Impact of regional bans of highly hazardous pesticides on agricultural yields: the case of Kerala

Agriculture & Food Security

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Impact of regional bans of highly hazardous pesticides on agricultural yields: the case of Kerala

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Abstract

Background: Removing highly hazardous pesticides from agricultural practice in low- and middle-income countries is crucial to ensuring community and environmental health and occupational safety of farmers. However, the approach has been challenged as threatening food production, despite evidence from Asian countries that curbing agricultural use of highly hazardous pesticides does not affect crop yields. In 2011, the state of Kerala, India, banned 14 highly hazardous pesticides resulting in a marked reduction in deaths from pesticide poisoning.

Objective: We aimed to determine whether the Kerala pesticide bans impacted agricultural yields.

Methods: We collected data on agricultural production, area under cultivation, and rainfall, published by the Kerala state agricultural department from 2004 to 2018 for eight key crops that had been treated with the banned pesticides. Trends in crop yields (total production/area under cultivation) and rainfall across 14 districts in Kerala were aggregated and analysed using joinpoint regression. These trends were evaluated to ascertain possible associations with the pesticide bans.

Results: The joinpoint regression analyses showed no evidence for any change in yield trends for any of the eight crops in the year of the pesticide bans (2011), or the subsequent year (2012), suggesting a negligible impact of the bans on crop yields. Steady trends of predominately reductions in overall rainfall, without any change around the time of the pesticide bans, was observed in Kerala throughout the period. No evidence of district-level changes in rainfall that might have offset any potential adverse impacts of the pesticide bans on crop yields was noted. Fluctuations in yield until 2018 could be explained by variation in rainfall, changes in land use, and agricultural policies.

Conclusion: We found no evidence of an adverse effect on agricultural yields in Kerala that could be attributed to bans of highly hazardous pesticides. This work provides further evidence that such pesticides can be withdrawn from agricultural use without affecting yields. Further studies are required for the whole of India after the national bans of 12 pesticides in 2018 to identify state-level effects of the bans.

Keywords: Pesticide regulation, Pesticide ban, Agricultural output, Food production, Pesticide poisoning, Kerala

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Introduction

Pesticides pose threats to human health and wellbeing [1]. They cause harm to the environment, pollute food and water, and are a threat to beneficial bio-diversity due to negative effects on non-target species [2, 3]. Stricter controls regulating the usage of highly hazardous pesticides can have a range of benefits: reducing pesticide suicide rates in farming communities [4, 5], preventing harm caused to human health by chronic exposures [6, 7], and preserving natural ecosystems [2]. Pesticide regulation and bans are frequently controversial as they are believed to potentially reduce crop yields. However, field studies from India have shown that sustainable methods, such as integrated pesticide management (IPM) and agroecology, do not significantly reduce yields or increase farmers' costs in comparison to conventional farming techniques [8–11].

Pesticide suicide is a particular problem in rural Asian communities, killing around 110,000–168,000 people each year worldwide [12]. India officially reported 24,064 deaths in 2019 from pesticide self-poisoning [13], although community level studies indicate that the actual number is probably around three times higher, at around 70,000 per year [12, 14]. Many pesticide suicides can be prevented by means restriction [15]—by banning highly hazardous pesticides [16–18]—as shown in Sri Lanka [4, 19], Bangladesh [5], India [20], South Korea [21], and Taiwan [22]. Self-poisoning with much less toxic pesticides after bans greatly reduces the risk of death [17]—as observed in high-income countries where few people have access to pesticides, most self-poisoning is with medicines, and few people die from self-poisoning [23].

Chronic exposure to pesticides among farm workers has been linked to health problems such as respiratory disorders, neurodegenerative disorders, and some types of cancer [6, 7, 24]. Indian field studies have reported other adverse health effects among farm workers such as muscle pain, headaches, blurred vision, tremors, sleep disorders, and cardiac problems [25–27]. Pesticide residues in food have been linked to chronic health effects such as immune suppression, hormone disturbance, reproductive defects, and cancers, even at low exposure dose [28–31]. Food samples in India have been found to exceed maximum permissible limits [32, 33] which indicates that bans on highly hazardous pesticides need to be scaled up nationally.

The harmful effects of hazardous pesticides on the environment have been a cause of concern among UN agencies and the international community [34, 35]. Many hazardous pesticides have been linked to environmental pollution, and are a threat to beneficial bio-diversity due to devastating effects on non-target species such as honeybees and earthworms [2]. Spraying of pesticides leads to air, soil, and, water pollution which can be prevented by using safer formulations or natural farming techniques [36]. Organic farming fields have five times higher plant species richness, 20 times higher pollinator species, and higher earthworm abundance as compared to conventional fields [37, 38].

While environmental harms and public health risks posed by pesticides that can be curtailed through prohibiting their use, a major objection to pesticide regulation to restrict or ban sales is the concern of potential impact on agricultural yields [39–41]. Were yields to be reduced, this would negatively affect farming community livelihoods, be reflected in changes to trade in food commodities reducing regional food self-sufficiency and increasing prices, and ultimately impact food security [42]. However, studies from Bangladesh, South Korea, Sri Lanka, and Taiwan indicate that pesticide bans do not affect agricultural output [21, 22, 43, 44]. Moreover, field studies from other regions in India have shown that sustainable methods, such as IPM and agroecology, do not lead to significant reductions in yields or significant increases in farmers' costs in comparison to conventional farming techniques [8–11].

After an initial national ban of 16 pesticides in 2018, the Indian government proposed to ban the use of 27 pesticides in 2020 (Box 1) [45]. This was heavily opposed by the pesticide industry citing concerns regarding decline in agricultural output and is still under review [46, 47]. In 2011, the state government of Kerala banned 14 highly hazardous pesticides (Box 1), while recommending substitutes for each banned pesticide [48]. The state had previously banned the organochlorine insecticide, endosulfan, in 2005, 6 years ahead of nationwide Indian bans [20]. These bans have resulted in a fall in pesticide poisoning deaths in the state [20], but their effect on agriculture has not been studied.

We here aimed to assess the effects of the 2011 pesticide bans on the yields of major crops in Kerala. Analysis of state-level yield trends may contribute to national pesticide regulation policy leading to elimination of highly hazardous pesticides from Indian agriculture. The national ban, if implemented, will be a significant step towards reducing pesticide suicide deaths and elevating agricultural safety standards by safeguarding the health of farmers and agricultural labours, who comprise approximately half of the Indian population [49].

Methods

Research setting

Kerala is the smallest state in south India and has significantly better human development indicators with higher rates of literacy, lower infant mortality rates, and a higher life expectancy at birth than the national average [50]. 16.7% of the population is dependent on agriculture and allied activities [51] even though structural changes have led to a constant decline in the agricultural sector's contribution to state gross domestic product which is coupled with a constant decline in area under cultivation for food crops in favour of cash crops in the state [51].

Plantation cash crops (tea, coffee and rubber) account for 62.1% and food crops (rice, pulses, and tapioca) account for 10.2% of the area under cultivation [51].

Data collected

We collected data on rainfall, crop production, and area under cultivation for the following crops in Kerala as their output data are routinely collected, and one or more of the banned pesticides were commonly used in their production [48]: banana (*Musa* spp.), plantain (*Musa paradisiaca*; *nendran* plantain being the main local variety), cashew (*Anacardium occidentale*), cardamom (*Elettaria cardamomum*), rice/paddy (*Oryza sativa indica*), pulses (mainly red gram and gram; *Cajanus cajan/Cicer arietinum)*, sweet potato (*Ipomoea batatas*), and tapioca/cassava (*Manihot esculenta*). These crops account for an estimated 20% of the total cultivated area in the state [51].

Data were based on crop surveys conducted by the Department of Economics & Statistics (DES), Government of Kerala [52]. Under the scheme for improvement of crop statistics, an annual review of the crop statistics system is published jointly by the DES and the National Statistical Office to ensure efficiency and accuracy in agricultural data collection through technical checks to strengthen the system. Annual economic reviews published by the Kerala state government were used to collect data regarding changes in rainfall that might affect yield [53].

Annual data for crop production and area under cultivation were compiled for the eight selected crops from across Kerala's 14 districts for the years 2004 until 2018, providing data for 6–7 years on either side of the 2011 pesticide bans. Average area under cultivation (hectare) and total crop production (tonnes) for the periods before and after the pesticide bans (2004–2011 and 2012–2018) and percent change between the two periods were calculated. Due to fluctuations in area under cultivation and subsequent crop production, yield was the measure used to analyse trends. Yield was calculated as total production/area under cultivation (kg/hectare).

Statistical analysis

We conducted joinpoint regression analysis to examine time trends in the yields of eight types of crops in Kerala during the period 2004–2018. We also used joinpoint regression to examine whether there was any evidence for a change in rainfall coinciding with the year of pesticide bans implementation to consider the possibility of increased rainfall offsetting adverse effects from the bans.

The joinpoint regression analysis involves no a priori assumption of when the impact of an intervention on outcomes would occur. Trend data are characterised by a combination of contiguous linear segments and 'joinpoints' (points at which trends change) in joinpoint regression models [54]. For the observations, (x_1, y_1),..., (x_n, y_n), where $x_1 \leq \ldots \leq x_n$ (x_is indicate time points, e.g. calendar years, and y_is are the yields of eight crops or rainfall), the model can be written as:

$$E[y|x] = \beta_0 + \beta_1 x + \delta_1 (x - \tau_1)^+ + \cdots + \delta_k (x - \tau_k)^+,$$

where k is the number of joinpoints, τ_ks are the unknown joinpoints and $a^+ = a$ for $a > 0$ and 0 otherwise. For example, if there is one joinpoint in year 2011 for the study period 2004–2018, the model is $E[y \mid x] = \beta_0 + \beta_1 x + \delta_1(x\text{-}2011)$ for the period 2011–2018 and $E[y \mid x] = \beta_0 + \beta_1 x$ for 2004–2011.

The joinpoint regression analysis compares a series of joined line segments to identify the combination that fits the trend data best using a permutation method. A procedure is employed to determine the number of joinpoints (i.e. k). For example, to determine up to two joinpoints, the procedure first tests the hypothesis of no change (H_0: $E[y|x] = \beta_0 + \beta_1 x$; i.e. $k = 0$) against the alternative hypothesis of two joinpoints (H_a; there exist τ_1 and τ_2 and $\tau_1 < \tau_2$ such that $E[y|x] = \beta_0 + \beta_1 x + \delta_1 (x - \tau_1)^+ + \delta_2 (x - \tau_2)^+$; i.e. $k = 2$). If the null hypothesis is rejected, then the similar procedure is applied to test the null hypothesis of one joinpoint ($k = 1$) against the alternative of two joinpoints ($k = 2$). Otherwise, the null hypothesis of no change ($k = 0$) is tested against the alternative of one joinpoint ($k = 1$). This approach is aimed to identify the smallest number of joinpoints supported by the trend data.

The test statistic was obtained by the grid search method suggested by PM Lerman [55]. The p-values and 95% confidence intervals (CIs) were computed using the permutation procedure for the following parameters: the number of joinpoints (k), the location of the joinpoints (τ_1, ..., τ_k) and the regression coefficients, δ_1, ..., δ_k, which indicated the magnitude of changes in yields or rainfall. Any change in trends in the crop yields in 2011 (i.e. the year of the pesticide bans) or in 2012 (i.e. the year immediately after the bans) would indicate a potential impact of the bans on the crop yield. By contrast, no change in crop yield trends in the two years indicates no evidence for an impact of the pesticide bans. In the analysis of rainfall, if any change in rainfall trend around the year of pesticide bans is identified, this may confound the impact of pesticide bans on crop yield; for example, an increased rainfall may benefit crop growth and offset any negative effects of pesticide bans.

Analyses were conducted using Joinpoint Trend Analysis Software version 4.9 made available by the National Cancer Institute US National Institute of Health [56]. The yield of eight types of crops and rainfall was used as the dependent variable in separate analyses; the coefficients in the models were the annual absolute changes in yields or rainfall per year, respectively. In this study, the number of joinpoints was limited to a maximum of two in each analysis to avoid over-fitting by introducing superfluous joinpoints, based on the recommendation from the Joinpoint Trend Analysis Software website [57]. When conducting multiple tests of hypotheses to identify joinpoints that fit the data best, the joinpoint program applies a correction procedure to maintain the overall probability of a type I error (i.e. concluding that there are one or more joinpoints when there are in fact none) at 0.05.

Results

Trends in crop yields

Overall, there was no statistical evidence of downturns in yields for any of the eight types of crops in 2011 (the year of implementation) or 2012 (the following year) in Kerala, indicating no adverse impact of pesticide bans on crop yields (Fig. 1).

A relatively stable upward trend was observed for the yields of banana, pulses, and rice—they increased 73.3, 26.9, and 36.4 kg/hectare annually, respectively (Additional file 1: Table S1). In contrast, a downward trend was observed for cashew with an annual reduction of 23.8 kg/hectare in 2004–2018; however, no change in yield trend was found in this period. There were fluctuations in the yields of cardamom, plantain, sweet potato, and tapioca, but these changes did not coincide with pesticide bans implementation. A minor decrease in cardamom yields (an annual change of − 3.5 kg/hectare) was observed between 2004 and 2010, followed by an increase of 44.9 kg/hectare annually in 2010–2017 and a fall of 210.8 kg/hectare in 2017–2018. Plantain showed a downward trend with an annual change of − 82.0 kg/hectare in 2004–2016, with a short-lived rise in 2016–2017 (9874.6 kg/hectare), but resuming to the original level with a 10,029.7 kg/hectare reduction in the next year. Sweet potato yields showed a sharp rise in 2004–2005 (11,376.7 kg/hectare), followed by a steady upward trend until 2018 (an increase of 168.5 kg/hectare annually). A steady upward trend, with a 1164.4 kg/hectare increase annually, was observed for Tapioca between 2006 and 2014, followed by a slight decline, with a 136.6 kg/hectare reduction annually from 2014 until 2018 (Additional file 1: Table S1).

Analysing trends in crop yields by district over the study period showed no potential impact of the pesticide bans on yield across all 14 districts in Kerala, with just two exceptions involving sweet potato yields in two of 14 districts (Additional file 1: Fig. S1). These involved a downward shift of slope in Malappuram from 2011 (− 22.4 kg/hectare annually; 95% CI − 88.1 to 43.3) and a drop in Thiruvananthapuram in 2012–2013 (− 310.1 kg/hectare; 95% CI − 317.7 to − 302.5) (Additional file 1: Table S1).

Trends in rainfall

There was no evidence for an increase in rainfall around the time of the bans that might have compensated for, and hidden, an adverse effect of the pesticide bans on crop yield. Overall, there was a slow reducing trend in rainfall (annual change − 46.9 mm, 95% CI − 78.5, − 15.3) in Kerala over 2004–2018 without a change in rainfall trends in or around the implementation year (2011) (Additional file 1: Table S2); the rainfall fell somewhat in 2008, 2011, and 2015–2016 compared to their preceding years, although joinpoint regression showed no evidence for a change in rainfall trends in these years (Fig. 2).

The steady trend in rainfall was found in most districts; exceptions included four districts (Ernakulam, Idukki, Kozhikode, Wayanad) that showed an overall downward trend, Kannur, which showed a change from a level-off trend to a downward trend in 2013, and Kasargod, which showed a change from an upward trend to a downward trend in 2011 (Fig. 2 and Additional file 1: Table S2). The trend for reduced rainfall across these districts did not appear to be favourable for crop growth.

Analysing district-level yield data, certain shifts in crop yields could be linked to abnormal rainfall in the form of unusually heavy or unexpected showers during certain months, leading to severe floods in 2007 and 2018 that affected crop yields (Additional file 1: Fig. S1). For example, there was a sharp drop in banana yields in Ernakulam (annual change − 2598.6 kg/hectare) and Thrissur (annual change − 7218 kg/hectare) in 2017–2018 (Additional file 1: Table S1).

Discussion

Yield changes of crops grown in Kerala

In this study, we found no evidence to indicate that the 2011 pesticide bans in Kerala had an adverse effect on crop yields in the state. State-level yields increased for most of the studied crops after the bans, except for cashew, which showed a downward trend prior to the bans. Yields have in general been increasing in India and globally due to a combination of fertilizer use, irrigation, and improvements in crop varieties and farmer management practices [58–61].

State policies and pricing may underlie the decline in cashew yields in Kerala. The crop is not recognised as a plantation crop by the state, resulting in high import duties on cashews and restrictive land ceiling laws that do not apply to plantation crops (such as rubber, which has been replacing cashew) [62, 63]. Consequently, there has been a trend to grow cashew trees on inferior, less fertile

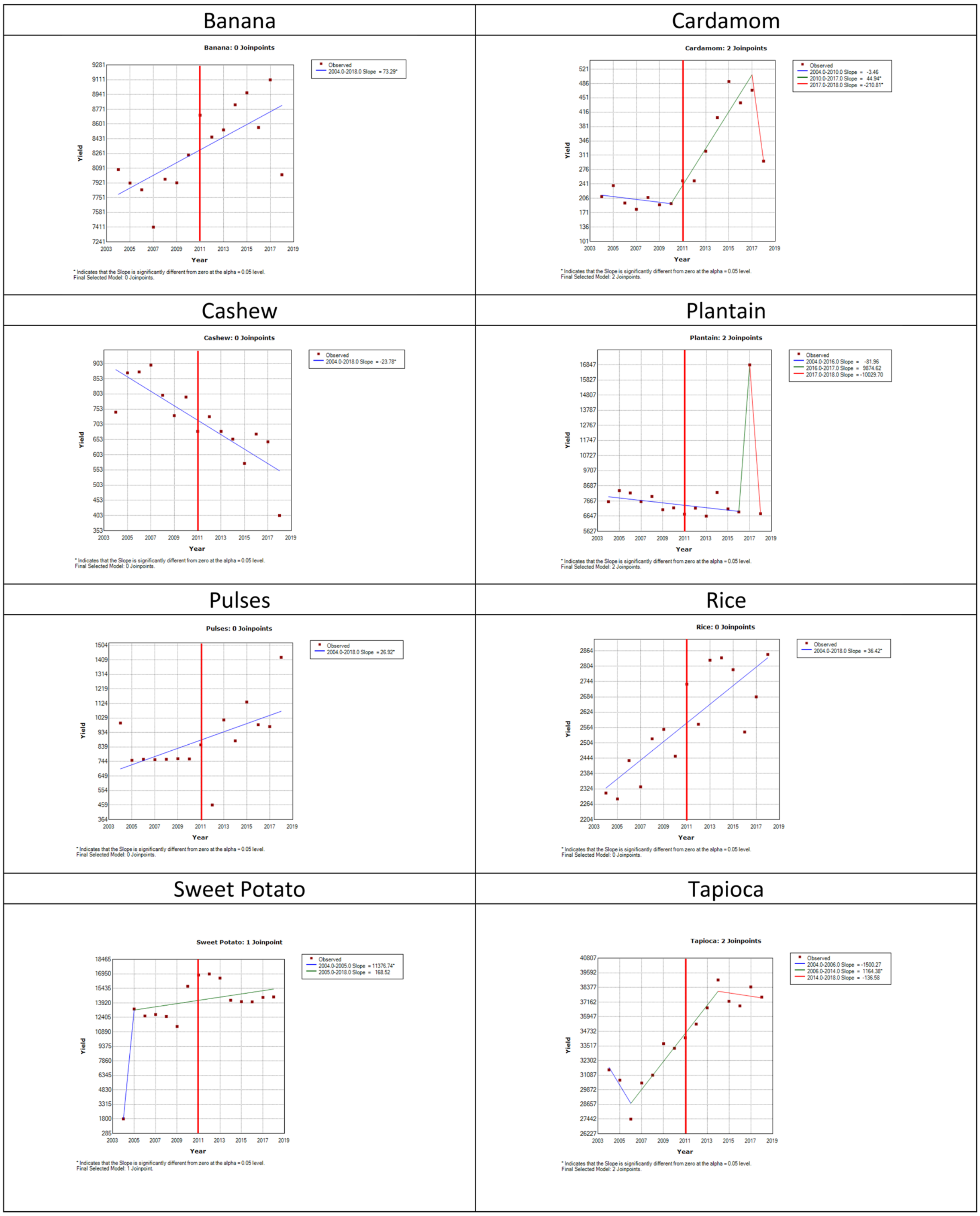

Fig. 1 Trend in the yields of eight crops in Kerala, India, in 2004–2018. Lines are estimated linear trends from joinpoint regression analysis. The vertical line (in red) indicates the year when the pesticide bans were implemented (2011)

land as a supplementary source of income for farmers [64]. Other issues affecting cashew include: unseasonal excessive rainfall leading to high humidity during flowering and fruiting periods and increased fungal disease [65, 66]; cashew stem and root borer and tea mosquito bug infestations in the north of the state due to inferior quality seeds; improper pest management resulting from labour shortages; and reduced incentives for farmers to

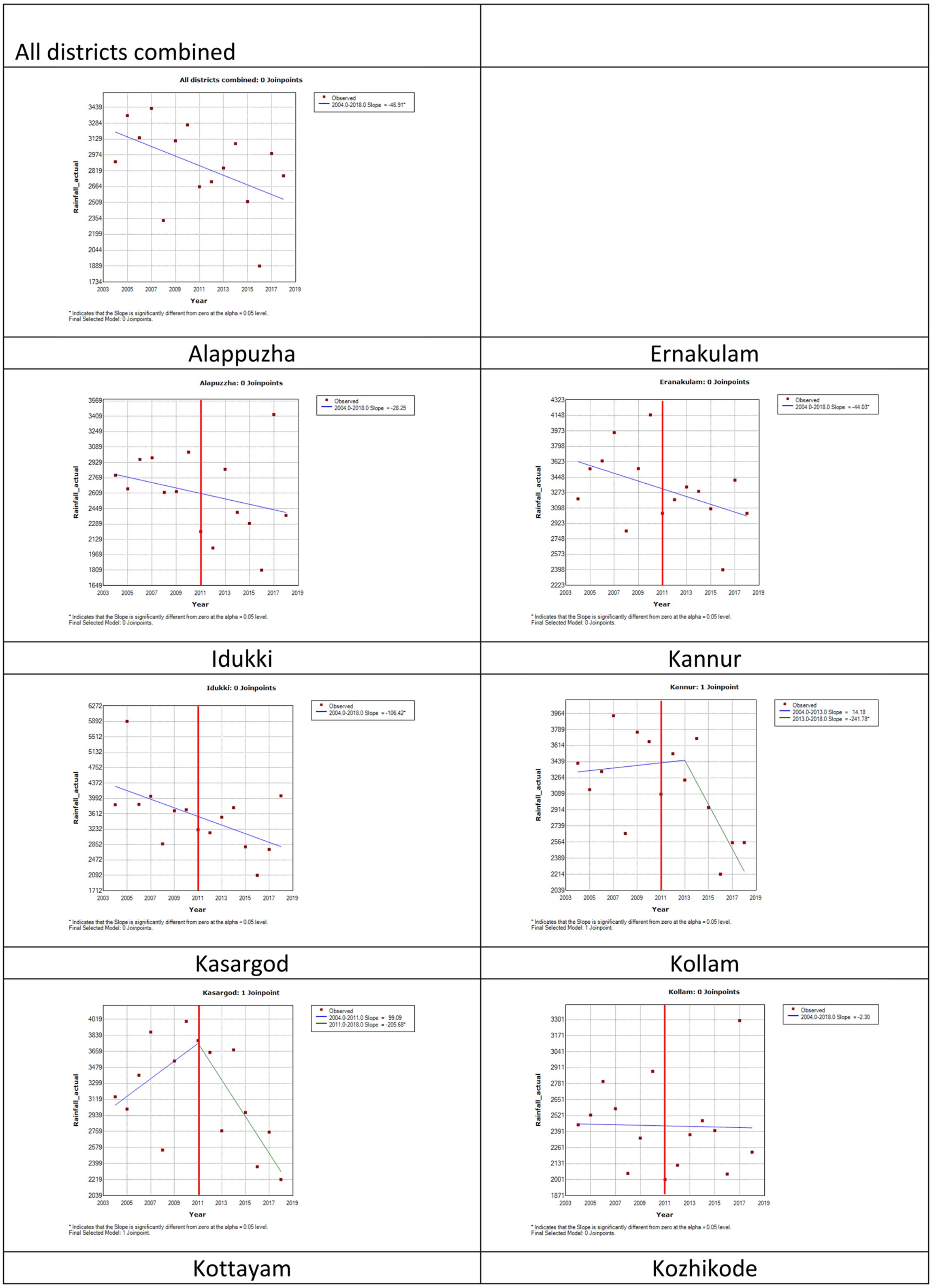

Fig. 2 Trends in rainfall in Kerala, India, in 2004–2018. Lines are estimated linear trends from joinpoint regression analysis. The vertical line (in red) indicates the year when the pesticide bans were implemented (2011)

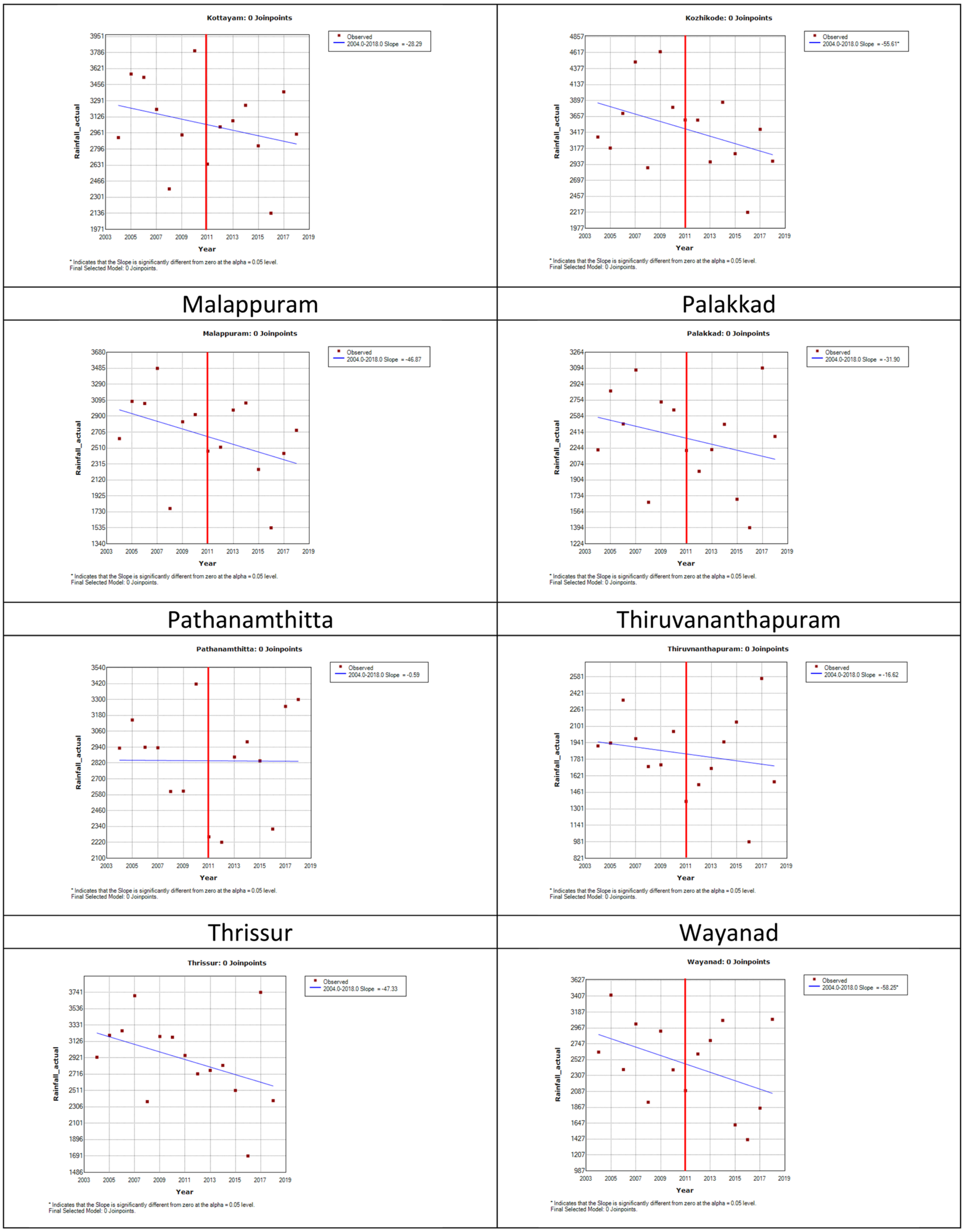

Fig. 2 continued

invest in cashew because of unfavourable crop prices [67]. The state-sanctioned substitute pesticides were found to be effective in research surveys conducted by Kerala Agricultural University [68]. Mozambique banned highly hazardous pesticides including endosulfan in 2011, but cashew production continued to increase [69, 70]. Therefore, combined with the pre-existing decline in cashew production, the pesticide bans do not appear to explain the decline in cashew yield.

State government agricultural policies may also have had a role in influencing yields of other crops. Cardamom cultivation was promoted due high value and steady exports, through provision of systematic credit and supply chains for the crop, procurement of high-quality seeds [71], and establishment of dedicated 'spice parks' consisting of auction centres, warehouses, banks, and quality assessment facilities [72]. Tapioca is primarily cultivated for household consumption. However, its starch is used in textiles, paper, and pharmaceutical products, leading to a high demand in the manufacturing sector, with moderate export demand [73].

Production of agricultural commodities

Over the period around the pesticide ban, the production in Kerala of the crops studied was almost constant. Total annual average production increased by less than 1% or 31,000 tonnes in the period after the ban (2012–2018) compared to the period prior to the ban (2004–2011). This relatively static total hides substantial shifts between crops and reductions in areas under cultivation, with yield improvements acting to offset the smaller cultivated areas (Additional file 1: Table S3).

Food crop production has been impacted by the reduction in area under cultivation, with plantation cash crops (e.g. coconut, rubber) displacing food crops, especially rice [51, 74]. The area under cultivation declined for all crops in this study from 2004 to 2018 (except banana and plantain which increased by 4.5% and 8.5%, respectively), dropping overall by 12.5% between 2004–2011 and 2012–2018. These declines contributed to the state's total cropped area decline over recent decades, from 3,000,000 hectares in 2000 to 2,584,000 hectares in 2016–17 [75]. Rice cultivated area drop by an average of 17.9% between 2004–2011 and 2012–2018, but offsetting yield increases limited production decline to 8.9%. Similar changes are repeated with higher declines in cultivated area and production for pulses and sweet potato with a fall in production of 38.4% and 26.1, respectively (Additional file 1: Table S3).

The declining trend in cultivated areas preceded the 2011 bans, due to factors such as reductions in area sown more than once per year and diversion of economic activity from agriculture to non-agricultural operations due to high input prices and labour cost [75]. The state government launched initiatives to promote rice cultivation and other food crops such as millets, pulses, and tubers to achieve greater self-sufficiency in meeting domestic food demand [51, 76, 77]. Kerala produced only 15% of its total consumption of food grains and 17% of its required rice, in 2009–2010 [78]. However, despite interventions to increase productivity and encourage farmers to increase the total area under production, there has been a shift from an agrarian economy towards a service sector-based economy since the early 1990s [53]. The declines in the GDP share of agriculture and allied activities, and the high workforce participation in other sectors have led to agricultural labour shortage [75] (Additional file 1: Table S4).

Pesticide regulation and trade

There is no World Trade Organization (WTO) standard for pesticides associated with the production process or the residues in food commodities. While standards such as the CODEX Alimentarius published jointly by the FAO and WHO [79] are encouraged by the WTO [80], pesticide regulations differ across countries [81]. Maximum residue limit (MRL) pesticide levels and other pesticide regulations are therefore a form of non-tariff measure affecting international trade [82–84], and can potentially be used as a method for protectionism [85].

Crop residues have a major economic impact on exports from India that would be ameliorated by reductions in pesticide use. Rejection of agricultural products exported from India by the importing countries because of MRL exceedances result in loss of income as well as increased costs for re-shipment or destruction of the rejected produce (Box 2). In 2018, over 16% of Indian farm exports to the European Union (EU) were rejected due to MRL exceedance [86]. India was one of the three countries with most import rejections to the United States of America (USA) due to MRL issues [87]. MRL guidelines are difficult to enforce in India where a large proportion of farmers are illiterate and enforcement difficult [81]. The lack of a ban on toxic pesticides in India has led buyers to shift their sources elsewhere. Countries such as Argentina, Cambodia, Kenya, and Uganda have implemented higher food safety standards resulting to India losing some of its EU market share [88].

A proportion of Indian farm produce sold domestically contains pesticide residues that exceed recommended MRLs [29, 89, 90]. Export produce tends to be more carefully monitored than domestically marketed produce because the cost of rejection is higher. Nevertheless, local populations have an equal right to safe food and the removal of hazardous pesticides from food production will benefit all consumers. Kerala is surrounded by other states without pesticide bans, which increases the probability of pesticide 'leakages' from neighbouring areas. The Kerala Agricultural University has launched the 'Safe to Eat' programme to ensure that food produce in Kerala is not contaminated with pesticides from other states [91].

Continued use and impact of highly hazardous pesticides

Farmers continue to use highly hazardous pesticides in the belief that they will produce better yields [92–94], despite evidence indicating that their use is not essential for maintaining yields [95, 96]. Awareness of, and adherence to, correct spraying protocols is very low among Keralan farm workers [97]. Studies from India show that farmers perceptions regarding pesticide usage are distorted due to high rates of illiteracy and low levels of awareness. Pesticides are erroneously considered to be "plant-growers" as well as "drug treatments" by farmers rather than lethal chemicals to be used judiciously [26, 98, 99]. This also leads to unscientific mixing of pesticides, and spraying them in higher than recommended doses [98]. Although pesticide suicides in Kerala have been declining since the bans in 2005 and 2011, an estimated 541 people still died from pesticide ingestion in 2018 [100, 101].

Limitations

This study could not establish a direct link between fluctuations in crop yields and pesticide bans due to the lack of primary data studying the effects of the bans. It is possible that other factors have influenced crop yields trends apart from rainfall and pesticide bans. However, there is no reliable quantitative data to analyse the effect of other issues. We relied on secondary research papers and government review reports to explain yield trends. Additionally, data on vegetable production could not be accessed for this paper, meaning that the analysis was limited to major food crops and cash crops.

This paper lacks a comparison state, due to major state-level differences in crops grown, quality of data collected, state policy, climate, and demographics—all of which confound a comparative analysis. Kerala, in particular due to its geographic location in India and high-quality data available for analysis, is different to other states.

Conclusion

This study found no evidence that the bans of 14 pesticides in 2011 had any observable adverse impact on agricultural yields in the state of Kerala. This is corroborated by research from other countries in South Asia where similar bans were implemented with no impact on agricultural yields [21, 43, 44]. Various factors such as government schemes, prices in the domestic and international market, seed procurement, and weather conditions were the factors reported to significantly influence area under agriculture and crop yields. This study adds to the evidence that highly hazardous pesticides can be removed from agriculture without affecting crop yields [18].

The Keralan bans were implemented with provision of safer alternatives as recommended by the state government. This example suggests that Indian state and central governments can remove highly hazardous pesticides from agricultural production to improve farm workers safety and food quality, without reducing yields. India took steps in this direction by banning 16 pesticides in 2018 and proposing in 2020 a ban of an additional 27 highly hazardous pesticides [45, 102]. These progressive measures will help eliminate highly hazardous pesticides, encourage sustainable forms of agriculture, and prevent many deaths from pesticide poisoning.

Box 1: Pesticides banned in Kerala in 2011 and proposed for national bans in 2020

Pesticide	Rat oral LD50 (mg/kg)	WHO hazard category
Kerala		
Phorate	2	Ia Extremely hazardous
Methyl parathion	6	Ib Highly hazardous
Carbofuran	8	Ib Highly hazardous
Monocrotophos	14	Ib Highly hazardous
Methyl demeton	40	II Moderately hazardous
Triazophos	82	II Moderately hazardous
Profenofos	358	II Moderately hazardous
Edifenphos	150	II Moderately hazardous
Tricyclazole	305	II Moderately hazardous
Oxythioquinox	500	II Moderately hazardous
Anilophos	473	II Moderately hazardous
Paraquat dichloride	150	II Moderately hazardous

Pesticide	Rat oral LD50 (mg/kg)	WHO hazard category
Thiobencarb	1300	II Moderately hazardous
Atrazine	c2000	III Slightly hazardous
National		
Acephate	945	II Moderately hazardous
Atrazine	c2000	III Slightly hazardous
Benfuracarb	205	II Moderately hazardous
Butachlor	3300	III Slightly hazardous
Captan	9000	U*
Carbendazim	> 10,000	U
Carbofuran	8	Ib Highly hazardous
Chlorpyrifos	135	II Moderately hazardous
2,4-Dichlorophenoxy acetic acid	375	II Moderately hazardous
Deltamethrin	c135	II Moderately hazardous
Dicofol	c690	II Moderately hazardous
Dimethoate	c150	II Moderately hazardous
Dinocap	980	II Moderately hazardous
Diuron	3400	III Slightly hazardous
Malathion	c2100	III
Mancozeb	> 8000	U
Methomyl	17	Ib Highly hazardous
Monocrotophos	14	Ib Highly hazardous
Oxyfluorfen	> 5000	U
Pendimethalin	1050	II Moderately hazardous
Quinalphos	62	II Moderately hazardous
Sulfosulfuron		Not listed
Thiodicarb	66	II Moderately hazardous
Thiophanate-methyl	> 5000	U
Thiram	560	II Moderately hazardous
Zineb	> 5000	U
Ziram	1400	II Moderately hazardous

Source: The WHO Recommended Classification of Pesticides by Hazard and Guidelines to Classification 2019 [3]

LD50 = dose at which 50% of animals die

According to the Indian Insecticides Act of 1968, pesticides are classified as red, yellow, blue, and green depending on their lethality. Red-labelled pesticides are extremely toxic (oral lethal dose: 1–50 mg/kg) while yellow-labelled pesticides are highly toxic (oral lethal dose: 51–500 mg/kg)

*U—unlikely to present acute hazard in normal use

Box 2

Saudi Arabia, which purchases 85% of Indian cardamom exports, detained four consignments due to the detection of pesticide residue above the MRL as specified by Saudi Arabia Food and Drug Authority in April–May 2018 [103]. Cardamom prices were severely hit and the Indian government had to step in with integrated pest management (IPM) techniques to avoid future incidents of export rejection. Despite this, cardamom continues to have high pesticide residues [104] and Keralan cultivators have been noted to smuggle in banned pesticides from neighbouring states [105, 106]. Owing to this, Saudi Arabia put a moratorium on Indian cardamom exports in August 2020 [107], with particularly severe effects for Kerala [108].

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40066-021-00348-z.

Additional file 1: Table S1. Results of joinpoint regression analysis of trends in crop yields, by crop type and district, in Kerala, India, in 2004–2018. **Table S2.** Results of joinpoint regression analysis of rainfall by district in Kerala, India, in 2004–2018. **Table S3.** Changes in average area under cultivation (hectares) and total production for each crop (tonnes), before and after the 2011 pesticide bans. **Table S4.** Shares of different sectors in Gross Value Added (GVA) and Employment, Kerala and India (2017–18). **Figure S1.** Trends in crop yields by district over the study period (2004–2018).

Acknowledgements

The authors would like to thank the National Crime Records Bureau, the Kerala State Planning Board, and the Department of Economics and Statistics, Government of Kerala, for provision of data. The Centre for Pesticide Suicide Prevention is funded by an Incubator Grant from the Open Philanthropy Project Fund, an advised fund of Silicon Valley Community Foundation, on the recommendation of GiveWell, USA.

Authors' contributions

Conceptualisation: ME, MD, and AS; statistical methodology: SSC and CYL; data analysis: AS, SSC, and CYL; writing: AS, ME, PA; writing—review and editing: ME, MD, IM, and SSC. All authors read and approved the final manuscript.

Funding

Not applicable.

Availability of data and materials

Data and materials for this study are available and will be provided to the journal upon request.

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Competing interests

The authors declare no conflict of interests.

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Received: 8 February 2021 Accepted: 19 November 2021
Published online: 22 January 2022

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