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Ecological pest control fortifies agricultural growth in Asia–Pacific economies

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The Green Revolution is credited with alleviating famine, mitigating poverty and driving aggregate economic growth since the 1960s. In Asia, high-input technology packages secured a tripling of rice output, with germplasm improvements providing benefits beyond US$4.3 billion yr^{-1}. Here, we unveil the magnitude and macro-economic relevance of parallel nature-based contributions to productivity growth in non-rice crops over the period 1918–2018 (across 23 different Asia–Pacific geopolitical entities). We empirically demonstrate how biological control resolved invasive pest threats in multiple agricultural commodities, ensuring annually accruing (on-farm) benefits of US$14.6–19.5 billion yr^{-1}. Scientifically guided biological control of 43 exotic invertebrate pests permitted 73–100% yield-loss recovery in critical food, feed and fibre crops including banana, breadfruit, cassava and coconut. Biological control thereby promoted rural growth and prosperity even in marginal, poorly endowed, non-rice environments. By placing agro-ecological innovations on equal footing with input-intensive measures, our work provides lessons for future efforts to mitigate invasive species, restore ecological resilience and sustainably raise output of global agrifood systems.

Global environmental change is undermining many of the UN Sustainable Development Goals, thus compromising endeavours to ensure economic growth, alleviate malnutrition, lift societal wellbeing and stabilize the Earth's life-support systems[1]. Although agrifood systems sustain the livelihoods of >2.5 billion people and help meet dietary requirements of a swelling human population, they also contribute to global warming, ecosystem decay and agrochemical pollution[2–4]. Agriculture-related habitat loss, natural resource degradation and a precipitous decline of biodiversity are pushing the Earth system to a state that is distinctly less conducive to societal development[5]. Given that the Asia–Pacific region is responsible for ~50% of global agricultural production and its farm output has experienced a steady 3.8% annual growth over the last five to six decades[6], the above externalities are believed to be particularly pronounced in that region.

As a powerful engine of economic development[7], agriculture supplies food and raw materials and acts as a source of capital formation, residual labour, foreign exchange and purchasing power. Although often perceived as a stagnant sunset industry, vigorous growth in smallholder agriculture permitted a rapid emergence and continual performance of Asia's newly industrialized Tiger Cub economies[8]. Post-1960s productivity growth in Asian agriculture has largely been credited to the Green Revolution, that is, varietal improvements of cereal staples deployed under high-input technology packages[6,9]. Founded on century-long progress in Mendelian genetics, double-yielding rice varieties are heralded as a key determinant of transformative growth in local agriculture. While improved rice germplasm surely unlocked the productive potential of large swathes of farmland, the role of other biological innovations that may have effected comparable technological change has largely been obscured.

As a nature-based innovation that conserves or enhances natural capital stocks[10], biological control involves the scientifically guided conservation, augmentation or introduction of beneficial organisms for the mitigation of crop pests, pathogens and weeds[11]. Classical biological control, the judicious release of non-native organisms against invasive pests, in particular, has achieved effective suppression of at least 220 different invasive pest insects worldwide, regularly at benefit–cost ratios of 5:1 to >1,000:1 (refs. [12–14]). At those rates of return, 80% of documented benefits of the entire Consultative Group of International Agricultural Research (CGIAR) in certain geographies emanate from a narrow set of biological control interventions[15]. Invasive pests inflict US$23–34 billion annual losses to Southeast Asian agriculture[16], thereby slowing rural economic growth and imperilling food security in settings with fast-growing populations[17]. As a self-sustaining technology, classical biological control (here termed 'biological control') provides a tailor-made solution for invasive pest issues in remote settings or smallholder farming systems. Classical biological control typically involves the scientifically guided introduction of exotic beneficial organisms to manage an exotic invasive species (or pest). Often, when faced with economically relevant pests, other forms of biological control are more suitable and rely upon in-field conservation or augmentation of endemic natural enemies[11].

While invasive species receive only scant attention from present-day scientists in the Asia–Pacific region[16], they were prime targets of development programmes during the colonial period and last half of the twentieth century[18–21]. With committed support through foreign donors and often firmly backed by the UN Food and Agriculture Organization (FAO), biological control reduced the threat of pests such as the coconut scale *Aspidiotus destructor* Signoret and the banana skipper *Erionota thrax* (Linnaeus) that jeopardized economic prosperity, food security and welfare of entire nations[19,22]. By contributing to a restoration of ecological balance and reducing the need for synthetic pesticides in invaded agrifood

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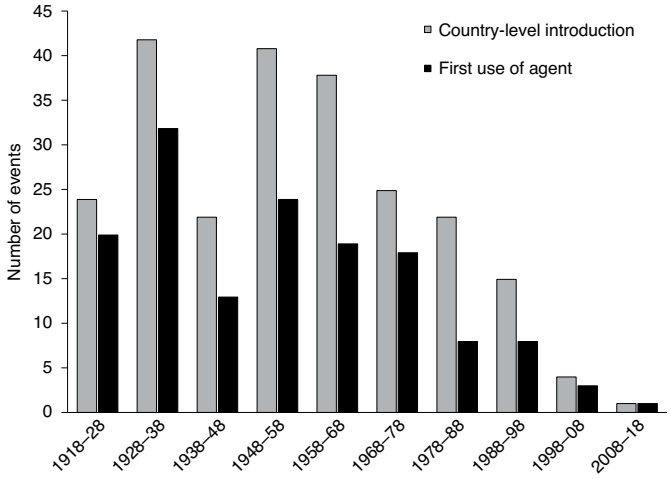


Fig. 1 | Timeline of insect biological control introductions across the Asia–Pacific region (26 countries). The total number of country-level introductions and first regional deployments of a given biological control agent is depicted for successive decades (1918–2018). For instance, BIOCAT contained two introductions of the larval parasitoid *Psyttalia humilis* (Silvestri) against Tephritid fruit flies: a first regional use in 1927 (Cook Islands) followed by a second country-level deployment in 1935 in Fiji. All introductions pertain to the deployment of insect natural enemies for insect pest management in local food and agricultural production. Records are drawn from the BIOCAT database.

systems[23], biological control can benefit biodiversity conservation at large[24,25]. More specifically, the deployment of organisms with high levels of host and habitat fidelity ensures maximum impact on (pest) targets and few, often transient, non-target effects[24]. Yet, following a small number of ill-advised introductions done in the name of biological control in the mid-1900s, regulatory hurdles surfaced and a more risk-averse attitude eclipsed its myriad societal benefits[13]. As pest invasions continue unabated and environmental consequences of their improper mitigation become more apparent[26,27], an ex-post valuation of the economic benefits of biological control can shine new light on this valuable practice[28].

To fully gauge the societal outcomes of historic biological control efforts in the Asia–Pacific, we use a 'food systems' perspective. By accounting for the multiple social and environmental contexts of agrifood production, such perspective blends biophysical facets of species invasion, pest-induced crop loss or the ensuing recovery of losses through biological control with the associated socioeconomic outcomes[29,30]. Using a food systems approach, we (1) systematically assess occurrence and fate of historical insect biological control introductions over the period 1918–2018; (2) quantify monetary impact of pest invasions and ensuing biological control at varying spatial scales; and (3) contrast locality-specific productivity growth trajectories (resulting from progressive technological change[31]) for rice and various non-rice commodities, reflective of either concurrent or disparate Green Revolution and biological control interventions. Our work provides compelling evidence of how ecological innovations contribute to agricultural growth and prosperity for multiple Asia–Pacific nations, including its Tiger Cub economies.

Results

Invasion history and biological control efforts. Over a 1918–2018 timeframe, the BIOCAT database contained records of 155 insect biological control agents, used against 69 invertebrate pests in the food and agriculture production sector of 26 different Asia–Pacific geopolitical areas (Fig. 1). Biological control agents (or so-called natural enemies) mainly comprised species within the taxonomic orders Hymenoptera (58%), Coleoptera (31%) and Diptera (8%), while pest targets were mainly Hemiptera (42%) and Lepidoptera (28%) (Fig. 2). A total of 17, 21 and 25 different species of Encyrtidae, Braconidae and Coccinellidae were used for biological control, with most releases conducted in Fiji (17%), Northern Marianas (12%), Guam (12%) and Indonesia (9%). Invasive pests of coconut were regularly targeted, followed by those on banana and citrus, with a respective 21, 14 and 12 geopolitical areas receiving (often multiple) releases on one of the three crops. Biological control further targeted pests in non-rice cereals and graminoids (for example, maize and sugarcane), orchard crops such as pineapple, cocoa, mango and guava, root crops, legumes or vegetables.

Out of the 252 unique country-level biological control interventions, 96 achieved establishment of the introduced natural enemies with an ensuing success rate of 40% (full or partial control). Once established, members of Hymenoptera and Diptera attained (country-level) biological control success rates of 46% and 67%, respectively. Overall, 39% of introduced natural enemy species attained lasting establishment and 48% of those subsequently secured full or partial pest control within at least one geopolitical area.

Expanding our analyses beyond BIOCAT database entries, we recorded a total of 75 natural enemies that provided full or partial control of 43 invasive pest targets in food and agriculture production sectors of 23 geopolitical areas (over the period 1918–2018). Non-exhaustive literature searches further revealed how 176 country-level biological control interventions provided at least partial pest control.

Productivity shocks and producer impacts. Invasive pests caused substantial reductions in the land productivity or yield of a range of crops; for example, the hispid *Brontispa longissima* (Gestro) inflicted 50–70% losses in coconut, the scale insect *A. destructor* regularly led to total loss of coconut, breadfruit or banana, while the fruit fly *Bactrocera dorsalis* (Hendel) impacted yield and marketability of mango by 82–95%. Using 2015 production and pricing statistics, historical pest invasions caused an aggregate farm-level economic loss of up to US$1.1 ± 3.1 billion per country annually (mean ± s.d.; $n = 23$ countries), with the highest impacts for Indonesia (US$14.71 billion). Per crop, an annual aggregate economic impact of US$1.1 ± 2.3 billion was recorded, with the highest (upper-bound) pest-induced losses for coconut (US$8.20 billion), cassava (US$6.8 billion) and banana (US$4.3 billion) (Extended Data Fig. 1). A relatively small complement of invasive pests further inflicted US$591 million losses per year in cabbage, US$604 million in citrus or US$1.2 billion in mango and guava.

Following the introduction of biological control agents, pest-induced losses were offset by a respective 59% or 79% under a conservative or high-impact scenario, for a total aggregate amount of US$14.57–19.53 billion annually (Fig. 3). For a high-impact scenario, this represents 2.5 ± 3.8% of current gross domestic product (purchasing power parity) (GDP (PPP)) of pest-invaded countries, with the highest contribution to the national economies of Vanuatu (14.7%), Tonga (9.1%) and Solomon Islands (8.6%) (Table 1 and Extended Data Fig. 2). Under a more conservative scenario, this equals 2.0 ± 3.0% of current GDP. In absolute terms, biological control yielded monetary benefits up to US$1.6–2.0 billion (Thailand), US$2.5–3.3 billion (Philippines) and US$7.3–10.2 billion (Indonesia) annually for a conservative to high-impact scenario range (Table 1).

Macro-economic analyses. Agricultural growth trajectories of the various countries differed substantially, with steep growth (that is, more intensive use of labour relative to land[6]) in rice-cultivating

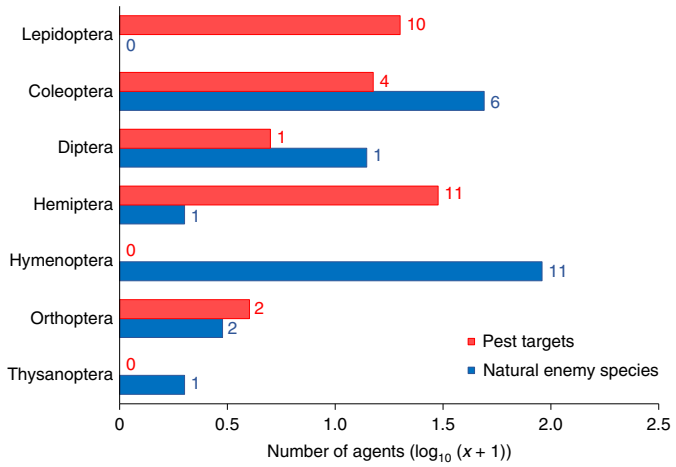


Fig. 2 | Insect natural enemies and their related pest targets, as used in historic biological control programmes in the Asia–Pacific region. For each insect order, the number of individual species of invasive pest targets (red) and biological control agents or 'natural enemies' (blue) is listed. Next to each bar, the number of families within a given taxonomic category is indicated. Records cover all biological control interventions, including failed and partially/fully successful interventions, from 1918 onwards. Records are drawn from the BIOCAT database.

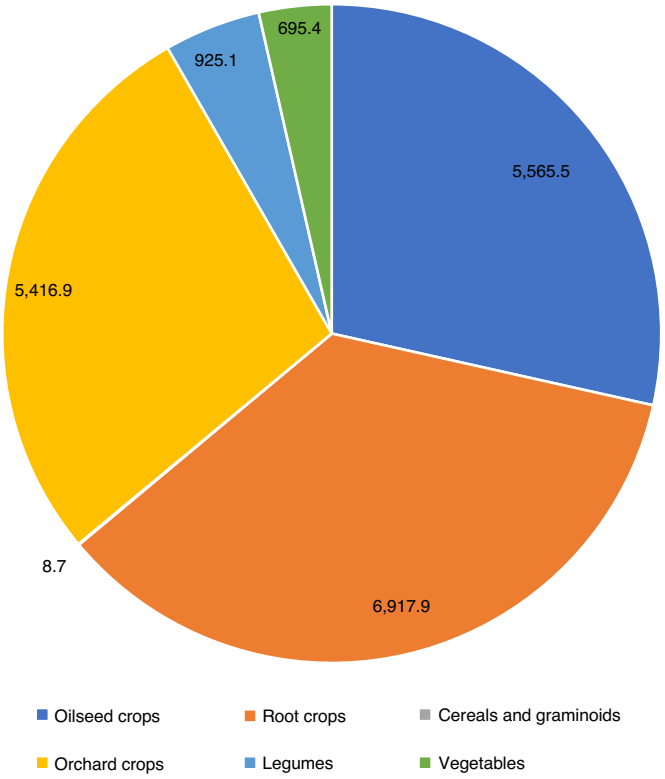


Fig. 3 | Aggregated annual economic value (million US$) of biological control interventions conducted across the Asia–Pacific over the period 1918–2018. Data are shown for a 'high-impact' scenario with US$19.5 billion total value across crops and commodities in the Asia–Pacific region (23 countries; 2015 US$). Oilseed crops include coconut and oilpalm; root crops cover cassava and taro; while orchard crops cover banana, breadfruit, cocoa, coffee and a range of perennial or annual fruit crops. Records are drawn from the BIOCAT database and complemented with extensive literature revisions.

economies such as Indonesia, Philippines or Thailand (Extended Data Fig. 3). In contrast, productivity paths of Melanesian countries were relatively flat (that is, intensification of land use relative to labour) while growth was comparatively stagnant in other countries, for example, Timor Leste and Tonga. These growth trajectories partially mirror the extent of in-country technological change. Land-saving technologies facilitate the substitution of other inputs for land[32]; while agricultural mechanization is clearly labour-saving, chemical and biological technologies are land-saving. Several of the countries that implemented land-saving biological control (Table 1) experienced rapid agricultural productivity growth.

In 1961, at the start of our impact assessment period, the agricultural sector in all countries except Vietnam was primarily dominated by non-staple commodities (in value; Fig. 4), comprising myriad vegetables, oilseed crops, cereals and graminoids, orchard crops and legumes. For the six rice economies, aggregate value of the non-rice subsector was 1.3–22.9 times higher than that of paddy rice. For Pacific Island communities, value of the non-staple subsector was 4.1–25.7 times higher than that of primary food staples (taro and sweet potato).

Countries that relied extensively on biological control in non-rice crops (for example, Indonesia) experienced comparatively rapid growth in output of the rice subsector (Fig. 4) with the most vigorous productivity growth during the 1970s (Extended Data Fig. 4). All remaining rice economies were typified by superior output growth of the non-rice subsector over five decades. For all Pacific Island communities except Samoa, initial pace of growth in the non-staple subsector surpassed that of key food staples (taro and sweet potato). Overall, aggregate agricultural growth mirrored that of the respective non-staple subsector, in both rice economies and across Melanesia.

Country-specific time paths revealed different sources of land productivity growth for commodities that were covered by biological control, as compared to paddy rice and other food staples (Fig. 5). Here, we attribute productivity growth in rice primarily to enhanced germplasm and high-input technology packages, while growth trajectories in non-staple crops are mediated to a lesser extent by Green Revolution technologies and can be partially ascribed to biological control. Land productivity growth in non-staple crops may equally relate to (crop-specific) advances in other biological or chemical technologies, for example, genetic gain, intercrop arrangements or agrochemical inputs. In all rice economies, rice crops experienced substantial area increases in addition to 303–494% maximum yield growth against a 1961 baseline. In countries that relied extensively upon biological control such as Indonesia, maximum yield growth in banana (1,222%) and cassava (323%) amply surpassed that of rice (303%) and can be partially ascribed to an effective recovery of pest-induced yield losses of 81% and 73% in the respective crops because of biological control. For instance, crop losses due to the invasive cassava mealybug were alleviated through releases of the parasitoid *Anagyrus lopezi* (De Santis). In rice economies, crops such as coconut were covered in multiple biological control campaigns and experienced yield growth between 126% (Philippines) and 279% (Vietnam). In Melanesia, yields of various oilseed and orchard crops that were covered in biological control endeavours experienced modest to substantial increases (coconut 145%, banana 148% and sugarcane 203%).

Over the period 1961–2016, the pace of rice yield growth in various countries was surpassed by that of other (biological control reliant) commodities at different times. In Melanesia, yield growth of sugarcane (158%) and coconut (106%) exceeded that of rice by 1962 and 1964, respectively. In Indonesia, Green Revolution rice yield growth was consistently higher than that of other commodities until 1989 when it was surpassed by that of banana. In the Philippines, yield growth in banana surpassed that of rice over the

Table 1 | Country-level monetary value of invasive pest attack and ensuing crop recovery enabled through biological control

Country	Number of impacted crops	Number of invasion events per crop	Annual monetary impact per crop (US$ '000)	Total annual recovery value (US$ '000)	Percentage of national GDP (PPP)
Fiji	11	1.6 ± 1.0	10,846 ± 25,641	94,936–118,457	1.25–1.55
Northern Marianas	12	1.5 ± 0.7	11 ± 11	105–132	0.01
Indonesia	11	1.3 ± 0.5	1,337,049 ± 1,692,304	7,278,555–10,220,064	0.27–0.38
Papua New Guinea	9	1.3 ± 1.0	95,419 ± 98,340	610,683–763,355	1.97–2.46
Philippines	9	1.3 ± 0.7	446,002 ± 613,228	2,544,157–3,346,961	0.36–0.48
Marshall Islands	3	1.7 ± 0.6	1,245 ± 1,211	2,989–3,736	1.54–1.92
Western Samoa	4	1.3 ± 0.5	8,552 ± 10,407	27,367–34,208	2.54–3.18
Cook Islands	6	1.5 ± 0.5	222 ± 212	773–1,039	0.26–0.35
Palau	5	1.4 ± 0.5	191 ± 235	764–956	0.25–0.32
Solomon Islands	2	1.0 ± 0	54,229 ± 51,694	86,767–108,459	6.87–8.59
Tonga	5	1.4 ± 0.5	10,008 ± 19,655	40,034–50,041	7.25–9.07
Micronesia (Federated States)	2	1.0 ± 0	9,564 ± 12,635	15,303–19,129	4.48–5.60
French Polynesia	3	1.0 ± 0	6,852 ± 11,404	16,467–20,558	0.30–0.37
Wallis and Futuna (France)	2	1.0 ± 0	1,515 ± 690	2,424–3,031	4.04–5.05
Vanuatu	3	1.3 ± 0.6	36,429 ± 57,024	87,428–109,286	11.77–14.72
Malaysia	2	1.0 ± 0	38,942 ± 36,407	62,307–77,885	0.01
New Caledonia	2	1.0 ± 0	877 ± 1,183	1,382–1,734	0.01–0.02
Vietnam	3	1.7 ± 0.6	513,177 ± 475,329	1,231,623–1,539,529	0.24–0.30
East Timor	2	1.0 ± 0	1,550 ± 1,962	2,479–3,100	0.03
Thailand	6	1.2 ± 0.4	343,622 ± 595,309	1,557,474–1,969,822	0.15–0.19
Cambodia	2	1.5 ± 0.7	452,443 ± 617,725	723,910–904,888	1.42–1.77
Lao PDR	1	2.0 ± 0	233,054 ± 0	186,443–233,054	0.49–0.61
Singapore	1	1.0 ± 0	20 ± 0	16–20	0

Annual impact figures (mean ± s.d.) are upper-bound measures, exclusively computed for invasive insect pests that were either partially or fully controlled through biological control, over the period 1918–2018. Per country, aggregate recovery values for all biological control interventions are presented for a high-impact to conservative scenario range, either in absolute terms or as percentage of national GDP (PPP; 2015 US$). For crops subject to multiple historical pest invasions in a given country, only the biological control intervention with the highest recovery value is taken into consideration. Patterns are shown for 23 countries in the broader Asia–Pacific region.

period 1974–2004. In Thailand and Vietnam, yield gain in coconut was pronounced for 1998–2010, which was a period that coincided with biological control releases against *B. longissima*.

Underlying these technological contributions to productivity growth is the changing demand for agricultural produce. As incomes increase over time, demand for non-staple crops tends to increase at a faster pace than that for staples, thereby driving the use of technological inputs and increasing their respective area under cultivation.

Discussion

Biodiversity-driven ecosystem services underpin sustainable food systems and safeguard societal wellbeing in the face of environmental change[11,33]. As a key constituent of global change, pest invasions result from an ecological imbalance that occurs, for example, when non-native species are released from population regulation by co-evolved natural enemies[34]. Scientifically guided introductions for biological control restore some balance, reconstituting ecosystem service delivery and alleviating pest-induced economic, environmental and societal impacts[24]. Here, we show how 75 different biological control agents mitigated 43 pest targets over the period 1918–2018. Biological control delivered durable pest control in myriad Asia–Pacific agriculture sectors, permitting yield-loss recoveries up to 73%, 81% and 100% in cassava, banana and coconut crops respectively[19,35]. The ensuing economic dividends are substantial, as pest-induced losses up to US$6.8 billion, US$4.3 billion and US$8.2 billion annually for the above crops were offset (at respective values of US$5.4–6.8 billion, US$1.4–2.2 billion and US$3.8–5.5 billion yr^{-1}, for a conservative to high-impact scenario range) (Fig. 3). These annually accruing benefits compare favourably with the US$4.5 billion Asia-wide benefit of improved rice germplasm[36]. By remediating persistent negative biotic shocks to agricultural production, biological control probably promoted technological change and growth within several agricultural subsectors. Nations such as Indonesia that prioritized the use of biological control enjoyed productivity gains in pest-afflicted banana (1,222%) and cassava (322%), far surpassing those of paddy rice (303%) (Fig. 5). Our work constitutes an empirical demonstration of how insect biological control helped solidify the agrarian foundation of several Asia–Pacific economies[18]. Doing so places biological control on equal footing with other biological innovations such as Green Revolution germplasm, spotlights its transformative impacts especially in light of increasing global agrochemical reliance[2] and celebrates the century-long achievements of dedicated yet often unacclaimed biological control pioneers.

Our findings are consistent with a recent global synthesis that demonstrated the immense economic value of biological control for arthropod pest management[28]. On the basis of 44 published studies from across the globe, values based on conservative 30-yr time horizons with a 10% discount rate showed that net present value (benefit–cost) of individual programmes targeting single pest species on single crops ranged from US$150,000 to over US$9

billion (2018 US$). Average benefits and costs were around US$37 and 0.6 million, respectively, for an ultimate benefit/cost ratio of over 61. Values in our study dwarf those from this recent synthesis[28] largely because they are founded on a much larger pest complex, more crops, an expansive geographic coverage and broader underlying assumptions.

Technological change and its associated productivity gain are engines of agricultural growth[31], yet are not exclusively due to improved genetics, mechanization or synthesized chemicals but also involve agro-ecological measures[8,37]. Invasive pests can cause large yield reductions (and coupled declines in land productivity) that can debilitate a country's agriculture sector and slow economic growth[38], with these impacts probably inflated in small economies or when degrading 'point-source' resources, for example, oilpalm plantations and associated export-geared value chains. Effective biological control of invasive pests can remove bottlenecks in farming operations, enabling permanent shifts of agricultural production isoquants[32] and potentially feeding forward into the overall economy[8,39]. Strong linkages exist between agricultural growth and the rural non-farm economy, with respective growth multipliers between 1.6 and 1.8 for Asia[38]. Considering how multipliers of Green Revolution agricultural growth differed between resource-endowed and marginal settings[9], we argue that biological control in (smallholder) non-rice crops such as cassava, banana or horticultural crops probably contributed to the stable, equitable 'miracle' growth of economies such as Indonesia[40]. In comparison with 'high-input' seed × agrochemical technologies, biological control can act as a self-sustaining innovation across sites with variable endowments and lift land productivity irrespective of local socioeconomic or biophysical context[32]. Furthermore, as a point-of-use cost-free alternative to input-intensive measures, biological control can improve financial solvency of farm operations—thereby alleviating poverty[39] and bolstering demand for consumer goods[38]. By elevating purchasing power of farm households while suspending backward linkages to (often foreign-owned) agrochemical suppliers[41], biological control potentially yielded higher multiplier effects to domestic economies than Green Revolution technology packages. Such household-level savings could be substantial, as exemplified by the US$1.3–2.3 billion yearly insecticide expenditure to tackle *Plutella xylostella* (Linneaus) in the world's cabbage crops[23]. Lastly, we theorize that a sequence of biological control successes in, for example, Indonesia or Philippines induced social-ecological change[32,42] that ultimately facilitated the roll-out of effective input-reduction initiatives such as UN-FAO's Farmer Field School programme[43].

Our projected US$14.6–19.5 billion regional benefit plausibly represents only a fraction of the full economic weight of biological control. Several caveats exist in our analysis: for example, uneven reporting of biological control outcomes between countries, a tendency for scientists to overstate impacts, irregular congruence between initial assessments and subsequent ground-truthing[44] and fragmented knowledge of in-country variability in incidence and impact of historic invaders. Conversely, production statistics for several pest-afflicted commodities are incomplete, unreliable or absent. Our estimates also do not account for cosmetic damage and quality loss to farm produce, foregone market opportunities, management costs[23], price shocks or rippling effects either backward or forward (that is, processors of raw produce such as copra) along the value chain—with the latter amplified by trade[45,46]. Moreover, various crops that were covered in biological control efforts (for example, banana and breadfruit) are not extensively traded in the marketplace and irregularly assigned a monetary value[19]. In addition, certain crops can overcompensate low-level pest attack[35]. The 30% lower estimated value of *E. thrax* biological control in Papua New Guinea (PNG), as compared to full-fledged assessments[19], exemplifies the conservative nature of our calculations even for a high-impact scenario.

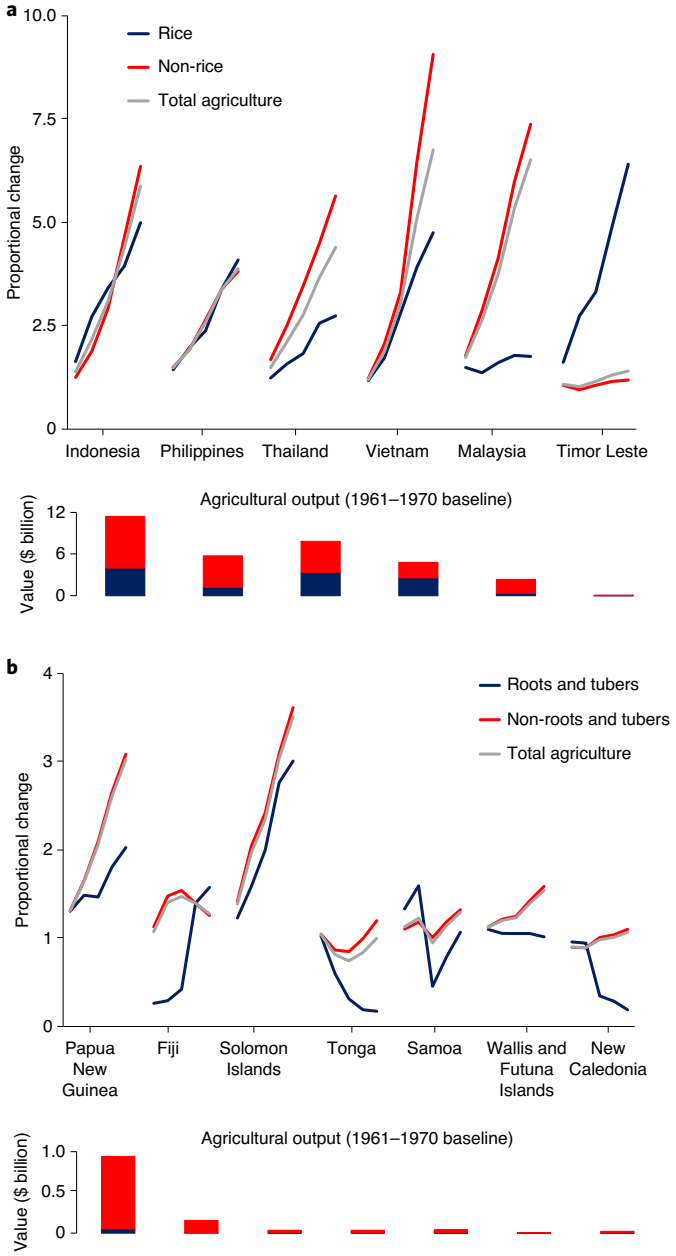


Fig. 4 | Differential growth trajectories of agricultural subsectors (food staple and non-staple crops) for selected geopolitical entities, over the period 1961–2016. a, For rice economies, graphs mirror the relative impact of Green Revolution rice technologies and other measures (for example, biological control) on yield or land productivity growth in rice and non-rice crops, respectively. **b**, For illustrative purposes, patterns are also shown for geopolitical entities that rely on root and tuber crops as primary food staples. Within **a** and **b**, countries are ranked in order of declining aggregate value of biological control interventions. For either food staples (red colour) or non-staple crops (blue), interdecadal proportional change in agricultural output is computed against a 1961–1970 baseline, shown as a bar chart below each graph ($ billion PPP). Agricultural output is expressed in monetary terms, as total value of agricultural production (2004–2006 average PPP $; FAO 2019).

The discipline of biological control finds itself at a crossroads. As pest–natural enemy interactions are tied to global environmental change[47], habitat loss, agrochemical pollution and insect biodiversity

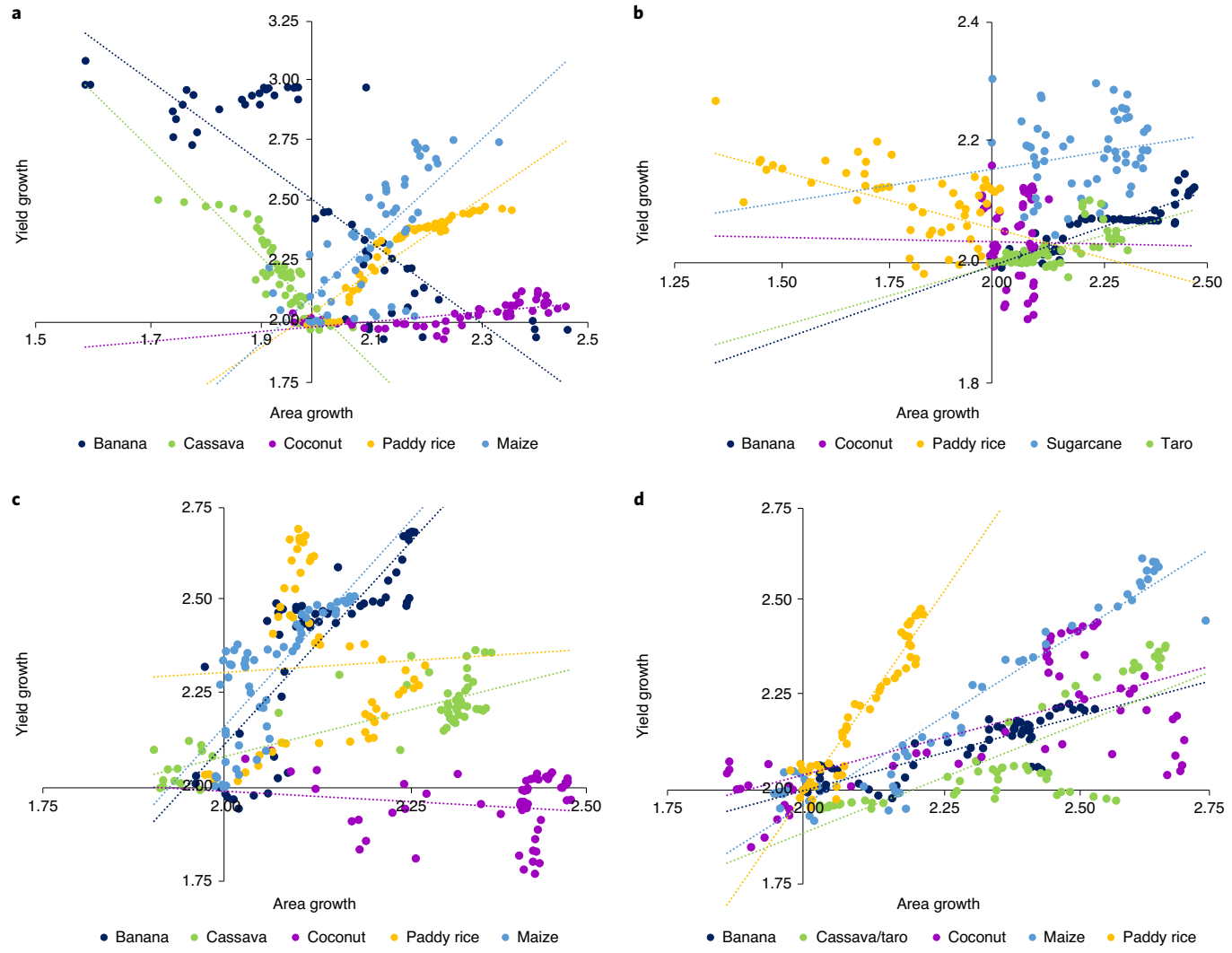


Fig. 5 | Time paths of land productivity (or yield) growth for different agricultural crops, over a 1961–2016 window. Interannual percentual growth (log_{10}) trajectories in area (*y* axis) and yield (*x* axis) for different crops are measured against a 1961 base year. **a**–**d**, Trends are presented for Indonesia (**a**), Melanesia (**b**), Philippines (**c**) and Vietnam (**d**). High-impact biological control interventions are made, at variable points in time often before 1960, in banana (Indonesia, Melanesia, Philippines), cassava (Indonesia, Vietnam), sugarcane (Melanesia), coconut (Indonesia, Melanesia, Philippines, Vietnam) and taro (Melanesia). Green Revolution dynamics for each geopolitical entity are reflected by time paths for paddy rice (and partially for corn). For each trendline, the intercept is reflective of past technological change in a particular cropping system. On the *x* and *y* axes, values above 2.0 reflect respective consecutive increases in cropping area and yield over time.

decline are causing net negative impacts[33]. Biological control equally suffers from declining institutional capacity, a lack of public recognition[48], fading attention by the CGIAR and increasingly stringent regulations[13]. Yet, modern biological control explicitly balances ecological risks with multifaceted benefits, and its judicious use can safely reduce invasive species impacts[17], ease vector-borne disease burden[49] and exert stabilizing effects on commodity markets[46]. Moreover, as biological control reconstituted 80% losses of breadfruit (the 'staff of life' of Pacific Islanders) or enhanced dietary carbohydrate intake of root, tuber and banana-consuming communities in eastern Indonesia and PNG, it potentially raised the carrying capacity of local food systems[9,50], enhanced workforce productivity[38] and generated 'win–win' outcomes for human and natural capital[51].

The Asia–Pacific region comprises prime biodiversity (island) 'hotspots' with high rates of endemism[27], which prove highly susceptible to species invasion or to misguided natural enemy releases, for example, as conducted pre-1945 in certain US territories[52]. For example, the ill-advised introduction of vertebrate predators such as the mosquitofish and cane toad during the period 1920–1940 or historic releases of the carnivorous snail *Euglandina rosea* (Ferussac) on various Pacific islands has caused lasting ecological damage[13]. Given that modern-day biological control aims to conserve local biota and restore native ecosystems[13,25], collaborative work between conservationists and crop protection scientists, for example, in island 'laboratories' can help define common denominators of success and raise rates of biological control success and ecological safety[53]. Also, it is important to underline how the chronicled events were made possible through dedicated science, globe-spanning partnerships and sustained funding commitments. As today's agricultural research-and-development investments dwindle[6], the relatively modest budget needs for biological control can be contrasted with its spillover benefits[12], the 40% of public funds diverted to 'maintenance research' for example, to resolve pesticide-induced resistance[54] and the vast sums of money that are currently rerouted to molecular or genomic sciences[48].

The Green Revolution is rightly credited with averting Malthusian famines, spurring structural transformation and delivering vast economic dividends[9,55]. While 'packaged' seed × chemical technologies in Asian paddy rice did secure an elevated supply of energy-dense foods, we argue that those achievements were paralleled by ecological innovations. In Green Revolution beneficiary nations such as Indonesia or the Philippines, successive waves of invasive species impacted 9–11 key agricultural commodities—often triggering food shortages, crippling rural agro-industries or cascading into chronic societal crises[19,26,42]. Scientifically guided biological control across this diverse portfolio of commodities helped solidify the agricultural base of heterogeneous rural settings, lowered poverty vulnerability and ultimately contributed to stable, sustainable and equitable growth of agricultural and non-farm sectors[8]. Moreover, the socioeconomic and environmental spin-offs of biological control plausibly outpace those of input-intensive Green Revolution technologies[2,3]. Given the impending change in global agrifood systems[4,8,30], our work underlines how nature-based solutions such as biological control can help secure a profitable production of sufficient nutrient-rich farm produce, while preserving our common natural heritage.

Methods

Data collection. As the basis for our assessment of historical biological control efforts, we consulted the BIOCAT2010.2 database[44] (ref. [56]). More specifically, we queried its 1 May 2017 updated version and extracted country-level records in August 2018 on natural enemy identity, release date, target pest and crop, and fate of the resulting biological control endeavour for all geopolitical entities within Southeast Asia (including South China), Melanesia, Micronesia and Polynesia. For subsequent analyses (see below), we also included records drawn from the global literature up to 2018. Only records of successful natural enemy establishment were retained and BIOCAT classifications were used to record locality-specific impacts of a given biological control event. On the latter, we exclusively considered events that resulted in either full or partial control of the target pest in any of its geopolitical areas. Also, we only accounted for efforts that targeted insect pests with a deployment of insect natural enemies, thus omitting introductions of entomopathogenic fungi, nematodes, viruses or bacteria. Detailed data on historical biological control interventions spanning an entire century (1918–2018) were thus collated, from which records for the US state of Hawaii were deleted. Similarly, for subsequent economic analyses, we removed data from the US territories of Guam and American Samoa and solely retained interventions that were aimed at resolving insect pest issues in the agriculture sector.

For macro-economic interpretations, the above dataset was complemented with a non-exhaustive review of the global literature for specific information pertaining to each invasive pest and introduced natural enemy (Supplementary Fig. 1). Google Scholar was used as a search engine to extract relevant records from the scientific literature, running queries between 15 May and 20 August 2019. More specifically, we screened the literature for data on pest-induced yield loss, pest incidence, natural enemy establishment and geographical spread, predation or parasitism levels, and extent of pest population reduction as mediated by biological control according to study authors (Supplementary Table 1; ref. [57]). The following search queries were adopted: ('biological control' OR 'predator' OR 'parasitoid' OR 'natural enemy' OR 'invasive') AND ('yield' OR 'productivity' OR 'incidence' OR 'loss' OR 'economic') AND 'country XX'. Additional searches were performed by specifying the scientific name of the target crop pest or natural enemy. For each literature record, information was extracted on geographical locality and host plant association of a given pest or natural enemy. If relevant data were available from publications that emanated from within the Asia–Pacific region, these were prioritized for subsequent analyses and economic interpretations. If country-specific records were absent for certain metrics (for example, pest-induced yield loss), these were complemented with literature records from other areas in the invaded range of a given pest (and introduced natural enemy). Despite eventual shortcomings within the original field studies, we tried to gauge pest-induced crop losses and yield recovery following biological control in a comprehensive fashion (see below). The latter was done using the BIOCAT classifications for biological control success rate, compiling 'complete' and 'substantial' control and treating 'partial' success separately. Also, although the original authors of the published studies potentially may have been biased towards reporting successes, overestimating success rates or inflating pest-induced crop losses, there were no other sources of bias in our work.

For each impacted crop, country-specific information on production statistics and pricing records was extracted from FAOSTAT (http://www.fao.org/faostat/) during August–October 2019. Crop- and country-specific data were thus collated on production level (harvested area, ha), yield (t ha^{-1}), total production quantity (t) and producer price (US$) for 2015, the most recent year for which data from most countries were available. We use the most complete and reliable production statistics but do not account for certain commodities that experienced important historic reductions in cropping area (for example, cassava in Indonesia). For geopolitical areas where no local information was available on producer prices for a given commodity, regionally averaged prices were used.

Data analysis and interpretation. Upon consolidation of all datasets, we plotted the number of biological control introductions over time and listed the identity of natural enemies (and associated pest targets) that were released in each geopolitical area. BIOCAT records were used to compute both country-level and regional rates of natural enemy establishment and success of the ensuing biological control efforts. Success rates were further compared between taxonomic hierarchies (order and species).

Given an overall absence of dependable, duly ground-truthed data on pest geographical distribution, incidence of pest attack and associated losses from the different Asia–Pacific countries over the period 1918–2018, several assumptions were made in our impact assessments. To quantify potential losses due to an invasive pest in a given area, we averaged maximum pest-inflicted productivity losses (percentual yield or marketability reduction, as extracted from the global literature) across its invaded localities and main host crops, and multiplied this by their respective 2015 local production quantity and producer price. Doing so often led to lower yield-loss estimates than in earlier invaded areas; for example, a 73% yield loss attributed to *Phenacoccus manihoti* attack on Asian cassava crops, as compared to an initial 80% loss in sub-Saharan Africa[58]. Despite eventual limitations and variable approaches to yield-loss assessment (for example, observational or experimental methods) in the original studies, we thus intended to gauge country-level impacts of each invasive pest in a consistent and comprehensive manner. Doing so yielded an (upper-bound) estimate of pest-inflicted economic losses, computed for current production scenarios in a particular area. This estimate was partially balanced by adopting a default value of 25% yield reduction for host crops of which pest-induced losses were unknown, which is a figure comparable to documented invasive pest impacts in the Asia–Pacific region and which does not account for further (off-farm) economic impacts. We quantified maximum economic loss as incurred by local farmers but did not account for losses along the value chain (including lowered consumer prices due to compromised produce quality), farm-level expenditures for pest management or foregone export earnings due to, for example, restricted international market access. Also, by using present-day FAOSTAT producer prices, we disregarded price elasticity in local markets following pest-induced changes to yield and production. As most commodities were non-traded and acted as key constituents of local diets (for example, pulses, banana and breadfruit), a perfectly inelastic demand could be assumed[58].

To then estimate economic benefits of a biological control intervention within a certain geographical setting, we adopted a conservative to high-impact scenario range. First, we multiplied the respective (pest-induced) economic loss with a BIOCAT-derived metric reflecting in-country success of the biological control effort. For instance, the banana skipper *E. thrax* caused 30% yield loss in the 76,000-ha banana crop of Papua New Guinea (total production: 1.2 million tonnes; producer value US$382 t^{-1}). The in-country release of the parasitoid *Cotesia erionotae* was deemed a 'complete success', resulting in a full, lasting suppression of *E. thrax* and an associated 100% yield-loss recovery (valued at US$136 million yr^{-1}). Such 100% yield-loss recovery does not assume an eradication of the invasive pest but reflects how introduced natural enemies can reduce pest populations below an economically damaging level. For natural enemies that resulted in variable rates of biological control success across the different countries or geopolitical entities in their introduced range, we used the highest level of success reported. In addition to a high-impact scenario, we considered a more conservative scenario by adopting either a 80–100% and 30–50% yield-loss recovery for fully or partially successful interventions respectively. Although the high-impact scenario probably captures an upper-bound of productivity gain following biological control, we concurrently do not account for non-negligible monetary benefits that accrue through lowered pest management costs (for example, expenditure on pesticide inputs), restored product quality, mitigated (either positive or negative) price shocks or cascading impacts along the produce value chain[22]. Both pest-induced economic losses and biological control related benefits were expressed in absolute terms and as percentage of the 2015 national GDP of each relevant country. To allow for eventual intercountry comparisons, GDP figures were calculated at PPP.

Macro-economic analyses. To track year-by-year land and labour productivity growth for each of the Asia–Pacific geopolitical entities, we used the graphical approach of Hayami and Ruttan[59]. More specifically, we expressed the value of country-level agricultural production and plotted the respective labour productivity as a measure of overall productivity. Aggregate agricultural production figures were drawn from FAOSTAT, with production value expressed in 2004–2006 average PPP prices (that is, international dollars). Estimates of agricultural labour employment and total agriculture area were obtained from the World Bank Data portal (https://data.worldbank.org/). This allowed visualizing starting points and temporal patterns in productivity growth for each country

over a 1960–2016 window, although agricultural employment figures were only available for most countries for 1991–2016. Similarly, through FAOSTAT, reliable agricultural production records for all Asia–Pacific countries or geopolitical entities were only available from 1960 onwards.

A comprehensive impact assessment of biological control interventions routinely entails contrasting crop yield or farm profitability pre- and post-intervention, or a comparison of yield trajectories between biological control recipient and non-recipient areas[28]. However, within the Asia–Pacific region, we encountered an overall absence of reliable historical records on yield of individual crops, pest invasion patterns, exact dates of country-level introductions and the ensuing establishment dynamics of biological control agents over the period 1918–2018. To address this data gap, we exclusively assessed the relative impact of (country-level) biological control interventions on land productivity growth over the period 1960–2016 and did so through a sequential process. To contrast impacts of biological control interventions on growth trends in non-staple crops with those emanating from Green Revolution rice technologies, we first computed the value of agricultural output of paddy rice in Asia's foremost rice economies and that of remaining agricultural produce for the respective country. For illustrative purposes, we also plotted patterns for countries that do not rely upon rice as primary food staple but instead mainly consume taro and sweet potato. The non-staple sector thus included all agricultural crops except for rice (that is, rice economies) or taro and sweet potato (that is, Melanesia). Second, we plotted growth trajectories of the above agricultural subsectors for each country or geopolitical entity, and measured interdecadal proportional change in respective output, as compared with a 1961–1970 baseline (averaged yearly agricultural output per country; US$ PPP). Third, for selected geopolitical entities, we drew time paths for different agricultural commodities including paddy rice and multiple biological control recipient crops, by plotting their respective interannual percentual growth in area (ha) versus yield ($t\,ha^{-1}$) against a 1961 base year. This allowed a quantitative partitioning of historical output growth for specific commodities among area expansion and yield enhancement, thus reflecting relative magnitude and type (land- or labour-saving) of commodity-specific technological change, for example, due to Green Revolution rice or biological control. For commodities that were covered in biological control campaigns, we equally compared year-by-year changes in yield growth with those of the locally prevailing food staple (paddy rice or taro—for Melanesia). When interpreting the above patterns, we recognize that myriad other exogenous and endogenous factors affect yields of a given crop within an Asia–Pacific country for example, by inducing technological and institutional innovation to varying degrees[32].

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

Data underlying the analyses are made available through Dryad Digital Repository at https://doi.org/10.5061/dryad.547d7wm45.

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References

1. Griggs, D. et al. Policy: sustainable development goals for people and planet. *Nature* **495**, 305–307 (2013).
2. Bernhardt, E. S., Rosi, E. J. & Gessner, M. O. Synthetic chemicals as agents of global change. *Front. Ecol. Environ.* **15**, 84–90 (2017).
3. Springmann, M. et al. Options for keeping the food system within environmental limits. *Nature* **562**, 519–525 (2018).
4. Pretty, J. et al. Global assessment of agricultural system redesign for sustainable intensification. *Nat. Sustain.* **1**, 441–446 (2018).
5. Rockström, J. et al. A safe operating space for humanity. *Nature* **461**, 472–475 (2009).
6. Alston, J. M. & Pardey, P. G. Agriculture in the global economy. *J. Econ. Perspect.* **28**, 121–146 (2014).
7. Johnston, B. F. & Mellor, J. W. The role of agriculture in economic development. *Am. Econ. Rev.* **51**, 566–593 (1961).
8. de Janvry, A. Agriculture for development: new paradigm and options for success. *Agric. Econ.* **41**, 17–36 (2010).
9. Pingali, P. L. Green revolution: impacts, limits, and the path ahead. *Proc. Natl. Acad. Sci. USA* **109**, 12302–12308 (2012).
10. Sayer, J. & Cassman, K. G. Agricultural innovation to protect the environment. *Proc. Natl Acad. Sci. USA* **110**, 8345–8348 (2013).
11. Bale, J. S., Van Lenteren, J. C. & Bigler, F. Biological control and sustainable food production. *Phil. Trans. R. Soc. B* **363**, 761–776 (2008).
12. Naranjo, S. E., Ellsworth, P. C. & Frisvold, G. B. Economic value of biological control in integrated pest management of managed plant systems. *Annu. Rev. Entomol.* **60**, 621–645 (2015).
13. Heimpel, G. E. & Cock, M. J. W. Shifting paradigms in the history of classical biological control. *BioControl* **63**, 27–37 (2018).
14. Simmonds, F. J., Franz, J. M., & Sailer, R. I. in *Theory and Practice of Biological Control* (eds Huffaker, C. B. & Messenger, P. S.) 17–39 (Academic Press, 1976).
15. Maredia, M. K. & Raitzer, D. A. Estimating overall returns to international agricultural research in Africa through benefit–cost analysis: a "best-evidence" approach. *Agric. Econ.* **41**, 81–100 (2010).
16. Nghiem, L. T. et al. Economic and environmental impacts of harmful non-indigenous species in Southeast Asia. *PLoS ONE* **8**, e71255 (2013).
17. Bradshaw, C. J. et al. Massive yet grossly underestimated global costs of invasive insects. *Nat. Commun.* **7**, 12986 (2016).
18. Huffaker, C. B. & Caltagirone, L. E. The impact of biological control on the development of the Pacific. *Agric. Ecosyst. Environ.* **15**, 95–107 (1986).
19. Waterhouse, D. F., Dillon, B. & Vincent, D. P. *Economic Benefits to Papua New Guinea and Australia from the Biological Control of Banana Skipper (Erionota thrax)* No. 434-2016-33658 (ACIAR, 1998).
20. DeBach, P. & Rosen, D. *Biological Control by Natural Enemies* (Cambridge Univ. Press, 1991).
21. Heimpel, G. E. & Mills, N. J. *Biological Control* (Cambridge Univ. Press, 2017).
22. Spennemann, D. H. Introduction of coccinellid beetles to control the coconut scale insect *Aspidiotus destructor* Signoret in Micronesia 1901–1914. *Oriental Insects* **54**, 197–215 (2019).
23. Zalucki, M. P. et al. Estimating the economic cost of one of the world's major insect pests, *Plutella xylostella* (Lepidoptera: Plutellidae): just how long is a piece of string? *J. Econ. Entomol.* **105**, 1115–1129 (2012).
24. Hoddle, M. S. Restoring balance: using exotic species to control invasive exotic species. *Conserv. Biol.* **18**, 38–49 (2004).
25. Van Driesche, R. G. et al. Classical biological control for the protection of natural ecosystems. *Biol. Control* **54**, S2–S33 (2010).
26. Ricciardi, A., Palmer, M. E. & Yan, N. D. Should biological invasions be managed as natural disasters? *BioScience* **61**, 312–317 (2011).
27. Bellard, C. et al. A global picture of biological invasion threat on islands. *Nat. Ecol. Evol.* **1**, 1862–1869 (2017).
28. Naranjo, S. E., Frisvold, G. B. & Ellsworth, P. C. in *The Economics of Integrated Pest Management of Insects* (eds Onstad, D. W. & Crain, P. R.) 49–85 (CAB International, 2019).
29. Liu, J. et al. Systems integration for global sustainability. *Science* **347**, 1258832 (2015).
30. Gordon, L. J. et al. Rewiring food systems to enhance human health and biosphere stewardship. *Environ. Res. Lett.* **12**, 100201 (2017).
31. Ruttan, V. W. Productivity growth in world agriculture: sources and constraints. *J. Econ. Perspect.* **16**, 161–184 (2002).
32. Ruttan, V. W. & Hayami, Y. in *International Agricultural Development* (eds Eicher, C. K. & Staatz, J. M.) Ch. 10 (Johns Hopkins Univ. Press, 1998).
33. Dainese, M. et al. A global synthesis reveals biodiversity-mediated benefits for crop production. *Sci. Adv.* **5**, eaax012 (2019).
34. Keane, R. M. & Crawley, M. J. Exotic plant invasions and the enemy release hypothesis. *Trends Ecol. Evol.* **17**, 164–170 (2002).
35. Thancharoen, A. et al. Effective biological control of an invasive mealybug pest enhances root yield in cassava. *J. Pest Sci.* **91**, 1199–1211 (2018).
36. Raitzer, D. A. & Kelley, T. G. Benefit–cost meta-analysis of investment in the International Agricultural Research Centers of the CGIAR. *Agric. Syst.* **96**, 108–123 (2008).
37. van der Ploeg, J. D. et al. The economic potential of agroecology: empirical evidence from Europe. *J. Rural Stud.* **71**, 46–61 (2019).
38. Haggblade, S., Hazell, P. B. & Dorosh, P. A. in *Transforming the Rural Nonfarm Economy: Opportunities and Threats in the Developing World* (eds Haggblade, S. et al.) Ch. 7 (IFPRI, 2007).
39. Wiggins, S., Kirsten, J. & Llambí, L. The future of small farms. *World Dev.* **38**, 1341–1348 (2010).
40. Timmer, P. C. in *International Agricultural Development* (eds Eicher, C. K. & Staatz, J. M.) Ch. 32 (Johns Hopkins Univ. Press, 1998).
41. Folke, C. et al. Transnational corporations and the challenge of biosphere stewardship. *Nat. Ecol. Evol.* **3**, 1396–1403 (2019).
42. Yletyinen, J. et al. Understanding and managing social-ecological tipping points in primary industries. *BioScience* **69**, 335–347 (2019).
43. Bottrell, D. G. & Schoenly, K. G. Resurrecting the ghost of green revolutions past: the brown planthopper as a recurring threat to high-yielding rice production in tropical Asia. *J. Asia-Pacific Entomol.* **15**, 122–140 (2012).
44. Cock, M. J. W. et al. Trends in the classical biological control of insect pests by insects: an update of the BIOCAT database. *Biocontrol* **61**, 349–363 (2016).
45. Reardon, T. The hidden middle: the quiet revolution in the midstream of agrifood value chains in developing countries. *Oxford Rev. Econ. Policy* **31**, 45–63 (2015).
46. Wyckhuys, K. A. G. Biological control of an invasive pest eases pressures on global commodity markets. *Environ. Res. Lett.* **13**, 094005 (2018).
47. Martin, E. A. et al. Assessing the resilience of 2 biodiversity-driven functions in agroecosystems under environmental change. *Adv. Ecol. Res.* **60**, 59–123 (2019).

48. Warner, K. D. et al. The decline of public interest agricultural science and the dubious future of crop biological control in California. *Agric. Human Values* **28**, 483–496 (2011).
49. Benelli, G., Jeffries, C. L. & Walker, T. Biological control of mosquito vectors: past, present, and future. *Insects* **7**, 52 (2016).
50. Dangour, A. D., Mace, G. & Shankar, B. Food systems, nutrition, health and the environment. *Lancet Planet. Health* **1**, e8–e9 (2017).
51. Rasmussen, L. V. et al. Social-ecological outcomes of agricultural intensification. *Nat. Sustain.* **1**, 275–282 (2018).
52. Henneman, M. L. & Memmott, J. Infiltration of a Hawaiian community by introduced biological control agents. *Science* **293**, 1314–1316 (2001).
53. Stiling, P. & Cornelissen, T. What makes a successful biocontrol agent? A meta-analysis of biological control agent performance. *Biol. Control* **34**, 236–246 (2005).
54. Sparger, J. A. et al. Is the share of agricultural maintenance research rising in the United States? *Food Policy* **38**, 126–135 (2013).
55. Trewavas, A. Malthus foiled again and again. *Nature* **418**, 668–670 (2002).
56. Greathead, D. J. & Greathead, A. H. Biological control of insect pests by insect parasitoids and predators: the BIOCAT database. *Biocontrol News Inf.* **13**, 61N–68N (1992).
57. Wyckhuys, K. A. G. et al. *Data from: Ecological pest control fortifies agricultural growth in Asia-Pacific economies* (Dryad Digital Repository, 2020); https://doi.org/10.5061/dryad.547d7wm45
58. Zeddies, J., Schaab, R. P., Neuenschwander, P. & Herren, H. R. Economics of biological control of cassava mealybug in Africa. *Agric. Econ.* **24**, 209–219 (2001).
59. Hayami, Y. & Ruttan, V. W. *Agricultural Development: An International Perspective* (Johns Hopkins Univ. Press, 1971).

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Author contributions

K.A.G.W. conceived and designed the experimental approach. K.A.G.W. performed trials and collected the data. K.A.G.W., Y.L. and W.Z. analysed the data. K.A.G.W., Y.L., W.Z., M.J.W.C., S.E.N., A.F., F.E.W. and M.J.F. co-wrote the paper.

Competing interests

K.A.G.W. is chief executive officer of Chrysalis Consulting, a firm that provides tailored support to biological control and biodiversity-friendly agriculture initiatives. The other authors declare no competing interests.

Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41559-020-01294-y.

Supplementary information is available for this paper at https://doi.org/10.1038/s41559-020-01294-y.

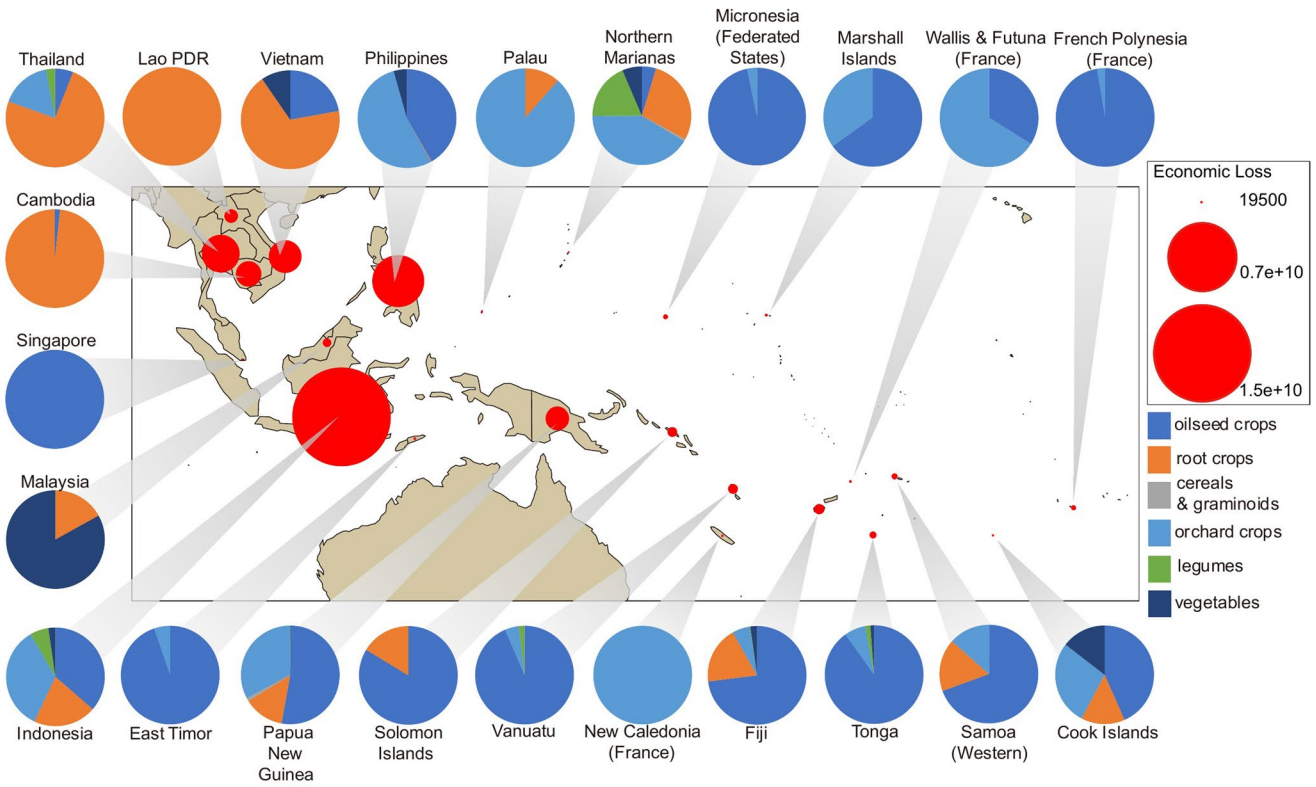
Correspondence and requests for materials should be addressed to K.A.G.W., Y.L. or W.Z.

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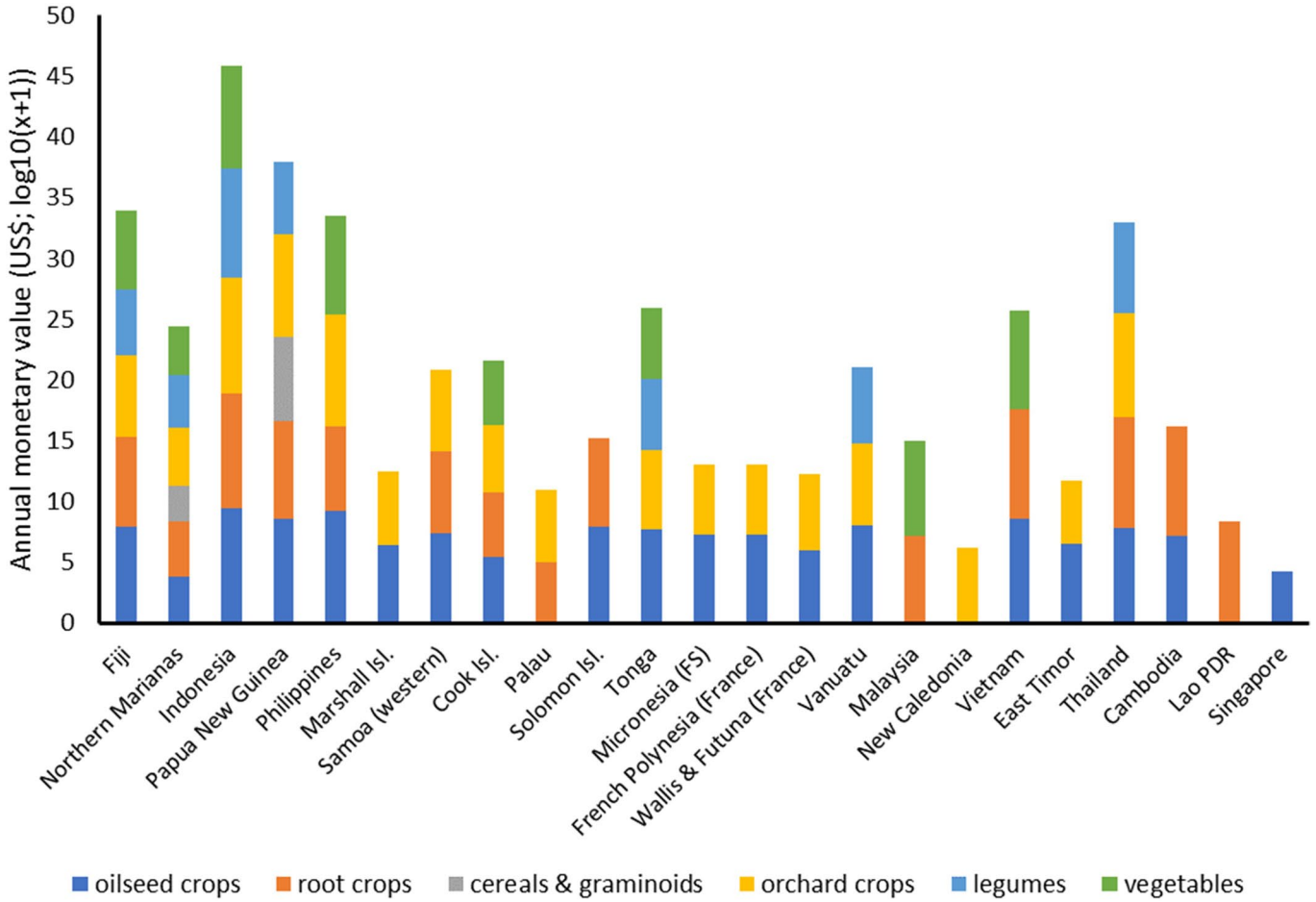
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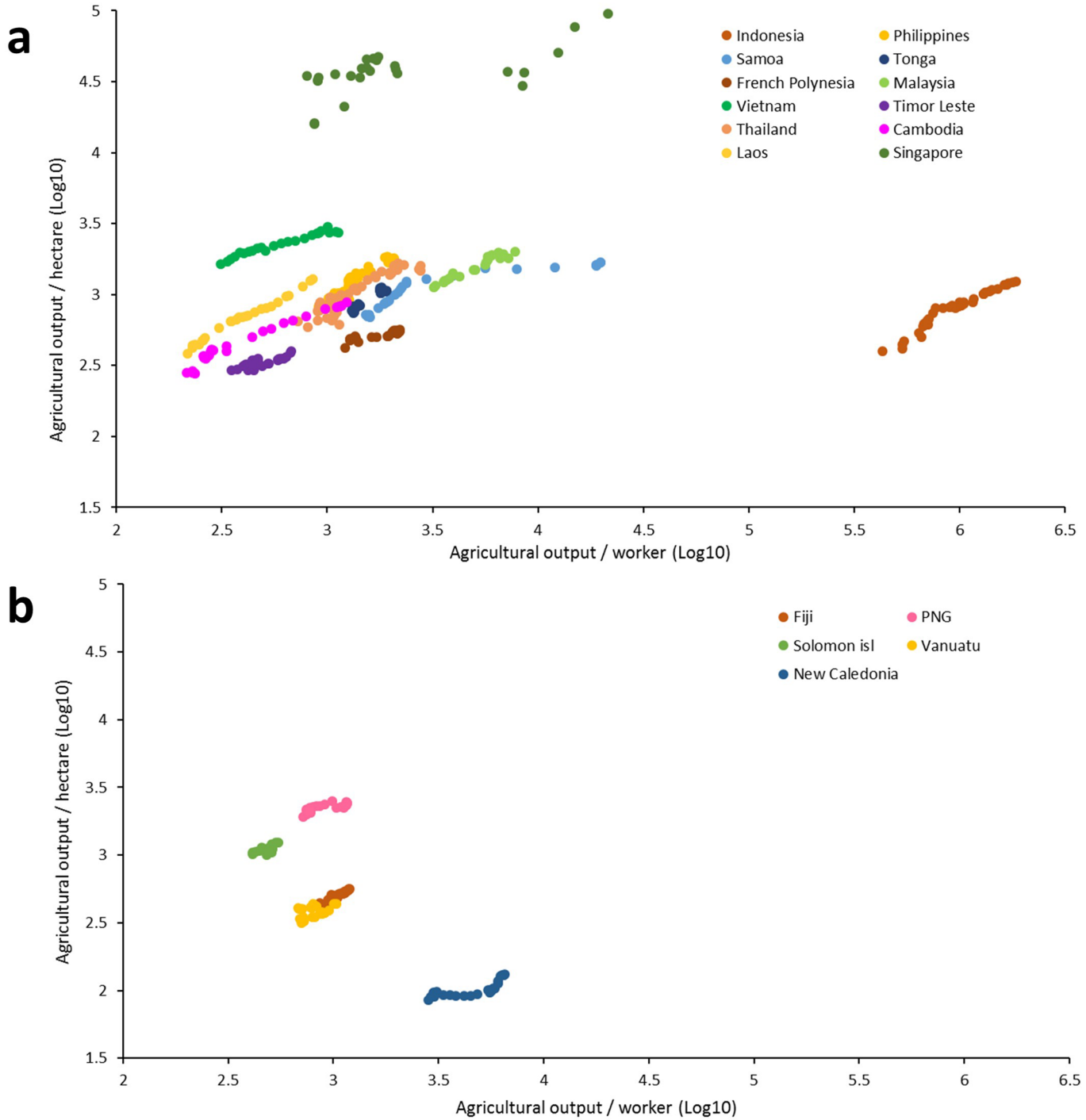
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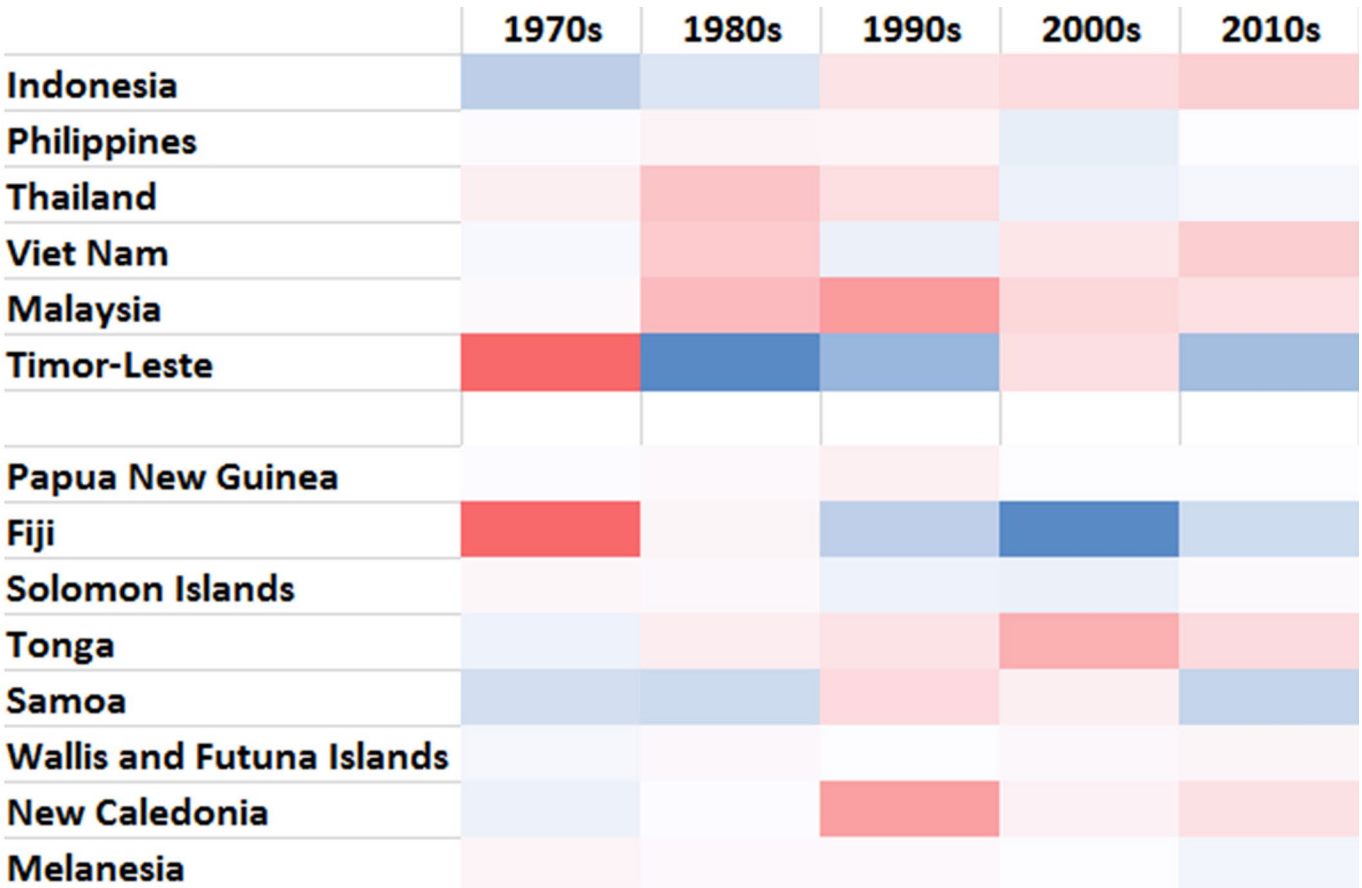
Extended Data Fig. 1 | Country-level economic impact (US $) of historic pest invasions that were either partially or completely resolved through biological control. For each country or geopolitical entity, the size of the red circle reflects the aggregate annual monetary impact of invasive crop pests over 1918–2018. Country-specific pie charts indicate the exact portfolio of commodities that benefited from invertebrate biological control, with the size of each slice reflecting the economic impact of respective pest invaders.



Extended Data Fig. 2 | Economic value of historic BC-mediated invasive pest mitigation, as aggregated per country and agriculture subsector. Annual monetary benefits are exclusively shown for a 'high impact' scenario - comprising invasive insect pests that were either partially or fully controlled through biological control, over 1918–2018. For each country, log-transformed impact values are calculated per agriculture sub-sector and stacked. Oilseed crops include coconut and oilpalm; root crops cover cassava and taro; while orchard crops cover banana, breadfruit, cocoa, coffee and a range of perennial or annual fruit crops.



Extended Data Fig. 3 | Historical trends in land and labour productivity across the Asia-Pacific region and for the Melanesia island group specifically (1961–2016). Agricultural output is expressed as the total value of agricultural production in 2004–2006 average purchasing power parity (PPP) agricultural prices (i.e., international dollars). Patterns are shown in panel a and b for different groups of countries / geopolitical entities. For most nations, agricultural employment figures were only be available from 1991 onward.



Extended Data Fig. 4 | Interdecadal growth spurts of distinct agricultural subsectors (that is, food staple, non-staple crops) for selected geopolitical entities within the Asia-Pacific region, over 1961–2016. Inter-decadal patterns are presented for geopolitical entities that either rely upon rice (top) or root & tuber crops (i.e., taro, sweet potato; bottom) as primary food staples. Within each heat map, proportional changes in the relative growth of food staple and non-staple crops over successive decades are depicted by a color scale. Bluer tones reflect relatively rapid growth of the staple crop output, while redder tones mirror more rapid growth of non-staple crops. Agricultural output is expressed in monetary terms, as total value of agricultural production (2004–2006 average PPP $; FAO 2019).

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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	Not applicable
Data analysis	Not applicable

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors/reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Research guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A list of figures that have associated raw data
- A description of any restrictions on data availability

Data underlying the analyses are made available through Dryad Digital Repository at https://doi.org/10.5061/dryad.547d7wm45.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☒ Behavioural & social sciences ☐ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Behavioural & social sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	Assess occurrence, fate and (on-farm) economic benefit of historical insect biological control introductions
Research sample	Historic accounts of 75 different biological control introductions (against multiple invasive pest targets) over a 1918-2018 timespan - covering occurrence / geographical coverage, fate, yield loss recovery and associated productivity growth trajectories of the target commodity.
Sampling strategy	Data extraction from existing database and the global scientific literature.
Data collection	Data extraction from the 2017 updated version of the BIOCAT2010.2 database, covering country-level records on natural enemy identity, release date, target pest and crop, and fate for all geopolitical entities. BIOCAT records complemented with a non-exhaustive review of the global literature for specific information pertaining to each invasive pest and introduced natural enemy.
Timing	Literature queries run between May 15 and August 20, 2019; FAOSTAT data access during August - October 2019.
Data exclusions	Records for the US State of Hawaii were deleted; for subsequent economic analyses, data from the US territories of Guam and American Samoa were removed & records were only retained for pest issues affecting the agriculture and livestock production sector.
Non-participation	Not applicable
Randomization	Not applicable

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology
☒	☐ Animals and other organisms
☒	☐ Human research participants
☒	☐ Clinical data

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging