government offices (i.e. the Bureau of Agriculture) or through groups closely aligned with colonial authorities (such as the Real Sociedad Económica de Amigos del País de Filipinas).

Map-making. To create Figs. 1 and 4, a digital scan of John Bach's 1929 map of the Philippine Islands was acquired from the National Library of Australia and georeferenced in QGIS. 126 points were georeferenced and fitted using a 2nd Order Polynomial, and the separate provinces of Camarines Norte and Sur were merged.

Results

Early U.S. Period, National Scale Land Use. According to the censuses and JRH papers, Philippine agricultural land increased from ~1.2 million hectares (ha) to ~3.6 million ha between 1903 and 1925 (Fig. 2). Cultivated land tripled between 1903 and 1921 and then oscillated between ~3.6 and ~3.7 million ha until 1925. Agricultural land use grew fastest between 1903 and 1910 as the archipelago recovered from the effects of the Philippine-American War, which temporarily depressed cultivation by as much as 20% (McCoy and de Jesus, 1982). In this period, six crops accounted for 93% to 99% of all reported land use: rice, sugarcane, corn, coconut trees, abacá plants, and tobacco (Fig. 3a). From 1903 to 1925, rice was the most commonly planted crop, and its land use increased 191%. Over the same period, land planted to corn increased 218%, coconut trees increased 233%, sugarcane increased 119%, abacá plants increased 384% and tobacco increased 128%.

The remaining 1%–7% of cultivated land grew a variety of crops, only some of which received consistent attention from colonial authorities. Coffee and cacao farming were meticulously recorded in the censuses and JRH papers, despite neither crop occupying more than 0.2% of Philippine fields in any given year. Both were likely included in the censuses due to their past or potential commercial value (Clarence-Smith, 2000; Topik, 2009). Coffee, prior to an outbreak of blight in the last years of the nineteenth century, was one of the archipelago's largest exports (Sastrón, 1895; Castro, 2003). Philippine cacao never achieved coffee's prominence in the international market, and it was mostly grown to satisfy local demand (Clarence-Smith, 2000). Notably, unlike the six major crops, land use for coffee and cacao decreased by 7% and 60%, respectively, between 1903 and 1925. Lastly, the cumulative land use of crops excluded from further analysis (see Methods) is depicted in Fig. 3A as "Excluded Crops." This category exhibited erratic growth between 1903 and 1925, but nonetheless increased by 269% in that interval.

Early U.S. Period, National Scale Production. Multiple products were derived from the eight crops described above (Table 1), but we only analysed agricultural goods whose production could be measured in kilograms (Figs. 2 and 3b). These are *palay* ("rough" or unhusked rice), granulated sugar (or sugar), abacá fibre (or abacá), tobacco, corn, copra (the dried flesh of coconuts), cacao and coffee. Production of all eight increased between 1903 and 1925: *palay* production grew 298%, corn production grew 377%, copra production grew 746%, granulated sugar production grew 292%, abacá production grew 170%, tobacco production grew 146%, coffee production grew 1270% and cacao production grew 142%.

Production proved highly individualised for each agricultural product and, for several, the year 1918 was exceptional (see Supplementary Notes). Of all eight products, *palay*, copra, and corn experienced the greatest growth. *Palay* production surged from 504 million kg in 1903 to 1.8 billion kg in 1918, momentarily fell in 1920, and then gradually rose to surpass 2 billion kg in 1925. Corn production, in contrast, surged from 1910 to 1918, reaching an absolute maximum of ~600 million kg in 1918 before decreasing to ~450 million kg from 1923 to 1925. Copra, however, experienced no surge in 1918. Instead, production grew from 43 million kg in 1903 to 210 million kg in 1918 before leaping to 362 million kg in 1920, after which it oscillated between 361 and 387 million kg.

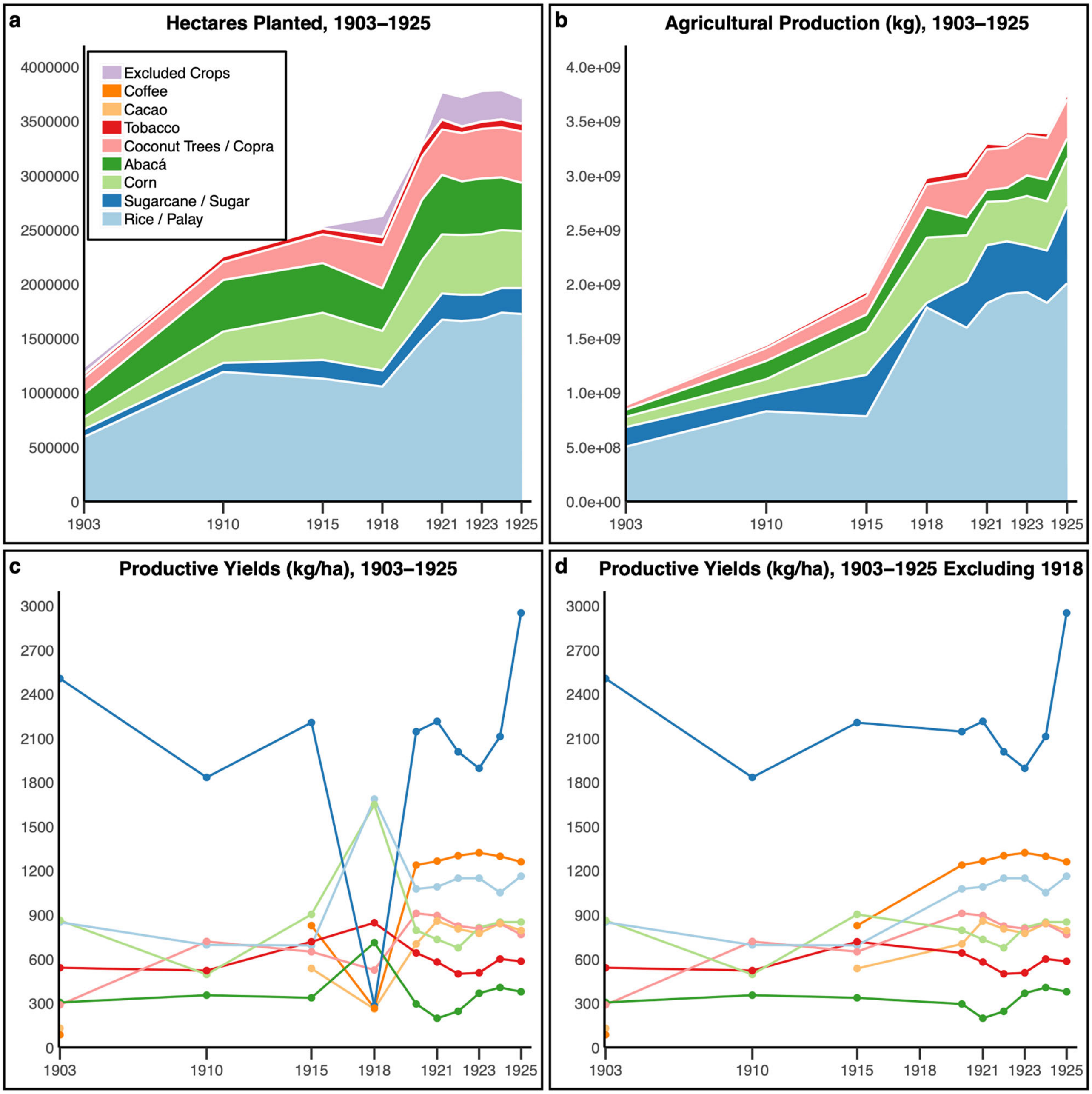

Fig. 3 National-Scale Land Use, Production, and Yield Data for the Philippine Archipelago, 1903–1925. a Area Planted for Major Crops in Hectares for the Philippine Archipelago. **b** Production of Major Agricultural Products in Millions of Kilograms for the Philippine Archipelago. **c** Yields in Kilograms per Hectare for Major Agricultural Products in the Philippine Archipelago. **d** Yields in Kilograms per Hectare for Major Agricultural Products in the Philippine Archipelago, Excluding the Year 1918. The category "Excluded Crops" is the sum total of reported land use for bananas, maguey, sweet potatoes, gabi, cassava, lumbang, castor beans, kapok, mandarins, pomelos, papayas, rubber, ubi, tugui, lanzones, oranges, pineapples and peanuts.

Granulated sugar, tobacco, and abacá production were more volatile. Sugar production decreased between 1903 and 1910, increased to 380 million kg in 1915, and then collapsed to 42 million kg in 1918—likely due to sugar mosaic virus (Asuncion, 1925; Abbott and Tippett, 1966). National production recovered by 1920, fluctuating between 400 and 500 million kg until 1925, when production reached a maximum of 710 million kg. Abacá production also vacillated, surging from 67 to 280 million kg between 1903 and 1918 before declining to 110 million kg in 1921. Production partially recovered afterwards, oscillating between 180 and 200 million kg between 1923 and 1925. Similarly, tobacco production rose from 17 million kg in 1903 to a maximum of 65 million kg in 1920. By 1922, production had decreased to 30 million kg and eventually stabilised between 1924 and 1925 at 42 million kg.

Cacao and coffee production were orders of magnitude smaller, but experienced consistent growth in this period. Cacao production increased from 459,000 kg in 1903 to 1.1 million kg in 1922 and then vacillated between 1.0 and 1.2 million kg until 1925. Coffee production, previously devastated by disease, soared from 86,000 kg in 1903 to 1.1 million kg in 1921 and 1.2 million kg in 1925.

Early U.S. Period, National Yields. Most products' yields (Fig. 3c) fluctuated between 1903 and 1925 rather than exhibiting clear growth. 1918 was an exceptional year for several agricultural goods, producing the highest reported *palay*, corn and abacá yields and the lowest sugar and cacao yields. These abnormal yields may be attributable to crop-specific factors like the sugar mosaic virus or may have resulted from external factors like natural hazards or the unique market conditions created by WWI. The latter would have permitted lower-quality goods to be profitably grown and sold and may thereby have momentarily increased production per hectare (Golay, 1997). Alternatively, higher production in 1918 may reflect differences in data collection between the mandatory civil censuses and reports made by the government's Statistics Office (Supplementary Notes). If data from 1918 are excluded from analysis (Fig. 3d), a clearer picture of productive yield emerges. Coffee, cacao, copra and *palay* yields all increased between 1903 and 1925. Corn, tobacco, abacá and sugar yields did not increase, instead oscillating within a fixed range, although each product reported exceptional years.

Abacá and tobacco yields exhibited the greatest stability between 1903 and 1925. Abacá yields fluctuated between 306 and 407 kg/ha, only falling beneath 300 kg/ha from 1920 to 1922. Tobacco yields exhibited similar behaviour, with yields oscillating between 500 and 601 kg/ha except from 1915 to 1920, when yields repeatedly exceeded this range. Corn and sugar exhibited greater volatility. Corn yields decreased 1% between 1903 and 1925, swinging from 496 kg/ha in 1910 to 904 kg/ha in 1915 and then ranging between 677 and 852 kg/ha. Sugar's reported yields fluctuated between 1897 and 2507 kg/ha from 1903 to 1924 before reaching a new high of 2953 kg/ha in 1925. Among the products whose yields increased, coffee experienced the greatest growth. Its yield increased 1,365% between 1903 and 1925, rising from 83 to 1239 kg/ha in 1920 and then shifting between 1261 and 1323 kg/ha. Cacao's yield followed a similar trajectory, growing 509% in the early U.S. period from 130 kg/ha to 859 kg/ha in 1921, after which it swung between that value and 775 kg/ha. Copra's yield grew 166% between 1903 and 1925, increasing from 289 kg/ha in 1903 to ~903 kg/ha in 1920–1921 before oscillating between 767 and 841 kg/ha until 1925. Lastly, *palay's* yield increased 37% in the early U.S. period, reporting yields between 693 and 851 kg/ha until 1920, after which yields undulated between 1052 and 1164 kg/ha.

The observed increases in yields for coffee and copra likely did not result from colonial interventions. As previously mentioned, commercial coffee production was decimated by disease in the late Spanish period. Increases in its yield are largely attributable to the outbreak's wane, while the observed decrease in coffee planting suggests colonial managers and farmers alike took little interest in the crop. As for copra, increases in its yield are largely attributable to how government reports calculated coconut and copra production. Both came from the same trees, so both had the same reported land use. However, between 1903 and 1918 the emphasis of production shifted from nuts (for food) to copra. In that period, total coconut tree farmland increased 166%, but total nut production fell 33%. In the same interval, copra production grew 390% (Census of 1918, 1920: 366–367) whereas copra yields grew 82%, suggesting a shift in production may account for the majority or entirety of the observed increase in copra yields. In contrast, gains in *palay's* and cacao's yields cannot be attributed to disease, counting conventions, or external factors.

Early U.S. Period, Provincial-Scale Data. In the sources consulted, provincial scale data was available for the years 1903, 1918 and 1925. As discussed in the Methods, we excluded Mountain Province from analysis, and data from 1903 was unavailable for the Batanes Islands as well as Mindanao's Lanao, Bukidnon and Agusan provinces, which in 1903 were part of "Moro Province." These exclusions aside, provincial-scale land use and production data for the eight aforementioned crops in the early U.S. period were assembled at all timepoints for 41 provinces and sub-provinces (Fig. 4).

Agricultural land use and production increased in all provinces, but gains were unevenly distributed. Likewise, the rates at which land use and production grew in each province and region were non-uniform, speaking to differing degrees of ecological transformation. Land use grew fastest in Mindanao, with provinces like Davao reporting average annual growth of 43% between 1903 and 1918. However, provinces in Mindanao also reported some of the lowest total land use in the entire archipelago. Conversely, provinces in Luzon, Panay and Cebu routinely reported the largest total land use—agricultural land in both Pangasinan and Cebu exceeded 200,000 ha by 1925—but also registered the lowest annual growth rates (see Supplementary Data). In all islands and provinces, growth in land use was driven primarily by one or two crops, suggesting increasing agricultural specialisation at the provincial scale over time.

Differential growth rates as well as regional specialisation in production were sufficient to skew national scale data. For instance, Pangasinan in 1918 reported an unprecedentedly productive year, generating ~594 million kg of *palay* from ~122,000 ha of farmland (an incredible yield of 4,872 kg/ha, more than double the expected maximum yield for rice prior to the Green Revolution; see Bray, 1994; Greenland, 1997). This amounted to 33% of all *palay* produced in the Philippines that year and caused an abrupt rise in *palay's* yield at the national scale (Fig. 3C). Other agricultural products' abnormal performances in 1918 may also be attributed to relative surges or collapses in production in specific provinces (Fig. 4). The suddenness and severity of those oscillations affirms that provincial scale yields must be directly assessed to confirm national scale trends. These oscillations also emphasise the now well-studied vulnerabilities of geographically specialised monoculture to external and localised disruptions such as diseases or natural hazards (Warren, 2016).

Early U.S. Period Productive Yields at the Provincial Scale. To demonstrate how yields changed across provinces during the early U.S. period, Fig. 5a–k plot all provinces' production as a function of their reported land use in 1903, 1918 and 1925. Figure 5a depicts *palay* production and land use for all provinces, while Fig. 5b, c graph the same relationship for the ten provinces that produced the greatest amount of *palay* at each timepoint. Figure 5c excludes Pangasinan at all timepoints due to its abnormally high production in 1918. The figures indicate all provinces, excepting Pangasinan, exhibited a strong, linear relationship between reported land use and production, especially the most productive provinces. *Palay's* productive yield appears to have grown significantly between 1903 and 1918, but not after. However, the three graphs confirm that these gains were minor relative to the massive expansion of paddy land. Extraordinary growth in *palay* production, then, was primarily owed to expansion complemented by modest gains in yield across multiple provinces.

Assessment of the other seven agricultural products (Fig. 5d–i) largely confirms trends seen at the national scale. Corn (Fig. 5d) exhibited no sustained growth in productive yield between 1903 and 1925, particularly once Cebu's extraordinary performance in 1918 is excluded from consideration. Likewise, abacá and tobacco (Fig. 5e, f) showed no appreciable or sustained change in yield in this period. Data for sugar (Fig. 5g) is inconclusive as this crop's yield was severely reduced in multiple provinces in 1918 due to disease. Data for copra (Fig. 5h), cacao (Fig. 5i) and coffee (Supplementary Fig. S5) all indicate sustained, clear and relatively large gains in productive yield across provinces in the early U.S. period. Copra yields increased over time with the largest gains transpiring between 1918 and 1925, likely due to factors discussed above. Cacao and coffee exhibited more erratic production

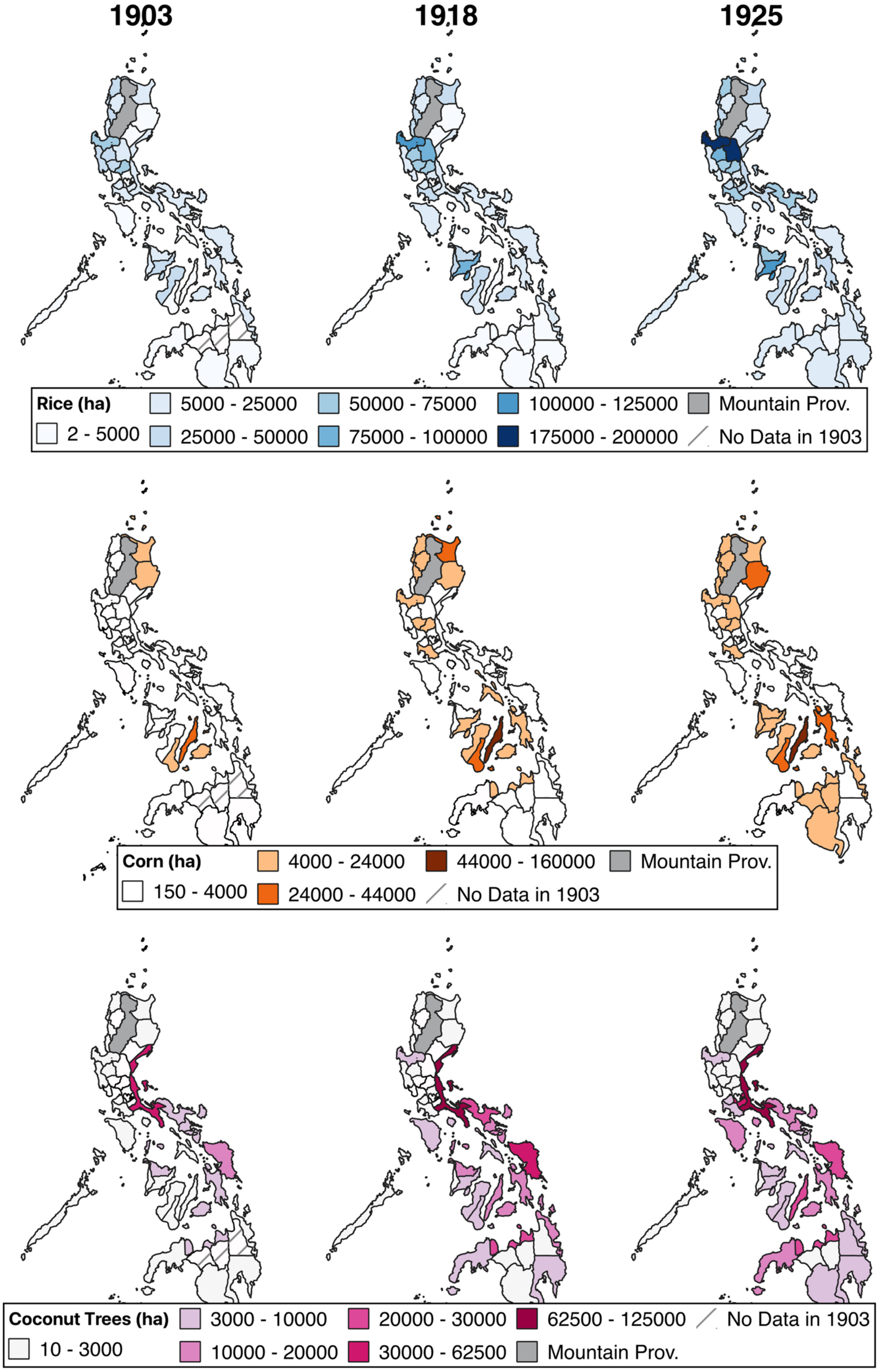

Fig. 4 Provincial-Scale Land Use Mapped by Province in 1903, 1918 and 1925 for Rice, Corn and Coconut Trees. Maps for Sugarcane, Tobacco and Abacá are included in the Supplement as Figs. S2–S4. Note that minor boundary shifts made to Pangasinan, Zambales, Ilocos Sur, La Union, Cagayan, Nueva Vizcaya and Misamis between 1903 and 1918 cannot be accounted for from census and statistical data (see Methods), but these changes do not prevent analysis. Data is not available for Agusan, Bukidnon and Lanao in 1903. Substantial boundary changes to Mountain Province mean it cannot be analysed at any timepoint (see "Methods" section).

relative to land use, particularly in 1903 due to blight and disruptions caused by the Philippine-American War. Nonetheless, their yields clearly increased during the early U.S. period, with coffee showing massive gains as the aforementioned blight subsided.

Late Spanish Period, quantified data. No census or statistical document from the late Spanish period is directly comparable to the U.S.-era censuses. Ecclesiastic censuses detailing parishes' annual baptisms, deaths and marriages provided colonial administrators a valuable, but imperfect, proxy for understanding

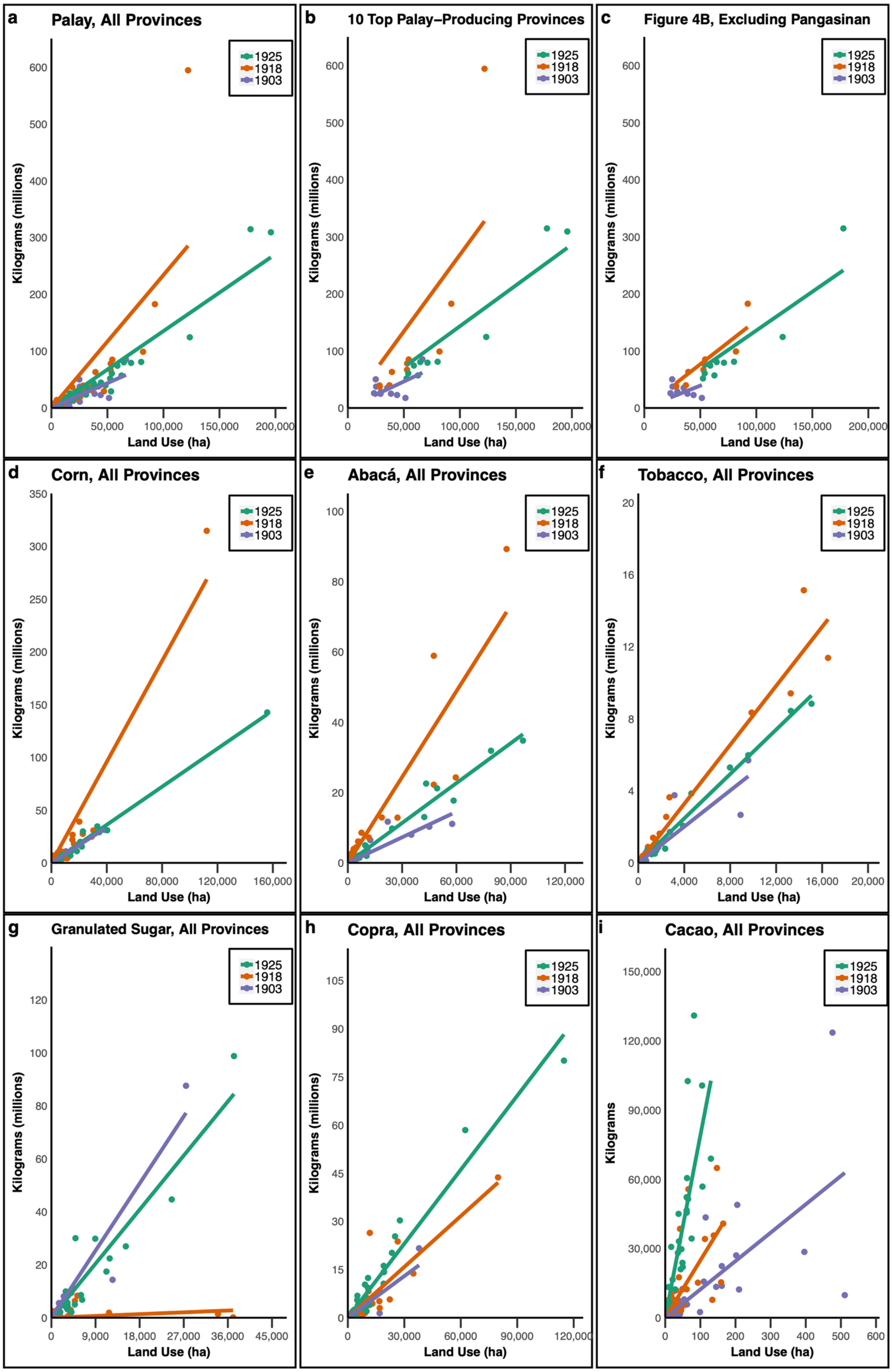

Fig. 5 Provincial-scale production compared to land use in the years 1903, 1918 and 1925. **a** *Palay*, All Provinces. **b** *Palay*, 10 Most Productive Provinces; (**c**) *Palay*, 10 Most Productive Provinces Excluding Pangasinan. **d** Corn, All Provinces. **e** Abacá, All Provinces. **f** Tobacco, All Provinces. **g** Granulated Sugar, All Provinces. **h** Copra, All Provinces. **i** Cacao, All Provinces. Linear Regression best-fit lines for 1903, 1918 and 1925 have the following R^2 values for each figure: (**a**) 0.806; 0.682; 0.934; (**b**) 0.821; 0.736; 0.955; (**c**) 0.761; 0.958; 0.935; (**d**) 0.962; 0.911; 0.989; (**e**) 0.861; 0.869; 0.977; (**f**) 0.844; 0.962; 0.990; (**g**) 0.933; 0.653; 0.885; (**h**) 0.789; 0.819; 0.967; (**i**) 0.592; 0.671; 0.830.

regional populations and predicting tax revenues (Cullinane, 1998; Gealogo, 2011). However, these ecclesiastic accounts did not regularly provide quantified data on agricultural production or land use. That began to change in the late 19th century as agriculture became of greater interest to colonial administrators (Buzeta and Brave, 1851; Cavada, 1876). The first civic census of the Philippines, an item comparable to the U.S.-era censuses in intent, design and organising principles, was the *Historia geo-gráfica, geológica, y estadística de Filipinas* authored by Agustín de la Cavada y Vigo de Mendez and published in 1876. Although his civic census quantified agricultural production for several major crops, it did not offer similarly complete reports of land use. Furthermore, the land use data presented was copied in large part from numbers reported in the 1870 Ecclesiastic Census, and much of Cavada's data, by his own admission, is incomplete (1876). After the *Historia* was published, agricultural data became increasingly common and reliable in official guides and subsequent accounts of the islands but often remained incomplete or partially based on rumour and hearsay (see Moya y Jimenez, 1883, Montero y Vidal, 1886; Puya Ruiz, 1887; Foreman, 1890; Millán y Villanueva 1891). Given the variable quality of the data, direct comparison of Spanish-era agricultural statistics to information found in U.S. censuses is not possible.

Comparisons between the two periods, then, must rely on proxies, the most accessible of which is export data from Spanish-era customs houses reported in the Census of 1903 (reproduced in Fig. 6). Customs house records only include the most common exports of the late Spanish period: granulated sugar, abacá, tobacco, coffee, indigo and tintarrón (a liquid dye). These records do not provide provincial-scale data, but research by de Jesus (1980), Larkin (1993), Legarda (1999) and Owen (1984) confirms sugar, tobacco and abacá production were concentrated in the same regions as in 1903. Coffee cultivation was largely confined to Batangas Province near Taal Lake and indigo cultivation primarily took place in the Ilocos region of northwest Luzon (Census of 1903, 1905). Figure 6 shows that all exports, while subject to some variation, increased between 1870 and 1890. After 1890, coffee exports collapsed due to blight; tobacco, indigo and tintarrón exports held relatively constant after 1892; and sugar and abacá exports exhibited continuous growth, reaching their absolute maxima of ~341 and ~107 million kg, respectively, in 1895.

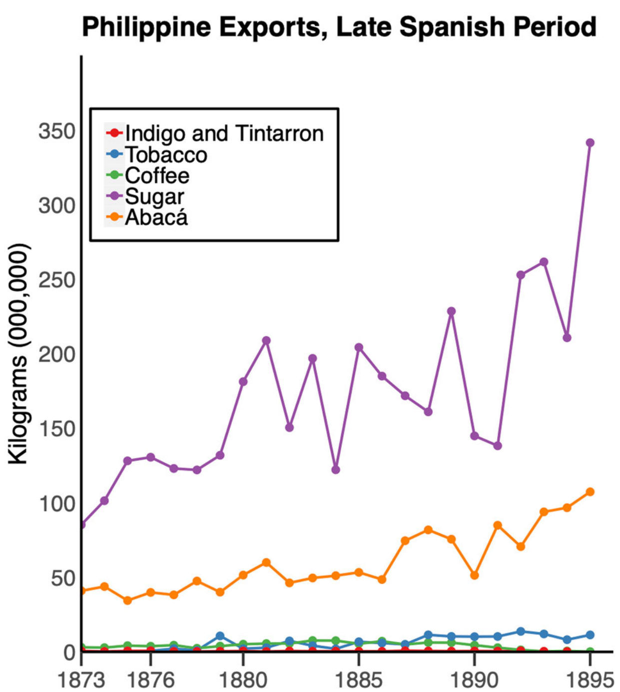

Fig. 6 Philippine Agricultural Exports in the Late Spanish Period. Data reported in the Census of 1903, based on records retrieved from Spanish export houses. For discussion of the reliability and accuracy of these official records, see Supplementary Notes.

Customs records give no data on land use or yields. However, historical research drawing upon difficult-to-access archival documents indicates that increased sugar and abacá production in the late Spanish period was primarily driven by expanding land use (Owen, 1984; Larkin, 1993). Implied is that, much akin to the early U.S. period, gains in productive yield for these exports were insignificant. Given the lack of other readily available, quantified proxies, further insights on land use, production, and yields in the late Spanish period must be derived from qualitative sources like government-produced farmers manuals, which detail the changes colonial administrators envisioned as essential to "improving" Philippine agriculture.

Late Spanish and Early U.S. Period Farmers' Manuals. Comparison of farmers' manuals produced between 1870 and 1925 can identify changes in the "best practices" colonial authorities promoted. Publications analysed here include several issues of the *Farmers' Bulletin* (1902–1910), a magazine published by the US Bureau of Agriculture in the Philippines to assist in the cultivation of commercial crops and foodstuffs; *Memoria Sobre el Cultivo, Beneficio y Comercio de Azúcar* (Gutierrez Creps, 1878), a nearly 80 page treatise on best practices for sugar cultivation produced as part of a competition held by the "Real Sociedad Económica de Amigos del País de Filipinas"[56]; and *Cultivo del Cacao y Café* (Patero and Changco, 1872), two forty-page descriptions of strategies for planting cacao and coffee in the Philippines published as a single book. We compare sources' self-rationalisation, how they present information, and their prescribed remedies for Philippine agriculture. By focusing on these themes, we minimise the subjectivity of our analysis while emphasising shifts in thinking (or "paradigms", as in Kuhn, 1996).

Manuals in both periods assumed Philippine agriculture would be vastly improved through the rigorous application of scientifically derived best practices, as established by European and US researchers. The manuals' impact on Filipinos, who comprised the vast majority of landowners and farmers, in the late Spanish period was limited by both the linguistic diversity of the islands and low literacy rates. In the early U.S. period, the implementation of a national education system in English lowered these two barriers substantially over time (Miller, 1911; Schueller, 2019). Manuals in both periods were also designed to partially overcome these impediments as evidenced by authors tailoring their works towards well-educated Filipino smallholders and landlords, particularly those in the Manila region. *Cultivo del cacao y café* was authored by Santiago Patero in Spanish and was translated to Tagalog by Vincente Changco, with text in both languages arranged in parallel columns on each page (1872), while several manuals of the *Farmers' Bulletin* were published in Spanish and English (e.g., Boudreau, 1904). These attempts at outreach suggest both regimes saw manuals as a way to influence bourgeois landowners' behaviour, likely with the expectation that changes would percolate to sharecroppers.

Manuals from both periods described cultivation as a step-by-step process. Comparing *Memoria sobre el cultivo, beneficio, y comercio de azúcar* with the first issue of *Farmers' Bulletin*, "A Primer on the Cultivation of Sugar Cane", typifies the template both manuals used. Their similar formats were used to convey similar advice. Both stress the importance of selecting good land

and agree the best soil is aerated, porous humus. Both underscore the importance of constant weeding and selecting for varieties of cane that produce the most valuable product. And, when discussing how to maintain high productive yields, both describe at length the disadvantages of Philippine shifting cultivation ("caingin" in texts; see Olofson, 1980) and the profitability of consistently applying fertiliser. This point of focus deserves further analysis since both manuals describe the repeated burning of forests and the resting of fields as wasteful and "idleness" (Gutierrez Creps, 1878: 43; Lyon, 1904: 9). To end "wasteful" practices, they provide instructions on creating and applying fertilisers made from domestic animal and plant waste, guano and inorganic compounds—*Memoria* offers ten pages of advice on manufacturing and applying fertiliser while expounding on its benefits (Gutierrez Creps, 1878; Lyon, 1904). Overall, the manuals' shared format and overlapping instructions underscore their shared assumption: that farmers' ignorance is the problem.

The manuals' proposals for raising production, meanwhile, are suggestive of the similar approaches both regimes employed, which has implications for yields in both periods. The Spanish-period manual, *Memoria*, advocated for the creation of an agricultural bank, the lowering of customs fees for Philippine sugars, mechanising refining processes whenever possible, and using model farms to develop and promote new ways of cultivating sugarcane (Gutierrez Creps, 1878). Many of these policies could not be implemented by cash-strapped Spanish administrators, but were adopted in the early U.S. period. The U.S. colonial regime established agricultural banks, lowered sugar tariffs, and provided loans to modernise sugar mills (Larkin, 1993). However, these changes failed to improve sugar yields before 1925, as our analysis indicates. Yields' failure to improve in the early U.S. period and the manuals' similar prescriptions imply that sugarcane cultivation did not markedly change between 1870 and 1925, and therefore yields would have been consistent across both periods (on sugar milling and refining, see Supplementary Notes and Table S1). Since other crops whose yields did not change during the early U.S. period—abacá, tobacco and corn—received less financing than sugar and experienced minimal mechanisation (Miller, 1911; Supplementary Notes), it is likely that their yields also did not markedly change in the late Spanish period.

Manuals also provide insights on products whose yields increased in the U.S. period. The lack of a coffee manual among the analysed volumes of *Farmer's Bulletin* confirms U.S. administrators' lack of interest in the former export crop, while the manual detailing coconut cultivation emphasises the newness of the copra industry and the relative lack of known best practices for monoculture (Lyon, 1905). As for cacao, comparing *El cultivo del cacao y café* and its counterpart in *Farmers' Bulletin*, "Cacao Culture in the Philippines", indicates Spanish-era cultivation strategies may have been more conservative. *Cultivo* advises readers that cacao cultivation in the Philippines is very difficult owing to strong winds, that it should be supplemented with coffee plantations, and that certain plants should be used to shelter cacao from typhoons and gales (Patero and Changco, 1872). "Cacao Culture", though, does not warn readers against typhoons, does not advise using coffee to supplement cacao, and suggests replacing non-commercial sheltering trees with abacá to improve profits (Lyon, 1902). This amounted to a "high-risk, high-reward" strategy where farmers could profit from cacao as long as no typhoons or strong storms struck their fields. Whether those suggestions were implemented, were successful, or caused cacao yields to increase after 1903 is unclear at present.

Of particular interest is how the *Farmers' Bulletin* discussed *palay*, by far the largest agricultural product by volume and land use. The *Bulletin's* "Modern Rice Agriculture" is unique among the series, reflecting the U.S. Bureau of Agriculture's familiarity with rice following the establishment of a thriving commercial rice industry in Louisiana in the 1870s–1890s (Boudreau, 1904). To improve production, the bulletin recommended adapting several mechanical threshers and ploughs previously developed for the bayous to Philippine wetlands. However, due to high costs and the socio-economic circumstances surrounding rice cultivation in the Philippines, most of these machines were not adopted (O. Corpuz, 1997). The pamphlet also recommended that planters grow *japonica* (short-grain) rice, which was more amenable to U.S. machinery and had a higher yield than the *indica* (long-grain) varieties commonly grown in the Philippines (Boudreau, 1904). These arguments would not have been compelling to smallholders who lacked machinery or grew rice for subsistence and its taste rather than profit (Corpuz, 1997; Kerkvliet, 2002). The pamphlet's final, and likely most impactful, recommendation was to develop Philippine irrigation. Widespread irrigation, it was hoped, would allow for two rice harvests per year while expanding cultivable land. Colonial authorities, investigators and local landholders all advocated for improving irrigation, and the expansions that did take place likely increased production and yields, including in the "rice basket" region of Nueva Ecija, Pangasinan and Tarlac (Boudreau, 1904; Census of 1918, 1920; McLennan, 1980 and 1982). Thus, for this single crop, policies specific to U.S. colonial institutions could have increased yield in ways the comparatively cash-strapped Spanish could not.

Discussion

Our analyses of the late Spanish and early U.S. periods quantify changing agricultural land use at the regional and national scales, permit commentary on the overall success of efforts to "improve" Philippine agriculture, and lay the foundations for historical-ecological research that links quantified human land use to specific environmental changes over time. In the early U.S. period, our results indicate total agricultural land use trebled. This cultivated land was primarily dedicated to growing rice, sugarcane, abacá plants, coconut trees, corn and tobacco. While each crop's total land use increased in the early U.S. period, these increases were not uniformly distributed across provinces and occurred at different rates over distinct spans of time, reflecting both increasing agricultural specialisation in Philippine provinces and the diverse constellations of geographic, socio-economic and cultural factors that characterised disparate regions (McCoy and de Jesus, 1982).

Production, like land use, greatly increased for each crop but also proved more volatile year-to-year. As a result, agricultural yields could exhibit considerable variation from timepoint to timepoint. Nonetheless, our analysis strongly suggests that the yields of granulated sugar, abacá, corn and tobacco did not significantly increase or decrease whereas the yields of copra and *palay* increased. Copra's increased yield is primarily attributable to how the census measured nut and copra production. As for *palay* yields, given that the U.S. initially lacked easily-applied fertilisers for rice fields and struggled to mechanise Philippine rice cultivation, their observed increase is likely owed to the expansion of irrigation, which U.S. administrators expressed strong interest in and Filipino landholders routinely encouraged (Boudreau, 1904; Tecson y Ocampo, 1908c; Census of 1918, 1920).

Quantitative data from the late Spanish period proved less reliable and could not be directly compared to U.S. period datasets. However, the strong similarities between late Spanish and early U.S. policies towards Philippine agriculture, the available quantitative data, and the relative consistency of yields in the early U.S. period all suggest agricultural yields did not increase in the late Spanish period. Spanish records indicate the islands' agricultural exports increased between 1870 and 1895, and previous historical research confirms that increased production of these export crops was primarily driven by expanding land use. Farmers' manuals also suggest cultivation strategies under late Spanish and early U.S. colonial authorities were largely identical, and routine complaints by colonial observers indicate fertilisers—which could have increased production per hectare—were not widely used between 1870 and 1925 (JRH Papers). It must also be noted that early U.S. colonial authorities implemented many of the programmes Spanish colonial observers envisioned for improving Philippine agriculture (see Bankoff, 2011), and these did not substantially increase most agricultural yields between 1903 and 1925. All evidence strongly implies that yields did not increase for any of the major Philippine agricultural products during the late Spanish period.

The failure of yields to increase in both periods raises questions about the efficacy of colonial policies to "improve" Philippine agriculture. The censuses and statistical counts colonial authorities used to track "agricultural improvement"—which, as stated previously, was defined as increased production through decreased "waste" (a.k.a. higher yields) with the end goal of maximising profits—do not show it. Instead, historical data indicate that the overall value of Philippine agricultural goods rose as did total agricultural production (Fig. 2), and that both were primarily realised through massive expansions of agricultural land. While colonial authorities bemoaned the "wastefulness" of this expansion, which replicated low-yield agriculture across an ever-widening region, their main objection was to cleared lands being left fallow (Census of 1918, 1920; JRH Papers). Thus, while it may be argued that colonial policies, including new transport infrastructure and agricultural banks, catalysed agricultural expansion that increased total production and profits, the goal of increasing agricultural yields was not achieved. Whether this means colonial policies to increase yields were not effective, were consistently confounded by factors like disease, locusts and natural hazards (see DeBevoise, 1995), or were never implemented in the vast majority of the Philippines is still to be determined.

The degree to which colonial policies were implemented, and where, would have profoundly affected local ecological transformations. Such changes were also predicated on the types of crops planted, the labour practices employed—e.g., smallholder agriculture, extensive plantations, or supervised convict labour (Larkin, 1993; Ventura, 2022)—and parallel expansions of commercial ranching and logging (Bankoff, 2007b and 2013; N. Roberts, 2014). Nonetheless, from the national scale data assembled here, we may broadly hypothesise on the ecological effects of late Spanish and early U.S. agricultural transformations on the Philippine Archipelago. For instance, we may assume that the trebling of agricultural land required converting large tracts of forests and wetland into farms. We may further infer that market and governmental pressures to increase production likely caused both old and new farms to experience shorter fallow periods, which would have impaired soil rejuvenation and secondary forest regrowth (Conklin, 1957; Olofson, 1980). Shorter fallows in conjunction with commercial logging likely decreased forest cover and contributed to erosion and landslides (Nelson et al., 1998), while the extension of commercial monocropping pressured Indigenous shifting cultivators, who had less land to practice less intensive agriculture (Boserup, 1965; Conklin, 1961). Notably, these expected consequences largely conform to Moore's theory of Capitalist Ecology, which contends that environmental devastation is the natural outcome of a capitalist-oriented world market system (Moore, 2007, 2010, 2014 and 2016).

This paper's provincial scale data also provides a starting point for detailing the local ecological changes prompted by late Spanish and early U.S. period agricultural transformations. For example, massive expansions in wet-rice cultivation in Nueva Ecija, Pangasinan, Tarlac and Pampanga likely led to the fragmentation of local wetland environs, which reduced the connectivity and resilience of those hydrological systems (Zedler and Kercher, 2005); decreased biodiversity associated with wetlands and forests (e.g., Zheng et al, 2021); and reduced consistent rainfall in those four provinces along with soils' ability to retain water, ironically jeopardising rice cultivation (McLennan, 1980). How land expansion progressed and how transforming ecologies affected ongoing internal migrations (Doeppers and Xenos, 1998) or the rising social tensions that produced the Huk Rebellion (Kerkvliet, 2002) are fruitful grounds for coordinated research between historians and environmental scientists.

Simultaneously, the two largest sugar-producing provinces in the Philippines, Pampanga and Negros Occidental, emphasise the importance of labour and land ownership in historic ecological change. Pampangan sugar growing was dominated by smallholders, but sugar in Negros Occidental was grown on large monocrop plantations primarily owned by several "sugar barons" (Larkin, 1993; Aguilar, 1994 and 2017). Greater concentration of land ownership permitted Negros Occidental's plantation-owners to purchase industrial centrifuges that Pampangan smallholders could not afford, and these centrifuges catalysed the continued expansion of sugarcane monoculture in Negros. As a result, Negros Occidental experienced greater soil degradation, and at a faster pace, than Pampanga. Pampanga, meanwhile, continued to specialise in both sugar production for local markets and rice growing, which initially curtailed environmental degradation despite Pampanga's high population density (Larkin, 1993). Other types of environmental degradation often associated with sugar, such as forest clearance and loss of biodiversity (El Chami et al., 2020), also occurred in Negros at a faster pace than they had in Pampanga, whose timber products were drawn upon since the Spanish first established their capital in Manila in 1571 CE (Larkin, 1982). These divergent outcomes therefore seem dependent not only on different patterns of labour, but also changing modes of colonial administration and the prominence of global exchange.

Lastly, the histories of abacá and copra production illustrate the role of "best agricultural practices" in producing divergent ecological outcomes. Starting with abacá, whose ecological impacts are not as well-studied as other commodities, Owen (1984) posited it was not especially detrimental to soils, noting smallholders reliably grew it for seventy years on the same plots of land. In support of this theory, ecological research demonstrates abacá plants are very demanding of soils, but fields can be used for decades if nutrients are returned by clipping the plants (Robinson and Johnson, 1953; Huke, 1963). Nonetheless, Dacudao's (2023) recent study of abacá plantations in Davao in conjunction with observations made by Owen (1984) suggest abacá plants in Davao grew taller and wider than plants in Luzon's Bikol Region. Whether that evidences gradual soil depletion in Bikol, the benefits of scientifically-informed agriculture in Davao, or that newly cleared soils in Davao momentarily possessed greater nutrients is unclear. Similarly, Ventura (2022) studied how penal colonies in Zamboanga and Palawan trained convicts to plant and tend coconut trees to prolong and enhance fertility, ultimately producing more nuts. These methods may have been more demanding of soils. However, it is unclear whether these techniques were widely employed by farmers in Tayabas, which planted ~115,000 ha to coconut trees in 1925 compared to ~19,000 ha in Zamboanga and ~2500 ha in Palawan (JRH Papers).

These examples again raise questions about the efficacy and extent of colonial policies and "scientific agriculture", and—in conjunction with labour practices, crop-specific factors and local geographies—are suggestive of the variety of ecological outcomes produced over time by commercial agriculture in the Philippines.

This brief discussion of regional ecological consequences provides a basis for our concluding argument. Our analysis suggests that, at the national scale, the Philippines's experience of nineteenth and 20th century agricultural expansion, driven by market integration at the behest of two colonial regimes, broadly aligns with experiences in the rest of the tropics described by Moore (2016) and Ross (2017). However, our data also draws into question those same colonial regimes' ability to effectively bring about the "agricultural improvements" they desired while also demonstrating the increasing geographical specialisation of Philippine agriculture in the late Spanish and early U.S. colonial periods. This outcome has historical and ecological implications. First, it emphasises the importance of local factors, such as capacity to ignore or resist colonial authority, labour practices, demography and geography in the extent and pace of agricultural expansion. Second, it suggests the ecological impacts of agricultural expansion in the late Spanish and early U.S. periods were highly variable by location, being affected by the crops planted, the rate of expansion, and the ways crops were cultivated, harvested and prepared for sale (see Kummer et al., 1994).

Detailing these diverse processes of environmental change is, we contend, essential for historians and ecologists alike. For historians, detailed historical ecologies permit new understandings of how local actors responded to their transforming surroundings, contextualising past decisions and actions. For Earth Scientists and ecologists, being able to define and connect the cumulative actions and structures of humanity—the Technosphere (Rosol et al., 2022)—requires enumerating their constituent parts. Our novel consideration of the censuses provides a starting point for appraising historical ecological change on these smaller scales, ultimately with the aim of helping to reassemble a more complete picture of human impacts on the Earth System (see Fluet-Chouinard et al., 2022) and specifically the repercussions of colonial interventions in the nineteenth and twentieth centuries. Moving forward, we suggest that comparisons should be made between the Philippines and other regions of today's "Global South" to further test colonial agricultural policies' efficacy and precisely describe their environmental legacies. Studies on ecological transformations in rice producing regions in this same period may show why Philippine *palay* yields increased (e.g., Adas 1974; see also Geertz, 1963), while comparisons to other commodity-producing regions outside the Philippines will further characterise the diverse ecological outcomes of commodity agriculture in this period (see Wells et al., 2018). Simultaneously, as our results indicate, the pursuit of this detailed and quantitative ecological history can provide new perspectives on long-standing historical questions, such as colonial policies' impacts. One potentially effective method for making such comparisons is historic land use modelling, which repurposes the metrology of improvement to assess and compare different societies and means of productions' impact on landscapes (Morrison et al., 2021; Findley et al., 2022). Such studies may ultimately demonstrate how the Anthropocene is comprised of regionally diverse outcomes, the results of uniquely local responses to pervasive global trends. And, once the Anthropocene is understood at smaller scales, previously unrealised solutions may begin to take shape.

Data availability

All data used in this paper is made available in the Supplementary Datasheets.

Received: 10 November 2023; Accepted: 10 June 2024;
Published online: 27 June 2024

References

Abbott EV, Tippett RL (1966) Strains of sugarcane mosaic virus (No. 1340). Department of Agriculture, Manila

Adas M (1974) The Burma Delta: Economic Development and Social Change on an Asian Rice Frontier, 1852–1941. University of Wisconsin, Madison

Amano N, Bankoff G, Findley DM, Barretto-Tesoro G, Roberts P (2021) Archaeological and historical insights into the ecological impacts of pre-colonial and colonial introductions into the Philippine Archipelago. Holocene 31(2):313–330

Aguilar Jr FV (1994) Sugar planter-state relations and labour processes in Colonial Philippine Haciendas. J. Peasant Stud. 22(1):50–80

Aguilar Jr FV (2017) Colonial sugar production in the Spanish Philippines: Calamba and Negros compared. J. Southeast Asian Stud. 48(2):237–261

Anker P (2001) Imperial Ecology: Environmental Order in the British Empire, 1895–1945. Harvard University, Cambridge

Asuncion S (1925) Mosaic disease and its effect on the sugar industry in the Philippine Islands. Philipp. Agric Rev. 18:33–38

Bach J (1929) Philippine Islands: 1:2,000,000/Compiled and Published by John Bach. Map. National Library of Australia, Canberra, Australia

Bankoff G (2007a) One island too many: reappraising the extent of deforestation in the philippines prior to 1946. J. Hist. Geogr. 33(2):314–334

Bankoff G (2007b) Colonising New Lands: Horses in the Philippines. In Bankoff G, Swart S (eds) Breeds of Empire: The 'Invention' of the Horse in Southeast Asia and Southern Africa, 1500–1950. NIAS Press, Copenhagen, p. 85-104

Bankoff G (2011) The science of nature and the nature of science in the Spanish and American Philippines. In: Ax CF et al (eds.). Cultivating The Colonies: Colonial States And Their Environmental Legacies. The Ohio University, Athens, Ohio, p. 78-108

Bankoff G (2013) 'Deep forestry': shapers of the philippine forests. Environ. Hist. 18:523–556

Boomgaard P (2007) Southeast Asia: An Environmental History. ABC CLIO, Santa Barbara

Boserup E (1965) The Conditions of Agricultural Growth: The Economics of Agrarian Change Under Population Pressure. Transaction Press, New Brunswick

Boudreau WJ (1904) Modern Rice Culture. Farmers' Bulletin 3. Bureau of Public Printing, Manila

Bray F (1994) The Rice Economies: Technology and Development in Asian Societies. University of California, Berkeley

Buzeta M, Brave F (1851) Diccionario Geográfico, Estadístico, Histórico De Las Islas Filipinas. José C. de la Peña, Madrid

Camenisch C, Jaume-Santero F, White S, Pei Q, Hand R, Rohr C, Brönnimann S (2022) A Bayesian approach to historical climatology for the Burgundian Low Countries in the 15th century. Clim Past 18:2449–2462

Castro BS (2003). Demythologizing the History of Coffee in Lipa, Batangas in the 19th Century. Dissertation, University of Adelaide

Cavada yMendezdeVigo,Adl (1876) Historia geográfica, geológica y estadiśtica de Filipinas, volumenes 1 y 2. Ramirez y Giraudier, Manila

Clarence-Smith W (2000). Cocoa and Chocolate, 1765-1914. Routledge, London

Census Office of the Philippine Islands (1920) Census of the Philippine Islands: Taken Under the Direction of the Philippine Legislature in the Year 1918. Bureau of Printing, Manila

Conklin HC (1957) Hanunóo Agriculture: A Report on an Integral System of Shifting Cultivation in the Philippines. Food and Agriculture Organization of the United Nations, Rome

Conklin HC (1961) The study of shifting cultivation. Curr. Anthropol. 2(1):27–61

Copeland EB (1908) Spanish agricultural work in the Philippines. Philipp. Agric Rev. 1(8):307–337

Corpuz AC (1999) The Colonial Iron Horse: Railroads and Regional Development in the Philippines, 1875-1935. University of the Philippines, Quezon City

Corpuz OD (1997) An Economic History of the Philippines. University of the Philippines, Quezon City

Cronon W (1983) Changes in the Land: Indians, Colonists, and the Ecology of New England. Hill and Yang, New York City

Crosby AW (1986) Ecological Imperialism: The Biological Expansion of Europe. Cambridge University, Cambridge, p 900–1900

Cullinane M (1998) Accounting for Souls: Ecclesiastical Sources for the Study of Philippine Demographic History. In Doeppers DF, Xenos P (eds) Population and History: The Demographic Origins of the Modern Philippines. University of Wisconsin, Madison, p. 281-346

Dacudao PI (2023) Abaca Frontier: The Socioeconomic and Cultural Transformation of Davao, 1898-1941. Ateneo de Manila University, Quezon City

de Jesus EC (1980) The Tobacco Monopoly in the Philippines: Bureaucratic Enterprise and Social Change, 1766-1880. Ateneo de Manila University, Quezon City
DeBevoise K (1995) Agents of apocalypse: Epidemic disease in the colonial Philippines. Princeton University, Princeton
Doeppers DF, Xenos P (eds) (1998) Population and History: The Demographic Origins of the Modern Philippines. University of Wisconsin, Madison
El Chami D, Daccache A, El Moujabber M (2020) What are the impacts of sugarcane production on ecosystem services and human well-being? A review. Annu Agric Rev. 65:188–199
Findley DM, Bankoff G, Barretto-Tesoro G, Hamilton R, Kay AU, Acabado S, Amano N, Kaplan JO, Roberts P (2022) Land use change in a pericolonial society: intensification and diversification in ifugao, philippines between 1570 and 1800 CE. Front Earth Sci. https://doi.org/10.3389/feart.2022.680926
Fluet-Chouinard E, Stocker BD, Zhang Z et al. (2022) Extensive global wetland loss over the past three centuries. Nature 614:281–285
Foreman J (1890) The Philippine Islands: A Historical, Geographical, Ethnographical, Social and Commercial Sketch of the Philippine Archipelago and its Political Dependencies. Sampson Low, Marston, Searle and Rivington, London
Elena A, Ordonez J (2000) Science, technology, and the spanish colonial experience in the nineteenth century. Osiris 15:70–82
Gealogo FA (1998) Historical demography in the philippines: current trends and future perspectives. Philipp. Soc. Sci. Rev. 55:90–102
Gealogo FA (2011) Counting people: nineteenth century population history of four manila arrabales using the planes de almas. Philipp. Stud. 59(3):399–423
Geertz C (1963) Agricultural involution: the processes of ecological change in Indonesia. University of California, Berkeley
Golay FH (1997) Face of Empire: United States-Philippines Relations, 1898-1946. Ateneo de Manila University, Quezon City
Greenland DJ (1997) The Sustainability of Rice Farming. CAB International Publishing, Wallingford, Oxfordshire
Grove RH (1995) Green Imperialism: Colonial Expansion, Tropical Island Edens, and the Origins of Environmentalism, 1600-1860. Cambridge University, Cambridge
Gutierrez Creps F (1878) Memoria sobre el Cultivo Beneficio y Comercio del Azúcar. Establacimiento Tipográfico de Celestino Miralles
Hamilton R, Wolfhagen J, Amano N, Boivin N, Findley DM, Iriarte J, Kaplan JO, Stevenson J, Roberts P (2021) Non-uniform tropical forest responses to the 'Columbian Exchange' in the Neotropics and Asia-Pacific. Nat. Ecol. Evol. 5:1174–1184
Hayden JR (n.d.). Joseph Ralston Hayden Collection. Print. University of Michigan, Bentley Historical Library. Folder 6, Box 14. Ann Arbor, Michigan, USA
Huke RE (ed) (1963). Shadows On The Land: An Economic Geography Of The Philippines. Bookmark, Manila
Ileto RC (1999) Knowing America's colony: a hundred years after the Philippine war. Philipp. Stud., Occas Pap. Ser. 13:1–70
International Institute of Agriculture (1937). The First World Agricultural Census (1930): A Methodological Study Of The Questions Contained In The Forms Adopted For The Purposes Of The Census In The Various Countries. Ditta C. Colombo, Rome
Jones PM (2016) Agricultural Enlightenment: Knowledge, Technology, and Nature, 1750-1840. Oxford University, Oxford
Kerkvliet BJ (2002) The Huk Rebellion: A Study of Peasant Revolt in the Philippines. Rowman and Littlefield, Lanham, Maryland
Krinks P (1975) Changing land use on a philippine frontier. Agric Hist. 49(3):473–490
Kuhn TS (1996). The Structure of Scientific Revolutions, 3rd edn. University of Chicago, Chicago
Kummer D, Concepcion R, Canizares B (1994) Environmental degradation in the uplands of cebu. Geogr. Rev. 84(3):266–276
Larkin JA (1982) Philippine history reconsidered: a socioeconomic perspective. Am. Hist. Rev. 87(3):595–628
Larkin JA (1993) Sugar and the Origins of Modern Philippine Society. University of California, Berkeley
Legarda BJ Jr (1999) After the galleons: foreign trade, economic change and entrepreneurship in the nineteenth-century philippines. Ateneo de Manila University, Quezon City
Lenzner B, Latombe G, Schertler A, Seebens H, Yang Q, Winter M, Weigelt P, van Kleunen M, Pyšek P, Pergl J, Kreft H (2022) Naturalized alien floras still carry the legacy of European colonialism. Nature. Ecol. Evol. 6:1–10
Lyon WS (1902) Cacao Culture in the Philippines. Farmers' Bulletin, 2. Bureau of Public Printing, Manila
Lyon WS (1904) A Primer on the Cultivation of Sugar Cane, Third Edition. Farmers' Bulletin, 1. Bureau of Public Printing, Manila
Lyon WS (1905) The Cocoanut: With Reference to Its Products and Cultivation in the Philippines. Farmers' Bulletin, 8. Bureau of Public Printing, Manila
Lewis S, Maslin M (2015) Defining the Anthropocene. Nature 519:171–180
Malhi Y, Gardner TA, Goldsmith GR, Silman MR, Zelazowski P (2014) Tropical forests in the Anthropocene. Annu Rev. Environ. Resour. 39:125–159
May GA (1980) Social Engineering In The Philippines: The Aims, Execution And Impact Of American Colonial Policy, 1900-1913. Greenwood Press, Santa Barbara
McCoy AW, de Jesus EC (eds) (1982) Philippine Social History: Global Trade and Local Transformations. Ateneo de Manila University, Quezon City
McLennan MS (1980) The Central Luzon Plain: Land and Society on the Inland Frontier. Alemars-Phoenix Publishing, Quezon City
McLennan MS (1982) Changing human ecology on the central luzon plain: nueva ecija, 1705-1939. In: McCoy AW, de Jesus EC (eds) Philippine Social History: Global Trade and Local Transformations. Ateneo de Manila University, Quezon City, p. 57-90
Millán y Villanueva C (1891) Ilocos Norte, descripción general de dicha provincial. El Eco de Filipinas, Manila
Miller HH (1911) Commercial Geography. The Materials of Commerce for the Philippines. Bureau of Public Printing, Manila
Montero y Vidal J (1886). Historia General De Filipinas Desde El Descubrimiento De Dichas Islas Hasta Nuestras Días. M. Tello, Madrid
Moore JW (2003) The *Modern World-System* as environmental history? Ecology and the rise of capitalism. Theory Soc. 32:307–377
Moore JW (2007) Silver, ecology, and the origins of the modern world, 1450-1640. In: Hornborg A, McNeill JR, Martinez-Alier J (eds.), Rethinking Environmental History: World System History and Global Environmental Change, Alta Mira, Lanham, Maryland, p. 123-142
Moore JW (2010) The End of the Road? Agricultural Revolutions in the Capitalist World Ecology: 1450-2010. J. Agrar Change 10(3):389–413
Moore JW (2014) The end of cheap nature. or how i learned to stop worrying about "the" environment and love the crisis of capitalism. In: Suter C, Chase-Dunn C (eds.), Structures of the World Political Economy and the Future of Global Conflict and Cooperation. LIT, Berlin, p. 285-314
Moore JW (2016) The rise of cheap nature. In: Moore JW (ed), Anthropocene or Capitalocene? Nature, History and the Crisis of Capitalism PM Press, Oakland, California, p. 78-115
Morrison KD, Hammer E, Boles O, Madella M, Whitehouse N, Gaillard MJ, Bates J, Vander Linden M, Merlo S, Yao A, Popova L (2021) Mapping past human land use using archaeological data: a new classification for global land use synthesis and data harmonization. PLoS ONE 16(4):e0246662
Moya y Jimenez FJ (1883) Las islas Filipinas en 1882; estudios históricos, geográficos, estadísticos y descriptivos. Establecimiento tipográfico de El Correo, Madrid
Nelson RA, Dimes JP, Silburn DM, Paningbatan EP, Cramb RA (1998) Erosion/productivity modelling of maize farming in the philippine uplands part II: simulation of alternative farming methods. Agric. Syst. 58(2):147–163
Olofson H (1980) Swidden and kaingan among the southern tagalog: a problem in philippine upland ethno-agriculture. Philipp. Q. Cult. Soc. 8(2/3):168–180
Orquiza RAD Jr (2012) Food, Class, and the American Imperial Experience in the Philippines, 1898–1940. Dissertation, Johns Hopkins University
Orquiza RAD Jr (2020) Taste of Control: Food and the Filipino Colonial Mentality under American Rule. Rutgers, New Brunswick
Owen NG (1984) Prosperity without progress: manila hemp and material life in the colonial Philippines. University of California, Berkeley
Pasquinelli M (2022) Labour, energy, and information as historical configurations. J. Interdiscip. Hist. Ideas 11:13:1–13:22
Patero S (1872) Cultivo del Cacao y Café. Ramirez y Giraudier, Manila. Tagalog Edition: Patero S (1872). Cultivo del Cacao y Café (trans. Changco V). Ramirez y Giraudier, Manila
Puya Ruiz A (1887) Camarines Sur, Descripción general de esta provincial en Luzon acompoñada de un plano. La Oceania Española, Manila
Roberts NE (2014) U.S. Forestry in the Philippines: Environment, Nationhood, and Empire, 1900-1937. Dissertation, University of Washington
Roberts P, Kaplan JO, Findley DM, Hamilton R, Caetano-Andrade VL, Amano N, Kay AU, Renn J, Winkelmann R (2023) Mapping our reliance on the tropics can reveal the roots of the Anthropocene. Nat. Ecol. Evol. 7(5):632–636
Robinson BB, Johnson FL (1953) Abaca: a cordage fiber. agriculture monograph 21. United States Department of Agriculture, Beltsville, Maryland
Rosol R, Nelson S, Renn J (2022) Introduction: in the machine room of the anthropocene. Anthropocene Rev, 4(1). https://doi.org/10.1177/2053019617701165
Ross C (2017) Ecology and Power in the Age of Empire: Europe and the Transformation of the Tropical World. Oxford University, Oxford
Roth DM (1977) The Friar Estates of the Philippines. University of New Mexico, Albuquerque
Sastrón M (1895) Batangas y su Provincia. Publisher not stated, Manila
Schueller MJ (2019) Campaigns of Knowledge: U.S. Pedagogies of Colonialism and Occupation in the Philippines and Japan. Temple University, Philadelphia
Smith W, Dressler WH (2020) Forged in flames: indigeneity, forest fire and geographies of blame in the Philippines. Postcolonial Stud. 23(4):527–545

Spencer JE (1966) Shifting Cultivation in Southeast Asia. University of California, Berkeley
Tecson y Ocampo P (1908a) Agricultural conditions in the province of nueva ecija. Philipp. Agric Rev. 1(2):88–90
Tecson y Ocampo P (1908b) Agricultural conditions in tarlac province. Philipp. Agric Rev. 1(7):301–304
Tecson y Ocampo P (1908c) Agricultural conditions in the province of pampanga. Philipp. Agric Rev. 1(10):432–437
Thomas JA, Williams M, Zalaswiewicz J (2020) The Anthropocene: A Multi-disciplinary Approach. Polity, Cambridge
Thompson EP (1967) Time, work-discipline, and industrial capitalism. Present 38:56–97
Topik S (2009) Historicizing commodity chains: five hundred years of the global coffee commodity chain. In: Bair J (ed). Frontiers in Commodity Chain Research. Stanford University, Stanford, p. 37-62
Tucker RP (2000) Insatiable Appetite: The United States and the Ecological Degradation of the Tropical World. University of California, Berkeley
U.S. Bureau of the Census (1905) Census of the Philippine Islands: Taken Under the Direction of the Philippine Commission in the Year 1903. United States Bureau of the Census, Washington DC
Ventura TM (2009) American Empire, Agrarian Reform and the Problem of Tropical Nature in the Philippines, 1898-1916. Dissertation, Columbia University
Ventura T (2016) From small farms to progressive plantations: the trajectory of land reform in the american colonial Philippines, 1900–1916. Agric Hist. 90(4):459–483
Ventura T (2022) Consider the coconut: scientific agriculture and the racialization of risk in the american colonial Philippines. J Transnatl Am Stud 13(1):45–67
von Ausdal S (2012) Productivity gains and the limits of tropical ranching in Columbia, 1850-1950. Agric Hist. 86(3):1–32
Warren JF (2016) Typhoons and the inequalities of philippine society and history. Philipp. Stud. 64(3/4):455–472
Wells EC, Pratt SM, Fox GL et al. (2018) Plantation soilscapes: initial and cumulative impacts of colonial agriculture in Antigua, West Indies. Environ Archaeol 23(1). https://doi.org/10.1080/14614103.2017.1309806
Williams M (2006) Deforesting the Earth: From Prehistory to Global Crisis, an Abridgement. University of Chicago, Chicago
Zedler JB, Kercher S (2005) Wetland resources: status, trends, ecosystem services, and restorability. Annu Rev Environ Resour. 30:39–74
Zheng Z, Ma T, Roberts P et al. (2021) Anthropogenic impacts on late Holocene land-cover change and floristic biodiversity loss in tropical southeastern Asia. Proc. Natl Acad. Sci, USA 118(40). https://doi.org/10.1073/pnas.2022210118

Acknowledgements

Research undertaken for this paper was funded by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement number 850709; PANTROPOCENE). David Max Findley, Noel Amano and Patrick Roberts also thank the Max Planck Society for additional funding.

Author contributions

Dr. David Max Findley performed all on-site and digital archival research, completed all data analysis, drafted the article, generated all figures, and led all revisions. Dr. Findley and Ms. Ivana Biong transcribed all data, and verified one another's transcriptions. Dr. Patrick Roberts provided editorial oversight for all components of the article at all phases and provided the resources for the study. Drs. Noel Amano and Rebecca Hamilton provided historical and contemporaneous sources from ecological sciences and provided edits to the article at various stages. Profs. Greg Bankoff, Patricia Dacudao, Francis Gealogo and Ruel Pagunsan provided additional archival documents as well as articles on the history and demography of Philippine provinces. Profs. Greg Bankoff, Patricia Dacudao and Ruel Pagunsan also provided edits and revisions to the article at various stages.

Funding

Open Access funding enabled and organized by Projekt DEAL.

Competing interests

The authors declare no competing interests.

Ethical approval

This article does not contain any studies with human participants and did not require ethical approval at any stage.

Informed consent

This article does not contain any studies with human participants performed by any of the authors and did not require informed consent at any stage.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1057/s41599-024-03310-z.

Correspondence and requests for materials should be addressed to David Max Findley or Patrick Roberts.