Biological control of an invasive pest eases pressures on global commodity markets

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Abstract

In an increasingly globalized world, invasive species cause major human, financial, and environmental costs. A cosmopolitan pest of great concern is the cassava mealybug Phenacoccus manihoti (Hemiptera: Pseudococcidae), which invaded Asia in 2008. Following its arrival, P. manihoti inflicted measurable yield losses and a 27% drop in aggregate cassava production in Thailand. As Thailand is a vital exporter of cassava-derived commodities to China and supplies 36% of the world’s internationally-traded starch, yield shocks triggered price surges and structural changes in global starch trade. In 2009 a biological control agent was introduced in Asia—the host-specific parasitoid, Anagyrus lopezi (Hymenoptera: Encyrtidae). This parasitoid had previously controlled the cassava mealybug in Africa, and its introduction in Asia restored yield levels at a continent-wide scale. Trade network and price time-series analyses reveal how both mealybug-induced production loss and subsequent parasitoid-mediated yield recovery coincided with price fluctuations in futures and spot markets, with important cascading effects on globe-spanning trade networks of (cassava) starch and commodity substitutes. While our analyses may not imply causality, especially given the concurrent 2007–2011 food crises, our results do illuminate the important interconnections among subcomponents of the global commodity system. Our work underlines how ecologically-based tactics support resilience and safeguard primary productivity in (tropical) agro-ecosystems, which in turn help stabilize commodity markets in a similar way as pesticide-centered approaches. Yet, more importantly, (judiciously-implemented) biological control can deliver ample ‘hidden’ environmental and human-health benefits that are not captured by the prices of globally-traded commodities.

Introduction

Globalization is rapidly transforming our planet and altering the way food is produced, traded, and consumed. About a quarter of the global volume of agricultural goods are now traded internationally between production and consumption. The global volume of food commodity exports has increased by >60% over the past two decades, and the number of international trade links continues to swell (Ducruet and Notteboom 2012, D’Odorico et al 2014, Carrasco et al 2017). Valued at >US$520 billion annually, the
world’s international food commodity trade presently draws upon at least 13% of the world’s pastures and cropland (MacDonald et al. 2015).

International trade brings about substantial economic, environmental, and societal benefits (Yang et al. 2006, Gephart and Pace 2015, Martinez-Melendez and Bennett 2016), but the externalities of this trade can shift ecosystem dynamics, aggravate environmental pollution, or modify ecosystem stocks and flows, often over large geographical scales (De Fries et al. 2010, O’Bannon et al. 2014, Pace and Gephart 2017). Trade also notoriously facilitates the arrival and spread of invasive species, exacerbates pressures on biodiversity, and undermines ecological resilience, particularly in the developing-world tropics (Hulme 2009, Lenzen et al. 2012, Steffen et al. 2015, Bradshaw et al. 2016). Despite this close interplay between the make-up and resilience of local (natural and agricultural) ecosystems and global food trade, ecologists rarely pay attention to commodity trade and financial markets (Pace and Gephart 2017, Galaz et al. 2015), while finance routinely ignores ecology (May et al. 2008, Scholten 2017).

Trade has become a potent force in enabling ‘tele-coupling’, a concept encompassing both environmental and socio-economic linkages between different regions of the globe (Liu et al. 2013). For example, tele-coupling links global increases in meat consumption to livestock over-grazing in Inner Mongolia (China), with cascading effects on soil degradation and severity of locust outbreaks (Cease et al. 2016). Tele-coupling enables the propagation of shocks, such as crop failure or environmental disasters, at a confined geographical location through commodity trade networks (Heady 2011, Puma et al. 2015, Gephart et al. 2016). Within these globe-spanning, coupled social-ecological systems, our inability to understand, predict, and control various types of interactions enhances systems’ inherent vulnerability to failure and further drives them toward instability (Helbing 2013). In the meantime, present conceptual and analytical frameworks tend to obscure potentially stabilizing forces (Crona et al. 2016).

Every major agricultural commodity shares in this tele-coupling, with the network of connections being highly heterogeneous across scales and commodity types. A number of commodities are themselves coupled and, consequently, shocks affecting one member of a group will often ripple across its members. This phenomenon is highly evident in association with the global starch market. Starch is a heterogeneous agricultural commodity and traded at a global scale. Differentiated starches derive from maize, potatoes, and wheat in the developed world, and from cassava in the tropics (Oster tag 1996). Worldwide, the most important source of internationally-traded starch is cassava; a widely-grown semi-perennial root crop that’s routinely harvested at 9–12 months. Cassava (or tapioca) plays a major role as a food staple in Africa, while in Asia it is mainly used for animal feed, ethanol, starch-based food products, sweeteners, fermentation products (e.g., MSG, lysine acid), or household items (Fuglie 2004, Delaquis et al. 2017).

Cultivated by >8 million farming families, Asia’s cassava crops proved virtually free of yield-limiting biotic constraints until the early 2000s (Graziosi et al. 2016). The 2008 invasion and ensuing continent-wide spread of the cassava mealybug, Phenacoccus manihoti (Hemiptera: Pseudococcidae) caused substantial cassava productivity losses in Thailand and neighboring countries. Over 2009–10, the Thai Royal Government mitigated P. manihoti attack through importation biological control (IBC; also known as ‘classical biological control’), which is the judicious selection and subsequent introduction of an effective, host-specific natural enemy from the pest’s region of origin (van Driesche et al. 2008, Heimpel and Mills 2017). IBC efforts were guided by a widely-acclaimed program against P. manihoti in Africa during the 1980s, which resulted in a continent-wide 50% recovery from yield loss and long-term economic benefits with net present value up to US $20.2 billion without negative ecological side effects (Herren and Neuenschwander, 1991, Zeddies et al. 2001). Key to success of this biological control program was the host-specific and environmentally-adaptable parasitic wasp Anagyrus lopezi (Hymenoptera: Encyrtidae), recovered in 1981 from Brazil’s Mato Grosso do Sul and the Paraguay River basin during a foreign exploration. In late 2009, soon after the mealybug appeared in Asia, this same parasitoid was collected in Benin, West Africa, and released at a nationwide scale in Thailand in mid-2010 (Winotai et al. 2010), followed by Cambodia and Laos (in 2011), Vietnam (2013), and Indonesia (2014) (see also Wyckhuys et al. 2018). In a first exploratory assessment of parasitoid establishment and impact, A. lopezi was reported from mealybug-affected fields at parasitism levels of 10%–57% (Wyckhuys et al. 2017), oscillated with local P. manihoti populations (Le et al. 2018) and enabled a lasting recovery of fresh root yield by 5.3–10.0 t/ha (Thancharoen et al. 2018, Wyckhuys et al. 2018).

In this study, we characterized the extent to which invasive pest proliferation and IBC may have interacted with the global bilateral starch trade network and pricing of multiple related agricultural commodities. Our work uses both primary and secondary data sets to illuminate how IBC-mediated pest suppression can affect global agricultural trade and have cascading impacts on related commodity prices. The events chronicled here coincide with the global food crises of 2007–2008 and 2010–2011 during which prices for globally-traded, commodity food crops—such as cassava—rose dramatically (Heady and Fan 2008). While we recognize the multi-causal nature of tele-coupling and the difficulty of unambiguously identifying drivers of shifts in pricing and trade flows, our research illustrates how ecologically-based pest management tactics help to restore the resilience of tropical
agro-ecosystems with potentially far-reaching societal benefits at a macro-scale through trade.

Materials and methods

Our study consisted of four different components, building from local information to global trends: insect surveys, analysis of production and export flows, trade network assessments, and time-series analyses. First, we employed region-wide surveys to quantify the magnitude and spatial extent of parasitoid-mediated *P. manihoti* population suppression (section 1). Second, we analyzed trends in production statistics and export prices for a select set of related commodities in Thailand over varying time periods (section 2). Third, we used network methods to examine shifts in global starch trade and cassava commodity exports from Thailand from 2005 until 2013 (section 3). Finally, we used a vector autoregressive time-series model (Stock and Watson 2001, Becketti 2013) to explore how the 2009–11 productivity loss and subsequent *A. lopezi*-mediated yield-loss recovery (2011–2013) were related to commodity prices in futures and spot markets for a set of competing (starch) crops (section 4). To fully capture IBC implications for Asia’s cassava crop, cassava starch exports and dynamics within the globe-spanning starch market, our analyses are conducted through lenses at varying spatial scale: trends in cassava production in Thailand and associated starch exports (sections 2, 3), mealybug pest and *A. lopezi* population levels impacting cassava crops across Southeast Asia (section 1), and the global starch market as affected by other traded agricultural commodities such as China corn, USA wheat or UK potato (section 4). See supporting information for further details regarding the methodology for each of the above sections.

Results

Regional pest and parasitoid survey

Multi-country surveys revealed that *P. manihoti* was the most abundant and widespread mealybug in local cassava crops during 2014–2017, and was recorded from 37.0% (n = 549) and 100% of fields (n = 52) in mainland SE Asia and Indonesia, respectively (figure 1) (Wyckhuys et al 2018). Among sites, *P. manihoti* reached field-level incidence of 7.6 ± 15.9% (mean ± SD; i.e., proportion mealybug-affected tips) and abundance of 5.2 ± 19.8 insects per infested tip in mainland SE Asia, and incidence rates of 52.7 ± 30.9% and 42.5 ± 67.7 individuals per tip in Indonesia. Field-level incidence and population abundance were highly variable among production contexts and countries, reaching respective (field-level) maxima of 100%, and 412.0 individuals per tip in eastern Indonesia. *A. lopezi* wasps were present in 96.9% of mealybug-affected fields (n = 97) in mainland SE Asia, yet were only encountered in 36.5% of sites (n = 52) in Indonesia. Rates of parasitism (i.e. the proportion of *P. manihoti* parasitized) were highly variable among sites, with marked differences between low-input systems and intensified systems, sites at different stages of the *P. manihoti* invasion and *A. lopezi* establishment, or sites with sandy, low fertility soil (figure 1). For example, in intensified systems, parasitism rates ranged from 10.7 ± 10.6% (n = 20; Dong Nai, Vietnam) to 67.1 ± 20.8% (n = 22) in late dry season in Tay Ninh (Vietnam). In fields where *A. lopezi* had effectively established, mealybug pressure was lower and associated with increasing levels of parasitism, reflecting suppression of local mealybug populations by the introduced wasp (ANOVA, F1,98 = 13.162, p < 0.001; R² = 0.118) (see also Wyckhuys et al 2018).

Historical cassava production, export and pricing statistics in Thailand

From 2006 until 2016, between 1.07 million and 1.45 million ha of cassava were harvested annually in Thailand. Cassava area steadily increased to 1.32 million ha in 2009, and subsequently fell to 1.18 million (2010) and 1.13 million ha (2011). This area decline coincided with country-wide *P. manihoti* outbreaks during 2009 (following the initial mealybug detection in 2008), as reported from at least 230 000 ha (Rojanaridpiched et al 2013, figure 2). The 2009–2011 area decline was concurrent with soaring prices of fresh cassava and starch (see below), and with province-level drops in crop yield by 12.59 ± 9.78% nationwide. Furthermore, country-wide aggregate yields declined from 22.67 to 18.57 t/ha, and total production dropped by 26.86% to 22.01 million tonnes of fresh root. By 2012, yields were partially restored and steadily increased to 21.42 ± 1.96 t/ha by 2015. Trends in regional cassava production partially mirrored patterns of those in Thailand: total production initially increased to 66.93 million tonnes in 2009 (yields of 19.42 t/ha), then fell to 62.04 million tonnes in 2010 (18.56 t/ha). While Thai production declined from 2009 to 2011, crop output surged in neighboring Cambodia, Lao PDR, Myanmar and Vietnam, with respective increases of 129.7%, 387.0%, 52.8%, and 16.0% over the same period (as related to a notable area expansion). As Thailand sources cassava from several neighboring countries, this area expansion—particularly during 2010–2011—helped meet national domestic demand for raw cassava and its derived products.

Over 2008–2016, Thailand’s trade in cassava-derived commodities represented an annual volume of 8.75 ± 2.31 million tonnes, at a value of US$ 2.58 ± 0.72 billion (figure 3). Exports were composed of 26% native starch, 9% modified starch, 56% chips, 3% pellets and 6% pulp in volume. From 2009 to 2011, total exports of cassava and its derivatives dropped by 6.1% in volume (or 445 761 tonnes) though its value increased by 59%,
suggesting under-supply and over-demand. Also, average annual prices increased by 66.2% (native starch), 34.5% (modified starch), 73.1% (chips), 76.2% (pellets) and 97.3% (pulp) (figure 4(A)). However, starch prices proved particularly volatile, with 138% and 162% increases in domestic and export prices respectively during July–August 2010 (figure 5). By July 2011, both domestic and export prices of Thai cassava starch had returned to equilibrium levels of 11–14.7 Baht kg⁻¹.

Structure and evolution of the cassava trade network
From 2005 to 2015, the global starch market more than doubled in volume from 3.84 million tonnes (106 exporters) to 7.98 million tonnes (116 exporters), representing an increase in value from US$1.10 billion to over $4.90 billion. Within this market, cassava starch occupied 47.1% in volume (and 30.7% in value) in 2005, and 62.9% (31.2% in value) in 2015. In 2015,
the 5.02 million tonnes of cassava starch were exported by 69 countries, of which Thailand accounted for at least 57.5% of volume and 75.9% of value. Throughout a 10 year time period covering two global food crises (i.e., 2007–2008, 2010–2011), Thailand’s cassava crop output and starch prices shifted as subject to international demand. Yet, from 2010 to 2011, price surges coincided with an 8 million ton drop in national cassava production as linked to *P. manihoti*-induced productivity loss (see also figure 4(B)). Within the export starch trade network, Thailand consistently represented the largest export flow, covering 36.9% of global trade in 2005 (in volume), and at least 36.3% in 2015 (figure 3). Thai starch exports consisted of 95.1% and 99.5% (volume) of cassava starch during both years, with similar shares of cassava starch in the starch trade noted for Vietnam. From 2009 to 2011, during the mealybug outbreak, there were notable structural changes in the cassava-derived commodity trade network with trade volumes
decreasing and trade values increasing (table 1). In 2009, when *P. manihoti* invaded, Thailand exported varying volumes of starch, tapioca pearl and other derivatives, and cassava roots, chips or pellets (RCP; table 1). Thai cassava exports went to a total of 98 (starch), 69 (tapioca pearl), and 25 (chips, pellets) countries (UN Comtrade). Exports of certain commodities declined substantially while that of others maintained relatively constant. The largest drops in volume were recorded for cassava roots and chips RCP (−14.3%), while traded volumes of processed commodities were less affected; the latter possibly driven by prices. RCP rely more on local supply as compared to starch, and impacts on processed commodities can be mitigated through storage and increased import of raw commodities. Furthermore, during the 2009–2011 mealybug outbreak, the (per-unit) value of globally-traded RCP (HS 71 410), starch (HS 110814), and tapioca pearl (HS 1903) increased by 88.6%, 81.7%, and 54.2%, respectively. Per-unit value shifts varied among the world’s regions, with the greatest increase for RCP to Europe and the Middle East (+311%–449%), for starch to the Americas (+102%), and for tapioca pearls to Africa (+83.6%).

From 2011 to 2013, when *A. lopezi*-mediated yield recovery was occurring in Thailand and neighboring countries, these structural changes in cassava-derived commodities reversed with trade volumes increasing and trade values decreasing (table 1). While RCP exports increased by 55.7%, traded volumes of tapioca pearls and other substitutes dropped by 12.6%. Per-unit value of RCP, starch, and tapioca pearls decreased by 13.5%, 5.3%, and increased by 7.4%, respectively. Per-unit value shifts again varied between regions, with the greatest decrease for RCP to the Middle East (−91.6%), for starch to the Americas (−21.5%), and

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**Figure 4.** Surge in average export price (US$/t FOB Bangkok) of Thai cassava starch following the late 2008 invasion of the cassava mealybug. The upper panel provides a breakdown of price trends, for multiple commodities include total starch and derivatives (i.e., native starch, modified starch), cassava chips and pulp. From 2011 onward, when *A. lopezi* had established and spread across mainland Southeast Asia, price levels of the various commodities are gradually yet differentially restored. The lower panel contrasts price trends for Thai cassava starch with temporal shifts in the FAO Food Price Index, and fluctuations in country-level cassava production.
for tapioca pearls to Africa (−9.6%). Hence, as Thailand’s cassava crop yields increased following IBC, export levels of the country’s cassava commodities were restored and (per-unit) export value lowered.

Over 2008–2013, complementary changes occurred in the imports of cassava-based commodities into Thailand, likely to meet growing global demand (for its in-country cassava-based industries) and under-supply through national production. In 2009, Thailand imported 324 171 tonnes of RCP (6 trade partner countries, as revealed through UN Comtrade), 228 tonnes of starch (13 partners), and 162 tonnes of tapioca pearls and other substitutes (5 partners), at respective values of US$ 17.23 million, $138 216, and $175 480. The largest trade shifts were recorded over the 2009–2012 time frame, when imports of RCP increased by 153% and starch by 1575% while tapioca pearl dropped by 76%. By 2013, import flows had stabilized with respective drops of 42.3%, 83.5%, and an increase of 48.9% for tapioca pearl.

Important shifts were recorded in the export trade of cassava, substitute grains, and derived products to China across time periods (figure S1). Exports of cassava RCP reached 6.42 million tonnes in 2009, surpassing those of wheat or corn. By 2011, RCP exports to China had fallen by 25.0%, corn exports had risen by 2356% in 2012, and wheat exports reached a high of 6.22 million tonnes by 2013. From 2012 onward, export levels of cassava were restored to 2009 levels, and those of corn and wheat declined. While it is beyond the scope of this paper to investigate the drivers of the substantial increase in corn imports by China during 2009–2012, the reduction in cassava imports may have well contributed to the growth in corn and wheat imports, given the substitutability of these commodities in the starch sector. Fluctuations in cassava starch exports were equally paralleled by shifts in the export of other starch types. Cassava starch exports reached a low of 707 065 tonnes in 2010, while those of potato and corn peaked (at 15 290 and 117 777 tonnes, respectively). In 2011, exports of wheat starch peaked at 3193 tonnes. After 2010 (and for wheat, 2011), exports of alternative starches diminished and those of cassava increased significantly. Over 2009–2013, the largest variability was recorded for export volumes of wheat and corn starch (coefficient of variation CV = 1.72, 2.17 respectively), as compared to potato and cassava starch (CV = 0.65 and 0.68 respectively). Variability in total starch export volume (all types) varied to a lesser degree (i.e., CV = 0.63).
Price trends in global futures and spot markets

Though cassava starch export price was not correlated with China Corn Futures prices or US Wheat (hard) export prices in the full time series (i.e., ‘full series’ of 13–15 years, depending on the commodity), significant correlations were recorded in the restricted time series (i.e., June 2008–December 2015, exclusively covering the major mealybug-related events (table S1)). For UK Potato prices, Thai cassava starch export price explained a greater proportion of variation in prices for the restricted time series as compared to the full one. Hence, pest-related events in Thailand correspond with pricing changes of other commodities in futures and spot markets alike, although impacts from the 2010–2011 food crisis cannot be overlooked.

Next, an alternative model, fit to the full time series data, was estimated including dummy variables for (1) the productivity loss phase, (2) the biological control-induced yield recovery phase, and (3) the entire events period (2009–2013), and their respective interaction terms with Thai cassava starch and chip export prices. In this model, we recorded significant correlations for the entire event duration (2009–2013), but also found Thai export prices for cassava starch and chip during the productivity-loss phase (2009–2011) to be correlated with US export prices for wheat (both hard and soft) (table S2). Yet, no statistically-significant correlations were found for the yield recovery phase. This is likely due to the myriad forces responsible for mitigating P. manihoti-induced export shocks including, for example, the following: (1) a nearly 300 000 ha regional expansion of cassava cropping area from 2009 up till 2011 to meet supply gaps (Wyckhuys unpublished); (2) an increase of Thailand’s cassava imports from neighboring countries to release pressure on its domestic production; (3) release of storable cassava-derived commodities such as starch, thus delaying the onset of price change; (4) structural adjustment in Thailand’s export industry; (5) an increased reliance by China on substitute crops such as corn and wheat (figure S1).

Discussion

This study reveals how effective, (sub)continent-wide biological control of an invasive mealybug helped

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Table 1. Evolution in Thailand’s export trade of cassava, cassava starch and other cassava-derived commodities. Bi-annual shifts in trade quantity (tonnes) and value (US$) are represented for a time period covering the late 2008 P. manihoti invasion, the 2009 A. lopezi introduction and the subsequent 2011–2013 country-wide distribution of A. lopezi. Export trade records are extracted from UN Comtrade.

| Country         | 2009 baseline quantity (tonnes) | 2009 baseline value ($’000) | 2009–2011 shift quantity (tonnes) | 2009–2011 shift value ($’000) | 2011–2013 shift quantity (tonnes) | 2011–2013 shift value ($’000) |
|-----------------|---------------------------------|-----------------------------|-----------------------------------|-------------------------------|-----------------------------------|-------------------------------|
| World           | 174307                         | +6.8%                       | 106321                            | +18.6%                        | 117323                            | +23.5%                        |
| China           | 504334                         | +0.1%                       | 135134                            | +135.5%                       | 136532                            | +116.6%                       |
| Asia (other)    | 1075230                        | +12.3%                      | 288110                            | +101.2%                       | 10611                             | +33.2%                        |
| Europe          | 26984                        | +53.1%                      | 8117                              | +177.8%                       | 6011                              | +40.1%                        |
| Middle East     | 37731                         | −36.8%                      | 10611                             | +18.6%                        | 4627                              | +13.9%                        |
| Africa          | 45118                         | +5.4%                       | 14809                             | +113.2%                       | 9815                              | −4.6%                         |
| Oceania         | 33239                         | −49.7%                      | 9815                              | −4.6%                         | 420                               | +69.5%                        |
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a Values not adjusted for US$ index.
recover cassava production in Thailand and ease (mealylbug-induced) shocks on export volumes and pricing for cassava starch and multiple globally-traded agricultural commodities. We show how Thailand, the center of the Asian *P. manihoti* invasion, acts as the world’s largest starch exporter (1.42–2.89 million tonnes, or 36% in global trade volume) and biggest supplier of cassava-derived commodities to China. Following its 2008 arrival, *P. manihoti* spread over extensive areas and inflicted 4 t/ha losses in aggregate crop yield in Thailand. The resulting 27% drop in national cassava production and ensuing 162% increase in starch export price caused cascading effects in the world’s bilateral trade network of starch and other cassava-derived commodities. Our work equally shows how the introduced parasitoid, *A. lopezi*, exhibits significant spatial variation in its degree of establishment and impact. Yet the *A. lopezi*-mediated yield recovery over 2011–2013, further magnified by a >250,000 increase in cassava cropping area over the same time period, contributed to a reduction in export prices of Thailand’s cassava starch, a dampening of price volatility in futures markets for certain substitute commodities, and associated structural changes in global commodity trade networks of cassava and other starch crops. Hence, ecologically-based management can alleviate invasive pest threats not only within the national territory of booming economies (Jenkins and Mooney 2006, Ding et al. 2008), but can equally help to safeguard supply of some of their internationally-sourced commodities. Beyond the structural impacts to trade networks, the events chronicled here have more far-reaching and less obvious environmental and social impacts at different (spatio-)temporal scales and related policy and governance challenges.

Invasive pests are of increasing importance in today’s globalized world, and inflict annual economic losses estimated at US $120 billion in the United States (Pimentel et al. 1997) and € 10 billion in Europe (Hulme et al. 2009). It is widely thought that the economic impacts of terrestrial invertebrates are comparatively high and greatly surpass their ecological impacts (Vilà et al. 2010), with insects causing at least US $70 billion globally in direct economic costs (Bradshaw et al. 2016). Furthermore, the above are likely to be gross underestimates for several reasons. First, potential economic impacts are unknown for nearly 90% of exotic species in Europe and likely for an even larger share in the developing-world tropics (Vilà et al., 2010). Second, though global trade is a primary driver of biological invasions (Molnar et al. 2008, Chapman et al. 2017), the impact of pests on trade has received virtually no attention. Our work underlines how the pest invasion can lead to shifts in trade flows, price volatility and (likely) shock propagation in global spot and futures markets. Estimating these costs at broad spatial and organizational scales will be challenging, but could permit more accurate impact estimates of invasive species.

We recognize that invasive species problems can emanate from mis-guided introductions of pest-controlling organisms (or natural enemies), and that arthropod biological control is not without (environmental) risk. Yet, over the past decades, the practice of IBC has matured considerably and now explicitly balances risk and benefit of species introductions, as to maximize their net societal benefits (De Clercq et al. 2011, Hajek et al. 2016, Heimpel and Cock 2017). Over its 130 year history, IBC has permitted the lasting control of >200 invasive insect species and multiple weeds worldwide oftentimes at exceptionally favorable benefit:cost ratios (up to >1000:1) (van Lenteren et al. 2006, van Driesche et al. 2010, Cock et al. 2010). IBC’s transformative potential for invasive species control is further accentuated by our study, in which the careful introduction of a highly host-specific parasitoid *A. lopezi* generates wide-ranging (socio-)economic benefits at minimal or no environmental cost (Wyckhuys et al. 2018).

The economic value of ecosystem services such as (insect-mediated) biological control has proven difficult to estimate, and current approximations of US $4.5 billion per year for US agriculture are likely conservative (Losey and Vaughan 2006, Landis et al. 2008, Naranjo et al. 2014). On-farm yield assessments, as conducted in sub-Saharan Africa following the 1981 *A. lopezi* release, revealed an IBC-induced productivity increase of 2.5 t/ha (Neuenschwander et al. 1989). Manipulative trials as conducted by Thanchareon et al. (2018) in Thailand show markedly higher yield gains of 5.3–10.0 t/ha. These are partially attributable to overall higher productivity of cassava in Asia compared to Africa (Delaquès et al. 2017). Based on those empirically-derived data, IBC provides direct economic benefits of US$200–704 per ha annually at farm-gate prices in Thailand, without accounting for changes in production costs, local elasticities of supply and demand, or insecticide payments. This successful case of IBC is likely to present favorable benefit-cost ratios, especially given the minimal cost of the *A. lopezi* introduction (Heimpel and Mills 2017, Naranjo et al. 2014), and the further magnification of effects through worldwide trade. Yet our work shows important spatial variability in levels of parasitoid establishment and dry-season *P. manihoti* parasitism, with a coefficient of variation CV = 1.07 (n = 131) for all fields and CV = 0.822 (n = 102) exclusively for sites with presence of *A. lopezi*. This is likely due to variation in climatic conditions, *P. manihoti* invasion history, soil fertility, farm size and vegetation composition, time since parasitoid introduction, or the extent of agricultural intensification. The misuse of insecticides in particular can undermine ecological resilience (Settle et al. 1996) and may nullify IBC-related benefits. Losey and Vaughan (2006) illustrate such a scenario with an estimate of $20.92 billion increase per year in crop damage in the United States in the case that biological control would be disrupted.
(e.g., through over-use of insecticides). Efforts to stabilize mealybug biological control (e.g., in-field diversification) can thus generate substantial spillover benefits, further magnified through global trade.

Global finance thus indisputably needs ecology (Scholtens 2017). On the other hand, national and global starch prices can act as feedback signals of Asia’s cassava crop performance (as reflected in crop yield) and broader resilience. Resilience in this instance is mirrored by the extent of recovery from pest attack and A. lopezi parasitism rate, and speaks to the ability of the agro-ecosystem to absorb (invasive) pest shocks (Crona et al 2016). IBC and other (nature-based) measures to restore or enhance this ecological resilience clearly have unexpected cascading benefits on collective societal welfare, including human health and food safety (e.g., Naranjo et al 2014). Our work thus echoes calls for an integration of agro-ecological metrics, sustainability standards or even biological control indices in the decision-making of financial actors (Galaz et al 2015, Meehan et al 2012, Tayleur et al 2016) or those along the food value chain (Sandhu et al 2008, Sukdev 2018). Amongst others, resilience measures in the ecological domain could complement the reserve-based tactics for price stabilization currently in place for certain countries or trade blocks. In this way, trade can act as a ‘restorative’ force and help to detect and counteract agro-environmental damage (Martinez-Melendez and Bennett 2016). Dietz et al (2016) ‘stress-tested’ financial firms to climate-related risks, and similar exercises could also be done for invasive pests or IBC implementation scenarios (Pace and Gephart 2017). Large agro-enterprises can lower some of those risks by assuming a direct role in restoring resilience, as evident through the leadership of the Thai Tapioca Development Institute (TTDI) in A. lopezi parasitoid mass-rearing and release. Other (Western) actors can also move away from their current role as profiteers, and contribute to the maintenance of biologically-diverse agro-ecosystems in the global South (Farley and Costanza 2010). Lastly, as an individual farmer’s crop and pest management decisions generate externalities at broad spatial scales, measures can equally be considered to either incentivize particular types of behavior and reward growers for safeguarding biological control (‘steward earns’), or to penalize them for abuse of pesticides (‘polluter pays’ models) (Sullivan 2011, Porter et al 2017). Incentivized ecologically-based management may thus have a role as a circuit breaker for potentially devastating and persistent trade-induced environmental and social effects. By the same token, efforts to monetize ecosystem services can also expose biodiversity and biological control to the vagaries of a (spatially, temporally) dynamic market, as evident in the 79% drop in value of bat-mediated insect control in United States cotton over less than two decades, due to lower commodity prices and the adoption of insect-resistant crops (Silvertown 2015).

Over the past decades, international trade has intensified and led to an increasing disconnect between consumers and producers, including small-holder farmers in the developing-world tropics (D’Odorico et al 2014, Gordon et al 2017). This equally holds for the rapidly-growing globalized market of cassava and its myriad starch-based foods, household items and other wares (figure 3). Our characterization of the structure and evolution of the world’s bilateral trade network of starch (and other cassava-based commodities) revealed how major cassava (starch) importers such as China are particularly vulnerable to P. manihoti-induced shocks, and continue to greatly benefit from IBC’s yield-restoring effects. Next, financial actors facilitated further tele-coupling (i.e., environmental and socio-economic connections between remote areas of the world, Liu et al 2013), thus enabling spillover effects on (derivative) markets of substitute agricultural commodities, such as corn, potato or wheat. In the meantime, ecological knowledge of cassava mealybug biological control had equally become more global and widely-accessible, permitting a swift implementation of A. lopezi releases. Despite our inability to detect clear causal patterns especially in financial systems (Soranno et al 2014), we exemplify how mealybug-induced (cassava) trade shocks can help to explain price overshooting, particularly for commodities exposed to high-speed, computerized algorithmic trade (Heady 2011, Galaz et al 2015). This is particularly interesting, as Asia’s P. manihoti yield shocks occurred early in the onset of the 2010–2011 food price crisis (figure 4(B)), and multivariate approaches had so far been unable to fully and unequivocally capture variability in and drivers of price fluxes (Hochman et al 2014). While research on the causes of the 2007–2008 and 2010–2011 food crises has identified rising oil prices, the demand for biofuels, changing Asian diets, financial speculation, amongst others (Heady and Fan 2008, Heady 2011, Tadesse et al 2014), much of the variation in food price increases is not explained (Hochman et al 2014). Moreover, the effects of various causal factors differ by crop and regional variation in food price increases is still poorly understood (Dawe and Morales-Opazo 2009). Therefore, while the price for cassava commodities was surely affected by the various factors driving the global food crises, regional factors such as the mealybug outbreak and parasitoid-mediated suppression also played a non-negligible role. Furthermore, we show how IBC can effectively dampen biotic pressures on commodity markets and has the potential to contribute to stabilization of prices and trade flows at broad spatial scales. This exploratory analysis invites further assessment of the drivers, impediments and repercussions of (cassava product) trade, and paves the way for a valuation of insect biological control (or other ecologically-based management tactics) as a stabilizing force in global financial markets.
It is well-established that agricultural trade liberalization and associated changes in both local crop production and global commodity prices can have unwelcome effects on local ecosystems (Lat 2004), land use (De Fries et al. 2010), biodiversity (Lenzen et al. 2012), water (Hoekstra and Hung 2005), and food security (Swinnen and Squiciarini 2012). Moreover, a growing body of literature shows that local changes to agricultural systems are driven by policy initiatives and agricultural practices elsewhere (Fargione et al. 2008). Our work suggests that these effects are also possibly due to structural changes across related commodity trade networks, likely making them less conspicuous and more difficult to track. Finally, the dynamics discussed here present a potential mismatch in temporal scales as the outbreak of an invasive pest and its subsequent mitigation occurred relatively quickly as compared to the more persistent and long-lasting effects as a result of farmer responses, including deforestation as new land was cleared for crop expansion.

In conclusion, our work constitutes a trans-disciplinary approach to illuminating the importance of invasive pests and importation biological control to global trade and finance. Our research adds a different (trade) dimension to earlier calls for a systems-approach to pest management and agricultural sustainability (Lewis et al. 1997), underscores the broad economic, environmental and societal interests of sustaining (insect-mediated) ecosystem services within tropical agricultural landscapes, and illuminates the transformative power of judiciously-implemented insect biological control. Furthermore, it emphasizes the urgent need for an integrated framework to track cross-scale tele-coupling between commodity and financial markets, (scientific) ecological knowledge systems in tropical agriculture, on-farm biodiversity, and ecosystem services (Carrasco et al. 2017, Galaz et al. 2015). During times of rapidly-declining insect populations and massive loss of biodiversity globally (e.g., Hallmann et al. 2017), we hope that our research makes insect biodiversity and biological control more visible to the qualitatively homogeneous and ‘one-eyed imperatives’ of capital (Castree 2002).

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Conflict of interest

The authors report no conflict of interest.

Author contributions

KAGW conceived and designed the experiments; KAGW, WZ, SDP and CEG analyzed the data; all authors co-wrote the paper.

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