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TOPICAL REVIEW

Mapping global research on agricultural insurance

Shalika Vyas[1,2], Tobias Dalhaus[2,*], Martin Kropff[3], Pramod Aggarwal[1] and Miranda P M Meuwissen[2,*]

[1] CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Borlaug Institute for South Asia, International Maize and Wheat Improvement Centre (BISA-CIMMYT), New Delhi, India
[2] Business Economics, Wageningen University and Research, Wageningen, The Netherlands
[3] Consultative Group on International Agricultural Research (CGIAR), Montpellier, France
[*] Authors to whom any correspondence should be addressed.

E-mail: tobias.dalhaus@wur.nl and miranda.meuwissen@wur.nl

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Abstract

With a global market of 30 billion USD, agricultural insurance plays a key role in risk finance and contributes to climate change adaptation by achieving Sustainable Development Goals (SDGs) including *no poverty, zero hunger*, and *climate action*. The existing evidence in agricultural insurance is scattered across regions, topics and risks, and a structured synthesis is unavailable. To address this gap, we conducted a systematic review of 796 peer-reviewed papers on agricultural insurance published between 2000 and 2019. The goal of this review was twofold: (a) categorizing agricultural insurance literature by agricultural product insured, research theme, geographical study area, insurance type and hazards covered, and (b) mapping country-wise research intensity of these indicators vis-à-vis historical and projected risk and crisis events—extreme weather disasters, projected temperature increase under SSP5 (Shared Socioeconomic Pathways) scenario and livestock epidemics. We find that insurance research is focused on high-income countries while crops are the dominating agricultural product insured (33% of the papers). Large producers in production systems like fruits and vegetables (South America), millets (Africa) and fisheries and aquaculture (South-east Asia) are not focused upon in the literature. Research on crop insurance is taking place where historical extreme weather disasters are frequent (correlation coefficient of 0.75), while we find a surprisingly low correlation between climate change induced temperature increases in the future and current research on crop insurance, even when sub-setting for papers on the research theme of *climate change and insurance* (−.04). There is also limited evidence on the role of insurance to scale adaptation and mitigation measures to de-risk farming. Further, we find that the study area of livestock insurance papers is weakly correlated to the occurrence of livestock epidemics in the past (−.06) and highly correlated to the historical drought frequency (.51). For insurance to play its relevant role in climate change adaptation as described in the SDGs, we recommend governments, insurance companies and researchers to better tune their interest to risk-prone areas and include novel developments in agriculture which will require major investments, and, hence, insurability, in the coming years.

1. Introduction

Agricultural insurance is a global billion-dollar industry growing at a fast rate. In 2019 alone, the insurance market was worth 30 billion USD (Wang *et al* 2020). Climate change is an important driver of agricultural system instability and is expected to increase the frequency and intensity of risks in many regions across the globe (IPCC 2018). Among different on-farm risk management tools available, one important strategy to manage these risks is agricultural insurance. State-supported insurance subsidies are common in many countries, amounting to over 20 billion USD annually (Hazell and Varangis 2020). Effective insurance policies stabilize farm income, reduce poverty (Sustainable Development Goal- SDG 1) and ensure a climate safety net for food producers (SDG 13). The welfare effects gained by insurance pay-offs can have multiple spill-over effects, including hunger reduction (SDG 2) (Siwedza and Shava 2020). Therefore, insurance is a key element in agricultural adaptation to climate change, among other risk management tools.

A synthesis of current agricultural insurance research can help in assessing the current work and in reshaping the future research agenda. However, evidence from existing reviews is scattered across different regions and sectors and is limited in scope. In fact, most systematic reviews on agricultural insurance are focused on index-based insurance only (de Leeuw *et al* 2014, Marr *et al* 2016, Vroege *et al* 2019, Benami *et al* 2021). Furthermore, no study has compared the literature with existing risks and historical crisis events. This paper addresses this gap by focusing on two objectives: (a) categorizing agricultural insurance literature by agricultural product insured, research theme, geographical study area, insurance product type and hazards covered, and (b) mapping research intensity by country for these indicators vis-à-vis historical and projected risk and crisis events—extreme weather disasters, projected temperature increase under SSP5 (Shared Socioeconomic Pathways) scenario and livestock epidemics. We first describe the data and methods, followed by an overview of global insurance research and a comparison of research intensity with risks. The results contribute to our understanding of different indicators of agricultural insurance dynamics, including the role of insurance in dealing with likely environmental change and alignment with risk hotspots.

Agricultural systems today face myriad risks, both biotic and abiotic in nature. Losses from pests and diseases in agriculture and livestock are significant, especially among smallholder farming systems in the global south (de Groote *et al* 2020, Mason-D'Croz *et al* 2020). At the same time, climate change and weather extremes drive major food shocks across the globe (Cottrell *et al* 2019). Extreme weather events (including heatwaves, drought, floods and cold waves) cause an average loss of 10% in cereal production alone (Lesk *et al* 2016), and reduce the food quality of many other crops (Kawasaki and Uchida 2016, Dalhaus *et al* 2020). Climate change (gradual change in temperature and precipitation over time) reduces global consumable food calories by 1% every year (Ray *et al* 2019), with additional losses in other sectors like livestock and fisheries (Lam *et al* 2020, Godde *et al* 2021). Weather extremes are increasing in magnitude, especially in the food-deficit, developing regions, which has major ramifications on food prices (Malesios *et al* 2020) and international trade (Burkholz and Schweitzer 2019). The magnitude and likelihood of extreme events are further expected to increase under projected climate change scenarios in many breadbasket regions (Kharin *et al* 2018). These risks and crisis events enlarge the need for farm risk management, which can include multiple strategies including crop and livestock management (improved nutrient and water management), diversification, using seasonal weather forecasts as decision support and ultimately, risk financing tools (including insurance). These farm management tools complement each other, and insurance solutions are often used if other risk management tools reach their limits (Meuwissen *et al* 2019). With the increasing severity and frequency of risk events in agriculture (Fischer *et al* 2021), there is an additional focus on viable insurance solutions to de-risk agriculture from weather and disease/pest risks. Comparing insurance research intensity with risks and crisis events can help in understanding this mismatch and can reshape the research agenda.

2. Data and methods

2.1. Selection of literature

A systematic review was conducted using a combination of search terms related to agricultural insurance in Scopus, a widely used scientific database for published research. The literature review was done based on the PRISMA guidelines (www.prisma-statement.org/), allowing a replicable list of results (also provided as a supplementary file (available online at stacks.iop.org/ERL/16/103003/mmedia)). We focus on the peer-reviewed literature and thus excluded grey literature sources. Thus, only peer-reviewed papers in journals that were indexed in Scopus at the time of publication are included in this review[4].

The combination of search terms used for the systematic review are provided in the supplementary information (supplementary section 1). We use a combination of 45 search terms, which comprehensively cover global agricultural insurance literature. We included papers published between 2000 and 2019 to focus on recent research on agricultural insurance. Since 2000, there have not only been more agricultural production shocks (due to both climatic and non-climatic factors) (Cottrell *et al* 2019), but the economic damages from extreme natural disasters (floods, extreme temperatures, droughts, storms, wildfires, and landslides) have also increased (Coronese *et al* 2019).

The initial search resulted in 1173 papers (figure 1). The next step required an initial abstract screening to eliminate duplicates and papers not available in English, leading to exclusion of 74 papers. After the initial screening, full-texts were accessed through the libraries of Wageningen University and Research and the International Maize and Wheat

[4] While this ensures a maximum replicability, we might miss single papers that were published before a journal got indexed (e.g. Turvey 2001 published in Applied Economic Perspectives and Policy, which was indexed in Scopus not before 2010). The omission of single papers is not expected to change the general validity of our results.

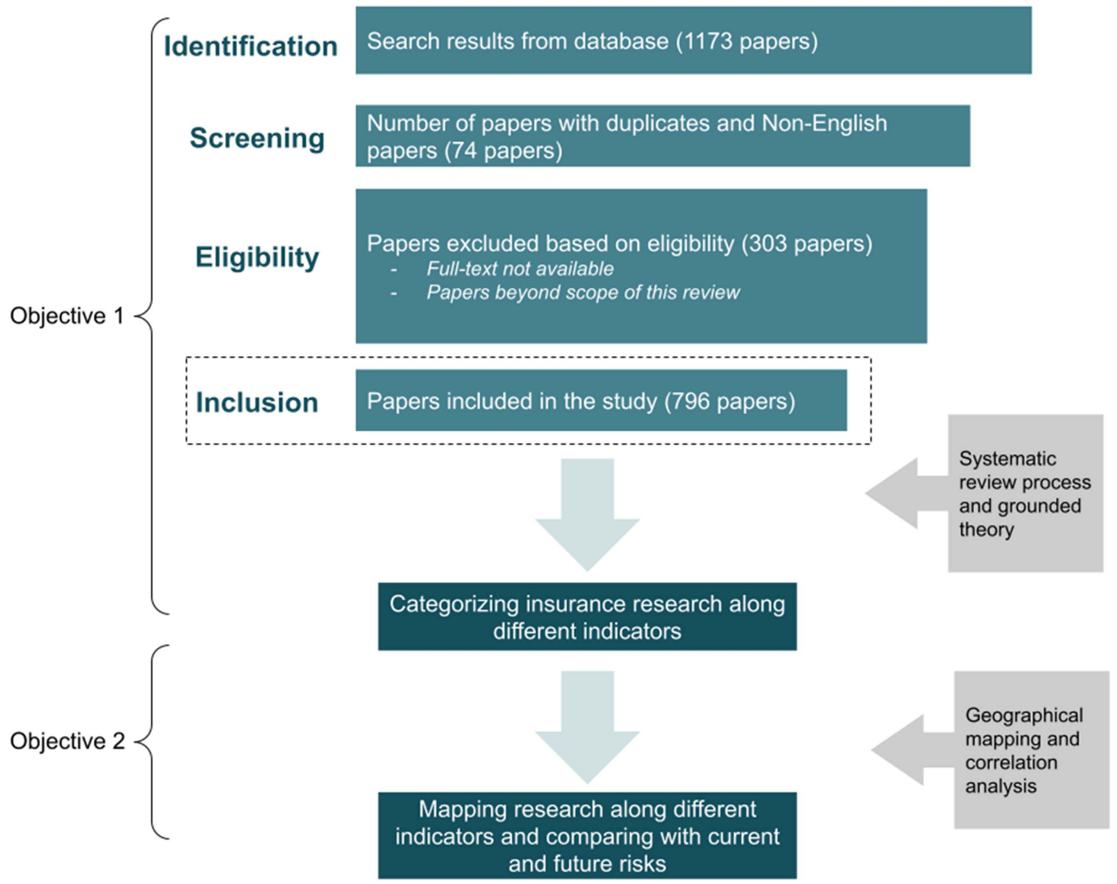

Figure 1. Schematic flowchart of the key steps of the systematic review. Grey blocks represent the methods used.

Improvement Center. All available papers were then scrutinized based on their content, and their fit with the scope of this review. We excluded papers that were (a) not related to agricultural insurance (for example, papers on health insurance or livestock disease epidemiology without a focus on insurance), (b) papers on meteorological databases and climatic events without any relation to agricultural insurance, (c) papers on crop yield distribution and statistics, without any implications of the findings on crop insurance, (d) papers based on crop production forecasting and monitoring, without any link with agricultural insurance and (e) papers on insurance for carnivore-livestock conflicts. This led to the further exclusion of 303 papers, resulting in a total of 796 papers included in this study.

2.2. Categorizing the literature

The list of 796 papers was reviewed thoroughly and information was collected to categorize papers by different indicators—agricultural product insured (e.g. livestock, fisheries, or crops like cereals, fruits etc), geographical focus (country and income group based on International Labour Organization and World Bank grouping-https://ilostat.ilo.org/resources/concepts-and-definitions/classification-country-groupings/), or insurance product type and hazard covered (e.g. drought, flood, total production risk etc). In case of multiple indicators, the paper was categorized under a separate category of multiple indicators. For instance, if a paper focused on multiple insurance product types, we put the paper in a separate category of multiple insurance product types. Similar steps were followed to collect information for other indicators (e.g. papers covering multiple hazards were grouped under multi-peril). For grasslands, the agricultural product was considered as livestock, and depending on the nature of the insurance product used, the papers were classified accordingly (indemnity-based livestock insurance or index-based livestock insurance (IBLI)).

Another indicator was the research theme. The research theme of the papers was identified based on grounded theory (Laplaza *et al* 2017). The initial coding process involved drawing key objectives and/or findings verbatim from the text. As the papers were reviewed, repeated ideas began to emerge from the data and these initial codes (or text) were then merged into two levels of categories (themes-level 1 and sub-themes-level 2). For example, Castañeda-Vera *et al* (2015) focused on selecting a suitable crop model for drought risk assessment to better capture crop-weather relations and improve insurance design. The paper was classified under the theme of 'basis risk' and sub-theme of 'crop-weather relations'. The categories developed through this process were constantly compared with each other and the process was iterated. At the end of the process, the papers were classified into six research themes, which consisted of 29 sub-themes in total. The coding tree and classification of each paper is provided in table 1 to highlight the grouping of papers into themes and subthemes. The papers with a broad discussion of agricultural insurance (including multiple theme overlaps) were classified under the theme of *Insurance policy analysis* (in particular, sub-theme *review*). Figure 1 was created using Google drawings and figure 2 with OriginPro software. R software was used for spatial data processing and visualization through maps.

2.3. Geographical mapping

To map the research intensity of these indicators by country vis-à-vis historical and projected risk and crisis events, the results obtained from categorizing the literature in the above step were mapped along with different indicators (agricultural product insured, research theme, type of insurance product, and hazard covered). To do this, the number of case studies per country for each of these indicators was determined from the review results and mapped using R software. Country-wise official boundaries were obtained from the World Bank (https://datacatalog.worldbank.org/dataset/world-bank-official-boundaries). The country was determined based on the research/focal study site(s) and not on the authors' affiliations. If a paper covered more than one country, both were included in the map. The maps, however, do not show regional papers (for example, papers on Africa or Europe in general), as the focus on the entire region can dominate countries with fewer papers in the mapping. For instance, we find a group of papers on developing countries in general that cover multiple crops/sectors, which would thus have been overrepresented in our maps. The distribution of regional papers along different indicators is shown in the supplementary information (supplementary tables 5–9).

2.4. Risk mapping

The results obtained from mapping the research intensity of papers along with different indicators in the above steps, were compared with three risk indicators—(a) the historical occurrence of weather-related disasters, (b) the projected mean temperature rise in the future, and (c) the occurrence of historical transboundary livestock diseases. These three risk indicators help in putting insurance literature into the context of the spatial patterns of key risks in agricultural systems. The data for the three risk indicators was collected from publicly available datasets and then mapped.

2.4.1. Historical weather disasters

To capture weather-related disasters since 2000 for every country, the international disaster database (www.emdat.be/) was consulted. These disasters were limited to meteorological and climatic events affecting agriculture (droughts, floods, extreme temperature and storms). The events were mapped jointly (sum of all the four disaster types).

2.4.2. Projected future weather risk under climate change

To capture future weather-related risk, the projected increase in the land surface temperature for 2050 was used as a proxy for a country's future climate risk exposure. The annual average projected temperature increase in the middle century (2041–2060) was calculated using the projected temperature from CMIP-6 (Coupled Model Intercomparison Project) data (https://interactive-atlas.ipcc.ch/). The temperature change for every country was calculated as the difference between the average annual temperature of mid-century (2041–2060) and the average baseline annual temperature between 1981 and 2010, based on the SSP5-8.5 scenario and mean of all the available (34) global climate models. The SSP5-8.5 scenario models the projected temperature change based on intensive fossil-fueled development with high mitigation challenges, and with a median global temperature response of 5-degree warming (Kriegler *et al* 2017). Although this scenario marks the upper extreme of greenhouse gas emission and fossil-use modelling, it helps in identifying hotspots of warming with limited pathways to green transition and sustainable energy alternatives. For comparison, results for other SSP scenarios are also provided in the supplementary information (supplementary table 4).

2.4.3. Historical animal disease outbreaks

The data on historical livestock disease outbreaks was collected from the FAO's Emergency Prevention System for Transboundary Animal and Plant Pests and Diseases (the EMPRES project—http://empres-i.fao.org/eipws3g/). The project provides a global comprehensive dataset of observed transboundary animal disease outbreaks at a gridded level, available from the year 2004. The total number of outbreaks for every country from 2004 to 2019 was calculated for livestock (including different sub-sectors—cattle, poultry, swine, sheep, and goats). The diseases covered in the dataset include African swine fever, Anthrax, Bluetongue, Bovine spongiform encephalopathy, Bovine tuberculosis, Brucellosis, Brucellosis (Brucella abortus), Brucellosis (Brucella melitensis), Brucellosis (Brucella suis), Classical swine fever, Contagious bovine pleuropneumonia, Foot and mouth disease, Influenza–Avian, Influenza–Swine, Japanese Encephalitis, Leptospirosis, Lumpy skin disease, Newcastle disease, Peste des petits ruminants, Porcine reproductive and respiratory syndrome, Rabies,

Table 1. Classification and number of papers in the review by research themes and sub-themes.

1. Basis risk ($n = 125$)
    - Aggregation bias and risk assessment ($n = 14$): Reducing basis risk by removing aggregation bias from crop yields and combining different sources of data for risk assessment.
    - Crop models ($n = 3$): Using crop models to better capture crop-weather relations and reduce basis risk (especially under data scarcity).
    - Crop-weather relationship ($n = 5$): Capturing crop-weather and physiological relationships to reduce basis risk, by accurate crop yield predictions.
    - Weather and climate data ($n = 47$): Using long-term climate data and weather risks to reduce basis risk, including remote sensing data and station-based weather data.
    - Contract design ($n = 56$): Improved contract design to reduce basis risk, including the trigger and index design.
2. Demand estimation ($n = 179$)
    - Preferences, farms and farmer characteristics ($n = 103$): Farmers preferences, farm types (size of the farm) and farm characteristics (age, gender, education etc) that influence demand for insurance.
    - Decision theory ($n = 39$): Demand estimation using decision theories (including both prospect theory and expected utility theory).
    - Willingness to pay ($n = 37$): Farmer's willingness to pay for agricultural insurance.
3. Insurance and climate change ($n = 36$)
    - Climate change impact on policy design ($n = 8$): Impact of climate change on production risk, insurance pricing and policy design of insurance.
    - Insurance for adaptation and mitigation ($n = 11$): Role of agricultural insurance to scale-out adaptation and mitigation in agriculture.
    - Insurance as financial adaptation ($n = 17$): Insurance itself as a financial adaptation to climate change and a safety-net for climate extremes/projected risks.
4. Insurance financing ($n = 198$)
    - Financial instruments ($n = 26$): Using bonds, futures and securitization for insurance financing.
    - Disaster finance, risk pooling and systemic risk ($n = 18$): Risk pooling and disaster risk finance to overcome systemic risk and finance insurance policies.
    - Risk transfer ($n = 15$): Financing insurance policies using risk transfer mechanisms including combining insurance with credit.
    - Agribusiness and private finance ($n = 6$): Insurance funding from public-private partnerships, private sector and contract farming.
    - Insurance pricing ($n = 85$): Pricing of insurance policies including premium rate making, and its impact on insurance feasibility.
    - Reinsurance ($n = 14$): Role of reinsurance in determining insurance feasibility.
    - Revenue plans ($n = 24$): Revenue insurance and feasibility of revenue plans.
    - Insurance subsidy ($n = 10$): State-supported insurance policies including subsidy for insurance and its impact on feasibility.
5. Insurance impact evaluation ($n = 130$)
    - Bundling ($n = 18$): Impact of bundling insurance with agricultural technologies.
    - Cropping mix and land use ($n = 25$): Impact of insurance on cropping mix, land-use patterns, tillage practices and crop acreage.
    - Farm efficiency ($n = 10$): Impact of insurance on farm efficiency (including technical efficiency of farms).
    - Farm income ($n = 28$): Impact of insurance on farm income (including the combination of insurance with cash transfers) and income inequality.
    - Input-use and negative environmental externalities ($n = 31$): Impact of insurance on input-use (e.g. fertilizers, pesticide, irrigation) and externalities (pollution, soil quality etc).
    - Resilience ($n = 2$): Impact of insurance on the resilience of farms.
    - Welfare ($n = 16$): Impact of insurance on welfare (welfare effects), social equity, economic growth and well-being of farmers.
6. Insurance policy analysis ($n = 128$)
    - Policy analysis ($n = 45$): Overview of agricultural insurance policies, qualitative and empirical policy analysis (including key trends, claim analysis and structural changes).
    - Review ($n = 70$): Reviews (including literature and systematic reviews), opinions, essays and policy briefs on insurance and its role in agricultural risk management.
    - Institutions for insurance policy delivery ($n = 13$): Institutional mechanisms for delivery of insurance policies (including mutuals, cooperatives, informal groups etc).

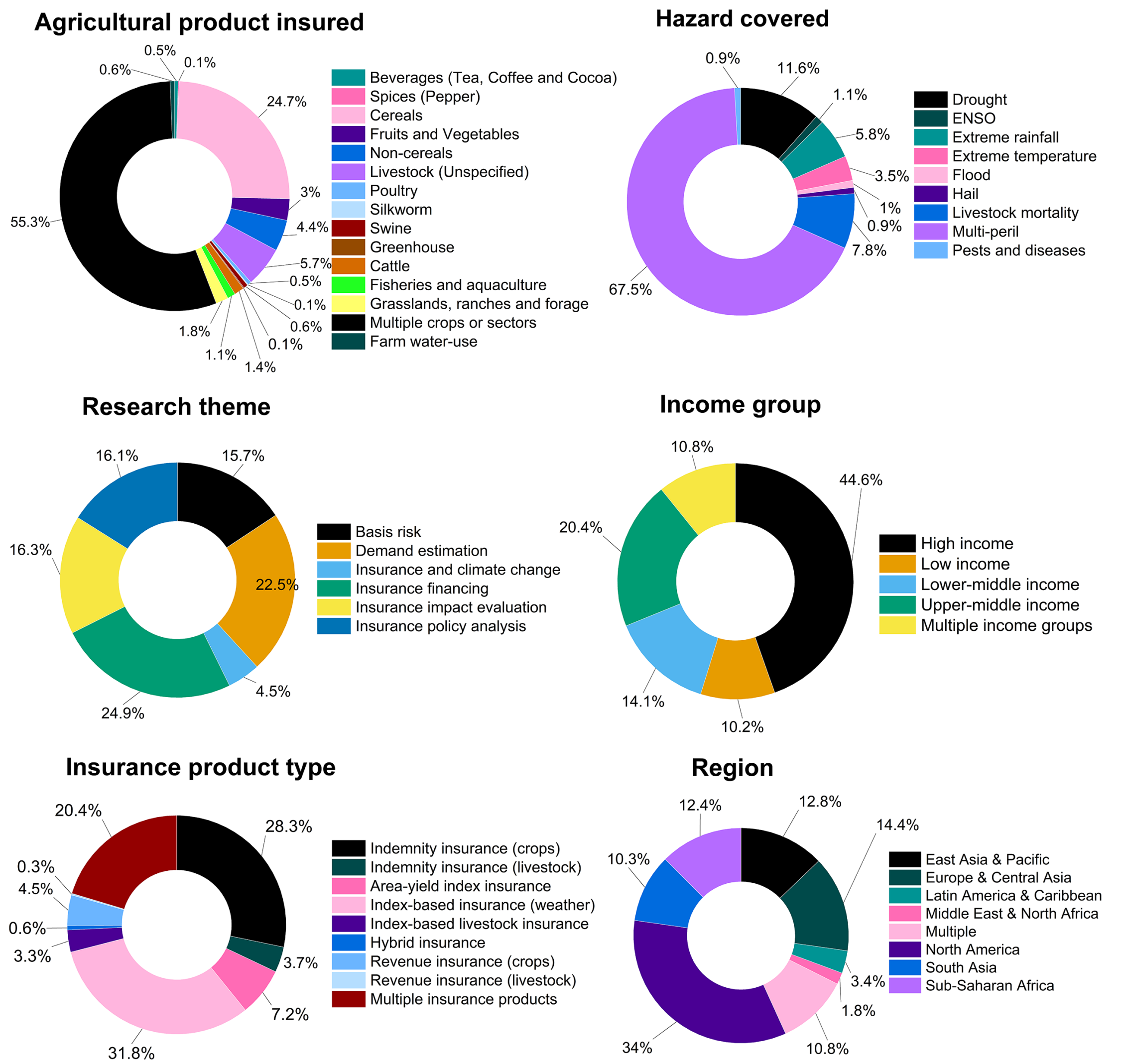

Figure 2. Summary of agricultural insurance research by agricultural product insured, hazard covered, research theme, income group, insurance product type, and the region.

Rift Valley fever, Rinderpest, Schmallenberg, Sheep pox and goat pox, and West Nile Fever. Due to a lack of data on appropriate risk indicators, fisheries and commercial aquaculture diseases were not included. Similarly, a risk indicator for pests and diseases of plants was not included.

2.5. Hypotheses

The research intensity and risk events for every country globally (calculated and mapped in the steps above) were compared using correlation analysis. Pearson's correlation coefficient (along with its significance level) was calculated using STATA software for three groups—(a) the number of papers on livestock insurance with historical livestock disease outbreaks and relevant extreme weather events (drought), (b) the number of papers on crop insurance with the historical frequency of extreme weather events, and (c) the total number of papers on agricultural insurance with projected mean temperature change by mid-century. Correlation analysis was also undertaken for specific subsets of papers (e.g. papers on insurance and climate change were compared with projected temperature increase and papers on different (extreme weather) hazards with historical hazard frequency). We, therefore, test the hypothesis that insurance research is targeted to the most relevant regions, based on the geographical distribution of current (and future) risks, as the assessment of the risk exposure is an important part of insurance policy development (Lloyds 2015). Historically, extreme weather events have had a significant impact on global and regional agricultural production (Lesk *et al* 2016, Cogato *et al* 2019, Vogel *et al* 2019). Therefore, they have a significant role to play in the design of both indemnity-based (where insurance claims are paid based on actual loss) and index insurance products (claims are paid based on a pre-defined index), and in building overall resilience (Hudson *et al* 2019). Disasters (including extreme weather events) are estimated to cost 520 billion USD per annum to the global economy and reported losses from extreme weather events have increased by 250% in the last two decades (UNISDR and CRED 2017).

Climate change may further increase the frequency and intensity of weather extremes during crop growing seasons, causing even greater losses in the future (Bouwer 2019). Thus, comparing recent and current research intensity with future climate risk (projected mean temperature increase) can show whether there is an alignment between current research and projected temperature increase hotspots.

For livestock, both crisis events (including extreme weather disasters such as drought and extreme temperature) (Food and Agriculture Organization (FAO) 2017) and animal diseases can cause significant production losses. Comparing research intensity of livestock insurance with the global distribution of relevant disaster events helps to identify any mismatch between the two, even though it is difficult to insure transboundary disease risk because of its systemic nature, lack of data availability on disease occurrence and losses, and influence of governmental surveillance strategies on the overall disease risk (Meuwissen *et al* 2003, 2013).

Spatial patterns of research intensity may not reflect the size of the agricultural insurance market or the need and capacity for insurance in a region. At the same time, not all historical (and future) risks are insurable and risk exposure alone may not imply insurability. However, an increase in temperature due to global warming has already increased the severity and magnitude of weather events (IPCC 2021). Further, our research helps in assessing the alignment between current research and risks. A mismatch can guide investments into insurance research in some regions, while also highlighting the need for alternative risk management solutions where agricultural insurance is not feasible, for instance, due to high frequency of disasters.

3. Results

3.1. Categorizing the agricultural insurance literature along different indicators

All included papers were classified into agricultural product insured, research theme, income group, insurance product type, and hazard covered (figure 2). Among the different agricultural products insured, cereal crops were the most prominent group with 24.7% of the papers, followed by livestock with 5.7% of the total papers, while most of the papers focused on multiple crops/sectors (55.3%). Among crops, limited focus on other crops was evident (for example, fruits and vegetables accounted for only 3% of the papers and non-cereals like millets, pulses, roots and tubers were focused in 4.4% of the papers). Among the papers focused on livestock, classical livestock types (most often cattle) were most frequently retrieved, followed by fisheries and aquaculture.

We find six research themes to be of key interest: basis risk, demand estimation, insurance and climate change, insurance financing, insurance impact evaluation and insurance policy analysis. The highest number of papers were found under insurance financing (24.9%) and demand estimation (22.5%). The lowest number of papers were on insurance and climate change (4.5%). Additionally, we classified the papers based on the country income group and found that most papers focused on high-income group countries (44.6%), followed by middle-income countries (34.5%). Only a limited number of papers were focused on low-income countries (10.2%).

When classifying the papers along the insurance product type, we find that 42.3% focused on index insurance (insurance payouts based on an index measurement), followed by 32% on indemnity-based insurance (insurance payouts based on actual loss at the insured unit). Only 5.1% focused on revenue-based insurance (insurance payouts based on the yield and price of the commodity). Approximately one-fifth of the studies (20.4%) focused on multiple insurance products. Regarding hazards covered, 67.5% of the papers addressed multiple perils. Among single hazards, droughts were most frequently studied (11.6%), followed by extreme rainfall (5.8%). Livestock mortality including risk from livestock diseases was studied in 7.8% of the papers. Other hazards like floods, hail and El Niño Southern Oscillations (periodic change in oceanic temperature, affecting global precipitation and temperature patterns) (Nguyen *et al* 2021), were less frequently addressed in the reviewed literature.

3.2. Research themes

The research themes were identified during the review process based on a two-step classification procedure. We first identified a sub-scheme which we then grouped into six main themes (table 1). In the following section, we briefly describe the main themes, sub-themes, and key findings, illustrated by selected papers.

3.2.1. Basis risk

Basis risk is the inability of index insurance to initiate payouts when a loss occurs to the farmer or vice versa when payouts are triggered in case of no losses. This can happen if the index used for insurance payouts, is not able to capture farmer's production losses. In this review, 125 papers focused on the issue of basis risk in agricultural insurance. For area-yield index insurance, basis risk arises from a lack of correlation between the area-trigger (spatially aggregated crop yield) and observed farm yield. Papers classified under the sub-theme of *aggregation bias* propose various ways to deal with this issue. For instance, Woodard *et al* (2011) use statistical methods such as copulas to design the area trigger. Other studies focus on improving the *contract design* of insurance. Wang (2020) proposes a grouping of farms based on similar crop yield profiles rather than based on an administrative area. Data scarcity is another contributing factor to basis risk, as the lack of quality data impedes efficient contract design. As a response, the use of crop modelling and publicly available remote-sensing based weather and vegetation data is proposed in studies classified under the themes of *crop models* and *weather and climate data* (Nieto *et al* 2012, Enenkel *et al* 2019). Generally, we observe that recent papers integrate advanced modelling techniques and emerging data sources into index insurance design to make loss estimates more precise and reduce basis risk. For example, capturing crop-weather relationships (another sub-theme identified) by integrating phenology data in the contract design has been proven useful to reduce basis risk (Conradt *et al* 2015, Dalhaus *et al* 2018).

3.2.2. Demand estimation

Estimating demand for insurance helps policymakers and insurance agencies to devise implementation strategies to pilot and scale insurance in new areas, and simultaneously, to understand and identify factors that reduce insurance demand in many regions. Hundred and three papers studied how farmers' *preferences,* and *farms and farmer's characteristics* affect insurance adoption. Factors like age (more farming experience), gender (male), education (higher education level) and loss experience with previous disasters positively affected the demand for insurance in all three sectors—agriculture, livestock and fisheries (Akintunde 2015, Akter *et al* 2016, Olayinka *et al* 2018). *Decision theory* was identified as another sub-theme. An emerging topic of interest is behavioural economic theories that might drive insurance demand such as compound risk, loss, or ambiguity aversion as well as probability weighting, where farmers depart from standard economic theory because payouts are unknown and ambiguous (as compared to premiums, which are certain and known) (Babcock 2015). This plays an important role in accurately estimating the demand for insurance, in addition to traditional risk aversion theory (Carter *et al* 2015, Elabed and Carter 2015). *Willingness to pay* (the third sub-theme) for an insurance product helps in determining the price farmers are willing to pay for insurance and target subsidies to pilot new insurance programs. In most cases, the commercial premiums in existing insurance schemes were found to be significantly higher than the farmer's estimated willingness to pay (Budhathoki *et al* 2019).

3.2.3. Insurance and climate change

The theme comprising the lowest number of papers (36) was insurance and climate change. The first sub-theme concerns the anticipated *impact of climate change on insurance policy design*. Modelled increases in agricultural losses from climate change were found to enhance insurance costs and increase premium rates for farmers in both developed (Tack *et al* 2018) and developing regions (Siebert 2016). To align insurance pricing with increasing risks and to address climate uncertainty while designing weather index insurance, climate modelling needs to be integrated with insurance policy design (Bell *et al* 2013).

The second sub-theme under climate change related insurance research was *insurance for adaptation and mitigation* (Linnerooth-Bayer and Mechler 2006). Such studies addressed the potential of insurance to complement or substitute ongoing adaptation and mitigation strategies. For example, crop insurance was compared with other adaptation strategies like crop diversification, which was found to negatively influence insurance adoption (Falco *et al* 2014). In the third sub-theme, insurance itself was recognized as a *financial adaptation* strategy to stabilize farm income under climate change (Muchuru and Nhamo 2019). However, climate insurance as an adaptive strategy (based on global risk-sharing principles) was argued to favour developed countries. Such insurance would be more expensive in developing countries, which are more exposed to higher risks (Duus-Otterström and Jagers 2011).

3.2.4. Insurance financing

The biggest group of papers (198) focused on different sources for insurance financing from *financial instruments* like catastrophic bonds and futures (Stein and Tobacman 2016, Komadel *et al* 2018), to *disaster risk finance* including combining risks over large geographical areas in a common pool. Moreover, the role of systemic risk in decreasing the viability of a common risk pool was also addressed (Feng and Hayes 2016, Porth *et al* 2016). Combining insurance with credit as a *risk transfer* mechanism was another sub-theme to support insurance financing in developing countries (Stein and Tobacman 2016, Collier 2020). Credit-linked index insurance models where insurance is built into a loan as contingent credit were found to decrease loan defaults and expand credit access (Farrin and Miranda 2015). Six papers explored the feasibility of *agribusiness or public-private partnership* for agricultural insurance, mainly in the US, where the federal crop insurance program allows public-private models in agricultural insurance. Other studies outside the US analyzed the legislative and legal reforms needed for an effective public-private model (Călin and Izvoranu 2018, Inshakova *et al* 2018). The viability of such public-private models was also explored with respect to their risk-sharing structures (Weng *et al* 2017).

Within the insurance finance theme, another sub-theme focused on *insurance pricing* (ratemaking) and tools and methods for calculating actuarially fair premium rates. The use of copulas for capturing extremes to aid effective premium estimation was identified as an emerging trend in more recent papers (Goodwin and Hungerford 2015, Bokusheva 2018).

Ratemaking under data scarcity was another research problem, especially in area yield-index and indemnity insurance. Under data-scarce conditions, the use of expert advice (Shen *et al* 2016) and a pricing strategy based on relationships between aggregated and farm yields were two of the investigated examples (Gerlt *et al* 2014). Another sub-theme relate to the combination of insurance with add-on *revenue protection plans*, which cover price risk along with production (yield) risk, to also provide coverage against market risks (Bulut and Collins 2014, Yehouenou *et al* 2018). Most of the large agricultural insurance programs across the world depend on *insurance subsidy*, which was another sub-theme, with a large focus on developing countries (Mahul and Stutley 2010). Subsidized insurance was found to have higher welfare gains for farmers in the risk-prone regions (as compared to farmers in less risky areas). However, in some cases, a higher expected utility was found for alternative risk prevention measures like cash-transfers, farm-input subsidies, and reduction in credit rates than for subsidized insurance (Ricome *et al* 2017).

3.2.5. Insurance impact evaluation

Among all papers on insurance impact evaluation, the *impact of insurance on input-use* including fertilizer, pesticides and irrigation use, and their consequent negative externalities including pollution and decline in soil quality, was the most frequently recurring sub-theme (31 papers). Many papers reported marginally increased input-use and crop acreage, particularly for cash crops, upon insurance (Cole *et al* 2017, Deryugina and Konar 2017). A few positive environmental effects of insurance were also noted, e.g. insurance was found to increase the use of soil conservation practices (Schoengold *et al* 2014), and insurance premium discounts were shown to support pest management practices (Beckie *et al* 2019). *Bundling* insurance with agricultural technology was another sub-theme, where insurance was found to increase the adoption of hybrid seeds, especially when subsidized (Foltz *et al* 2013, Freudenreich and Mußhoff 2018). Some papers discussed how insurance enhanced *farm efficiency* and, in some cases, also increased the technical efficiency of farms (Roll 2019). The role of insurance in increasing farm *resilience* was an emerging field of study (Kron *et al* 2016). Insurance was also found to increase the *welfare* of households in the presence of poverty traps (Chantarat *et al* 2017) and to increase the well-being of livestock farmers (Tafere *et al* 2019).

3.2.6. Insurance policy analysis

The papers in this research theme focused on *policy analysis* of existing insurance schemes. These included empirical analyses of insurance policies and examination of structural changes in insurance policies over the years (Coble *et al* 2013, Zarkovic *et al* 2014, Siwach *et al* 2017). The other types of papers *reviewed* insurance policies—from qualitative reviews to opinion pieces and essays on insurance and its larger role in risk management. Some reviews focused on specific issues in insurance like basis risk (McElwee *et al* 2020), the use of remote sensing for insurance (de Leeuw *et al* 2014), and insurance for a specific sector like grasslands (Vroege *et al* 2019). Another sub-theme in the field focused on the role of *institutions and policy delivery* of insurance. These included the use of collectives (Pacheco *et al* 2016), insurance delivery by collaborating with existing local institutions (Bélanger 2016), and the role of mutuals (Meuwissen *et al* 2013).

3.3. Mapping and comparing the research intensity with historical and future risks

3.3.1. Geographical mapping along different indicators

Figures 3–6 present the mapped results. Indicators comprising only one single country are not shown (but are provided in supplementary information).

3.3.1.1. Agricultural product insured

From all the agricultural products insured (figure 3), we find that insurance research on multiple crops/sectors has the highest geographical coverage (based on the number of countries covered), followed by papers that cover cereals. Only very few papers cover fruits and vegetables, and other (non-cereal) crops—most of them in India, China and the US. Papers on insurance for beverages (tea, coffee and cocoa) is limited to China, India and Ghana (Okoffo *et al* 2016). For livestock, the spatial extent of the insurance research is limited as well, with papers on cattle insurance focusing on six countries—the US, India, Ethiopia, the UK, the Netherlands and Kenya. Papers on livestock (with multiple or unspecified sectors) are distributed in different countries across the globe. Papers on fisheries and aquaculture are limited to the US, China, Vietnam, Norway and Nigeria (Beach and Viator 2008, Nguyen and Jolly 2019).

3.3.1.2. Research theme

Figure 4 presents the geographical distribution of papers according to the research theme. The themes with the highest number of papers were *insurance financing* and *demand estimation*, while *insurance and climate change* had the lowest number of papers. Most of the themes covered North America and Asia, and very few themes focused on Africa, South America and South-east Asia. The US was most frequently studied for every theme, along with India for the research theme on insurance and climate change (Jangle *et al* 2016, Ogra 2018). These results indicate the type of insurance research conducted in a given country.

3.3.1.3. Insurance product type

Figure 5 shows maps of countries by types of insurance products. For index insurance (for crops), the

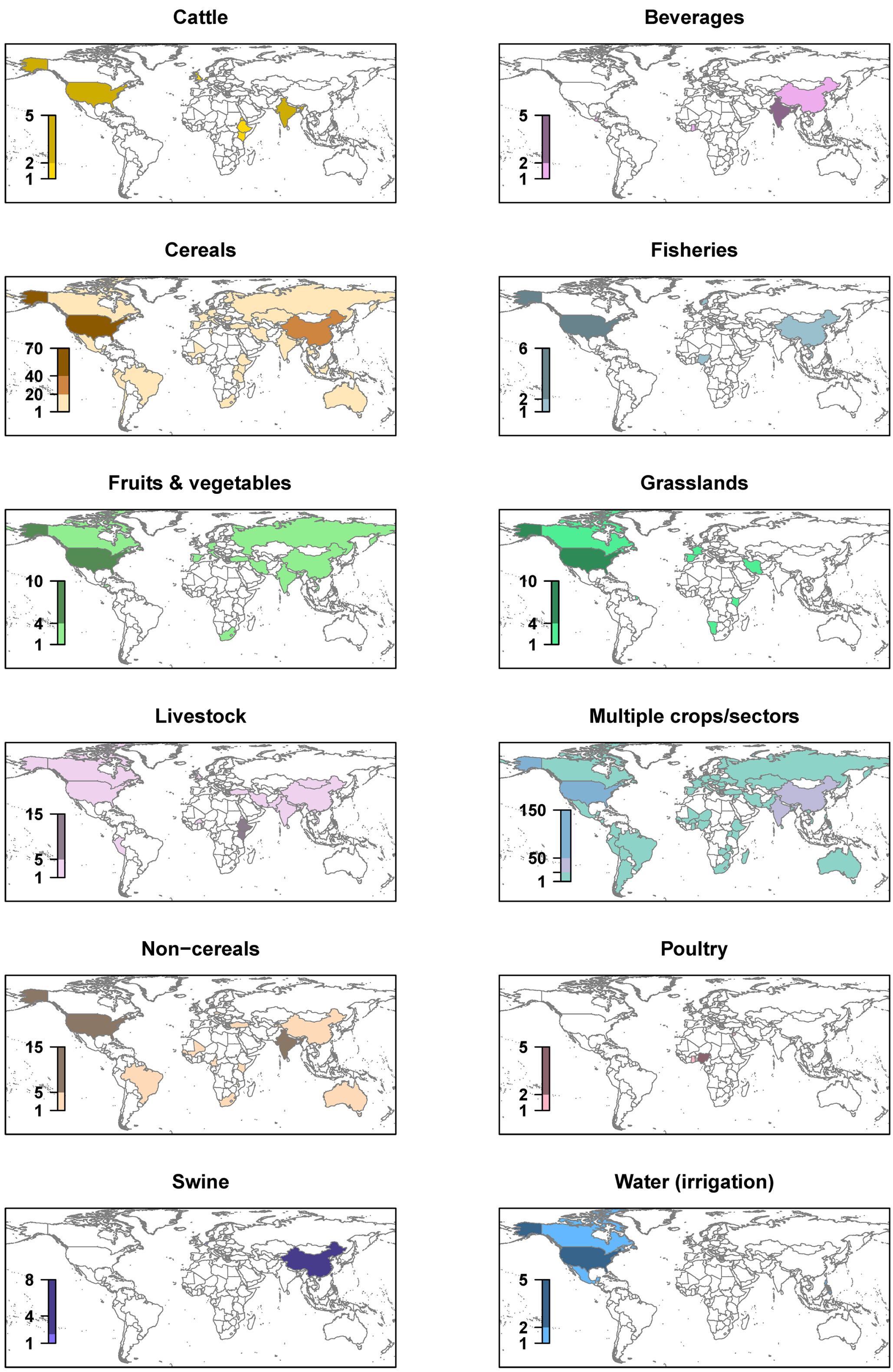

Figure 3. Panel of maps showing the geographical distribution of agricultural insurance research literature by agricultural product insured.

highest number of studies was found for China, India and the US. Index insurance for livestock (commonly known as index-based livestock insurance-IBLI) was concentrated in eastern Africa (Ethiopia and Kenya) and Mongolia (Bageant and Barrett 2017, Johnson *et al* 2019). The highest research intensity for indemnity insurance (for crops) was found in China and the US, although several papers were also found in Europe (Mahul and Vermersch 2000, Capitanio *et al* 2011). Most papers on area yield index insurance were related to the US and India, where the area-yield insurance policy is most common. It is important

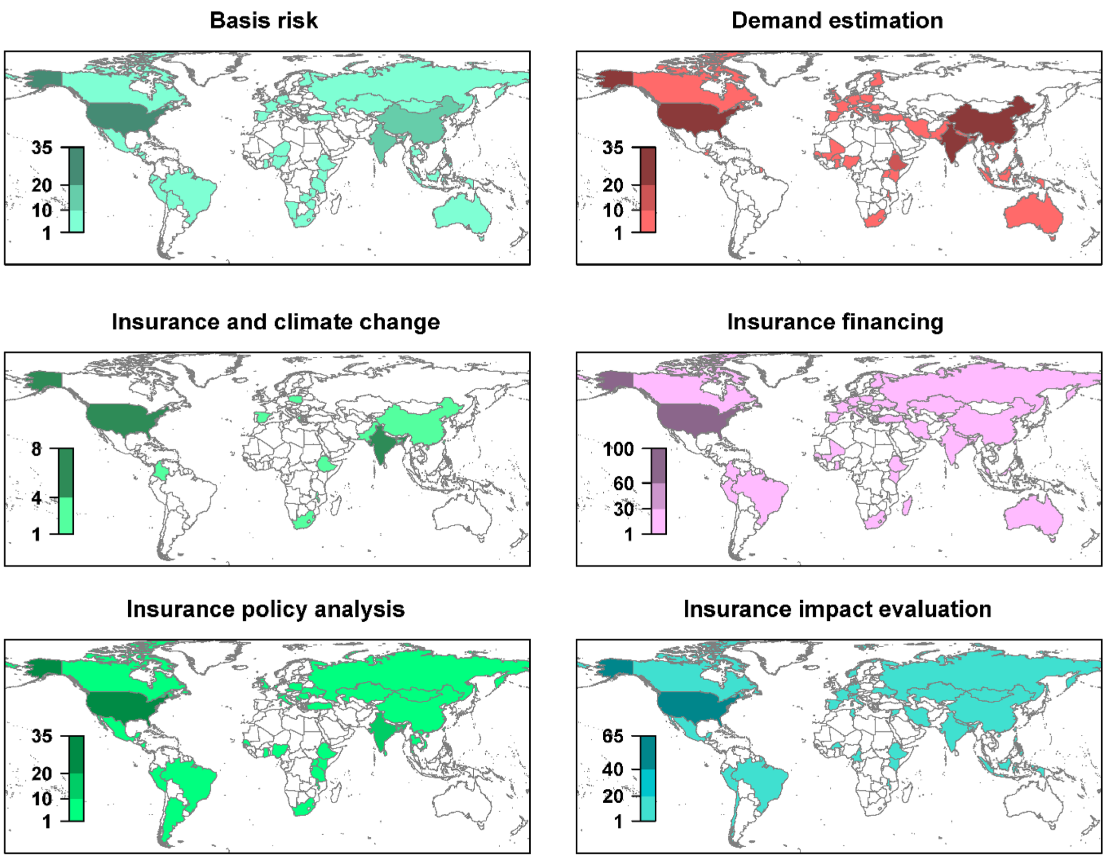

Figure 4. Panel of maps showing the geographical distribution of agricultural insurance research literature by research theme.

to note that, unlike index insurance, none of the papers from Africa (except South Africa), focused on area-yield insurance and revenue insurance, mainly due to data scarcity of crop production statistics. Papers on revenue insurance (crops) were found in the US, Canada, Spain, Italy and Iran (Goodwin *et al* 2018).

3.3.1.4. Hazards covered

Papers were also classified based on the hazards they covered (figure 6). Studies focusing exclusively on hail insurance were found in Canada, the Netherlands, Germany, Switzerland, Australia and South Africa (van Asseldonk *et al* 2018). Incidentally, the highest probability of hail is found in the US, India, Pakistan, Argentina, Laos, Vietnam and many countries in middle Africa (Prein and Holland 2018). For floods, only a few papers were found for India, Pakistan, China, Vietnam and the US (Matheswaran *et al* 2019). Very few papers, from North and South America, focused on El Niño Southern Oscillation events (Khalil *et al* 2007, Tack and Ubilava 2015). There were a considerable number of papers on drought and these were evenly distributed throughout the world (although South America was not focused in the reviewed papers). Very few studies examined the role of agricultural insurance for pest and disease management and these occurred in developed countries (Norton *et al* 2016, Beckie *et al* 2019). In comparison, the highest losses from pests and diseases in cereal crops are observed in South Asia and Sub-Saharan Africa (Savary *et al* 2019). Papers in the review which focused on extreme temperature were from China, the US, India, Germany, Turkey, Malaysia and Kazakhstan (Conradt *et al* 2015). Other hazards types—uneven rainfall, multiperil hazards and livestock mortality, were distributed globally.

3.3.2. Risk mapping and hypothesis testing

Figure 7 compares the above results with current and future risks. There is a significant correlation between weather-related disasters and the distribution of papers on crop insurance, with a correlation coefficient of .75***. However, when the total number of papers per country identified in this review (including both crops and livestock) are compared with projected mean temperature change, a poor correlation is observed (.18). The correlation further decreases when selected papers from the theme *insurance and climate change* are compared with projected temperature increase hotspots (non-significant correlation of −.044). Similarly, a negative correlation (−.06) is observed between the number of papers on livestock and the total number of livestock epidemics throughout the world. This is expected as very few

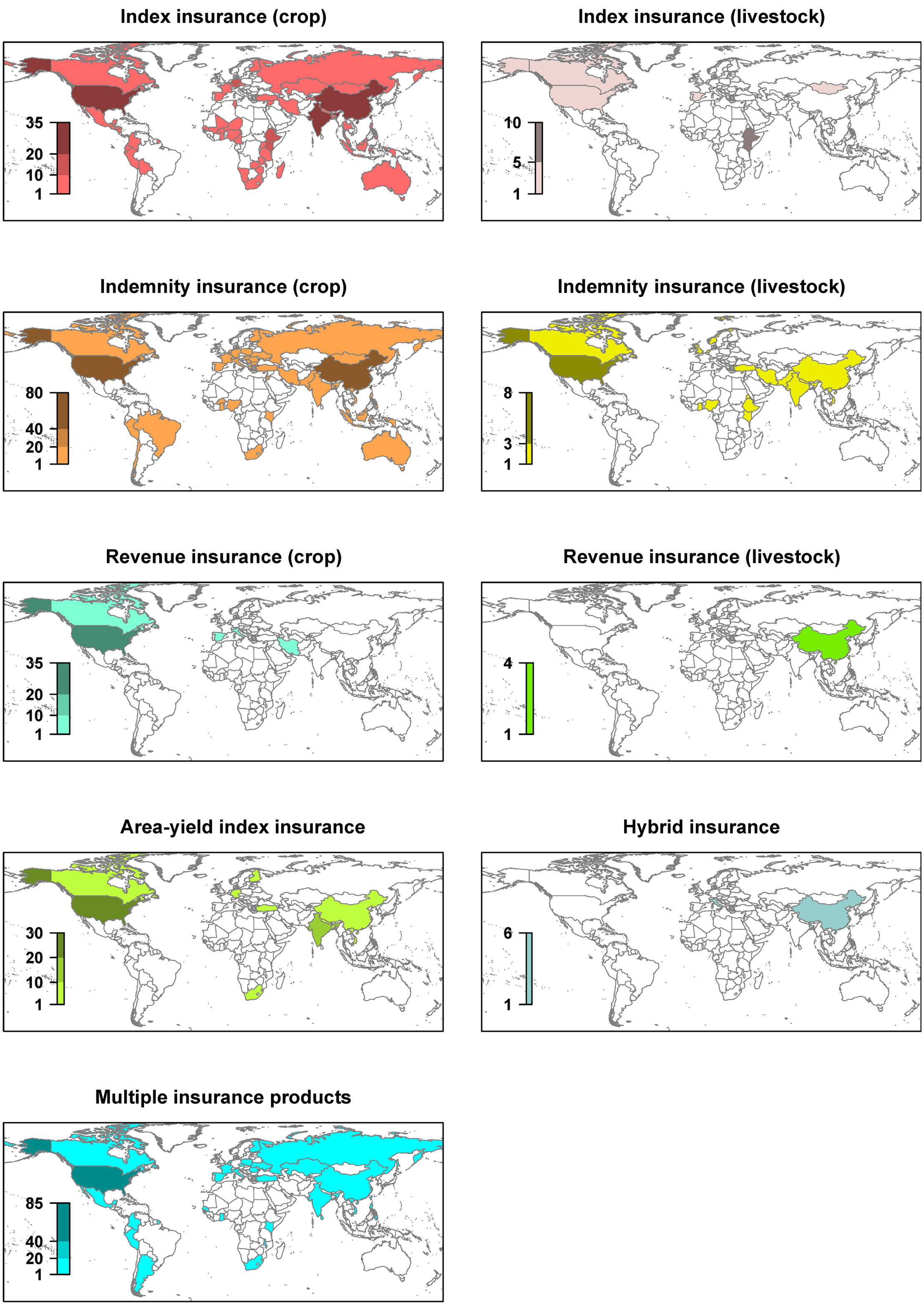

Figure 5. Panel of maps showing the geographical distribution of agricultural insurance research literature by insurance product type.

papers from the livestock sector focused on pests and diseases (figure 6). However, it is interesting to note that livestock epidemic hotspots like China, Indonesia, France, Germany and Italy are not eminent in research on this matter. In comparison, many papers in the livestock literature are focused on droughts, which explains the higher correlation with drought events (.51).

The above results provide a broad overview of the correlation of literature with four risk indicators. Even when the number of papers by different indicators are compared with extreme weather events, poor

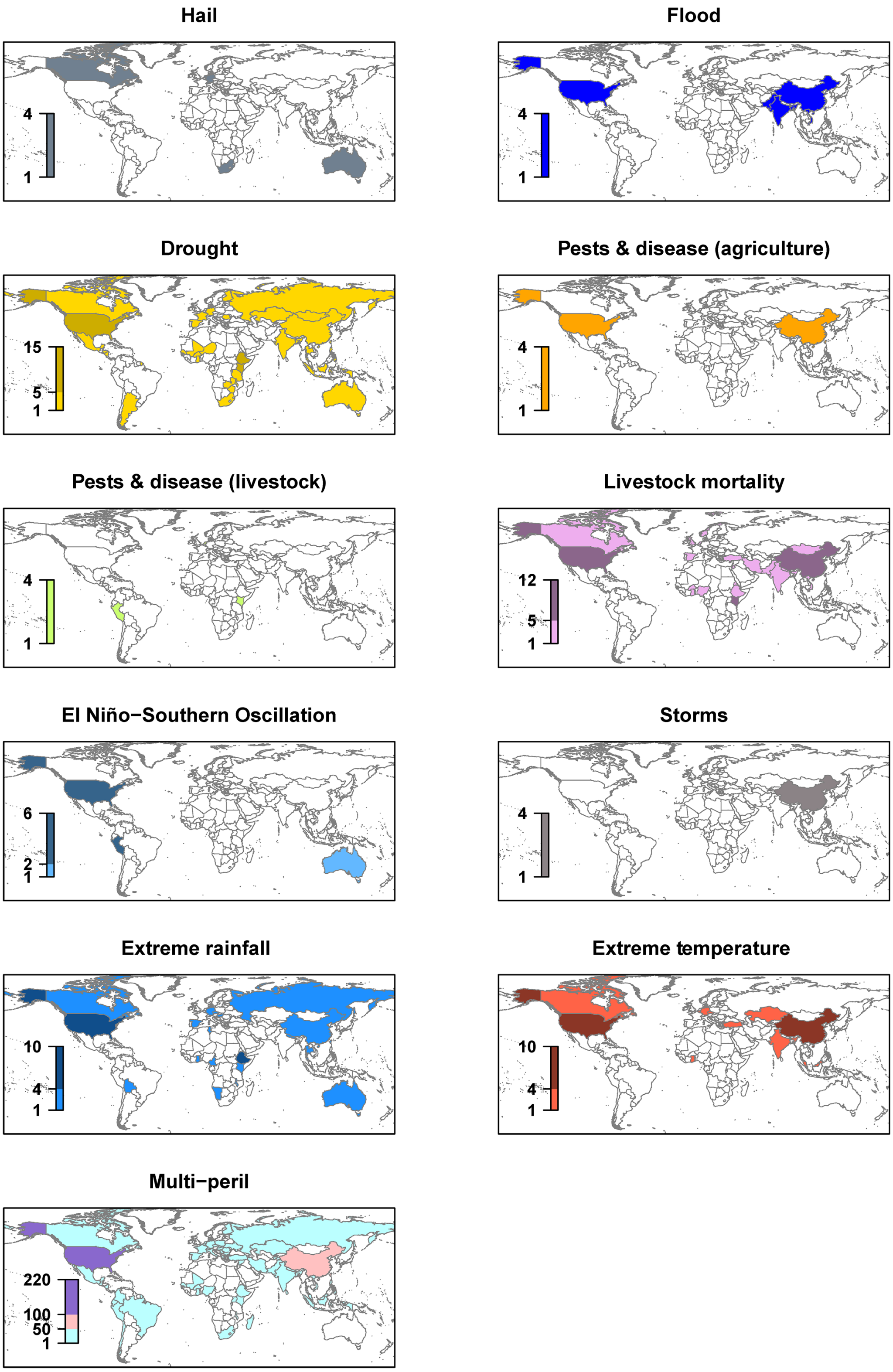

Figure 6. Panel of maps showing the geographical distribution of agricultural insurance research literature by hazards covered.

correlations are observed (supplementary table 3). For instance, the correlation between the studies on drought with observed drought incidences was .32, with the highest drought disasters observed in the US and China while studies focused on Eastern Africa. Similarly, for floods, most flood-prone countries of South and South-east Asia are not identified as focus areas in our literature review. By comparison, the correlation between papers on extreme rainfall and observed storm disasters is higher (.58). Insurance research on extreme temperature is also poorly correlated with observed temperature events (.03).

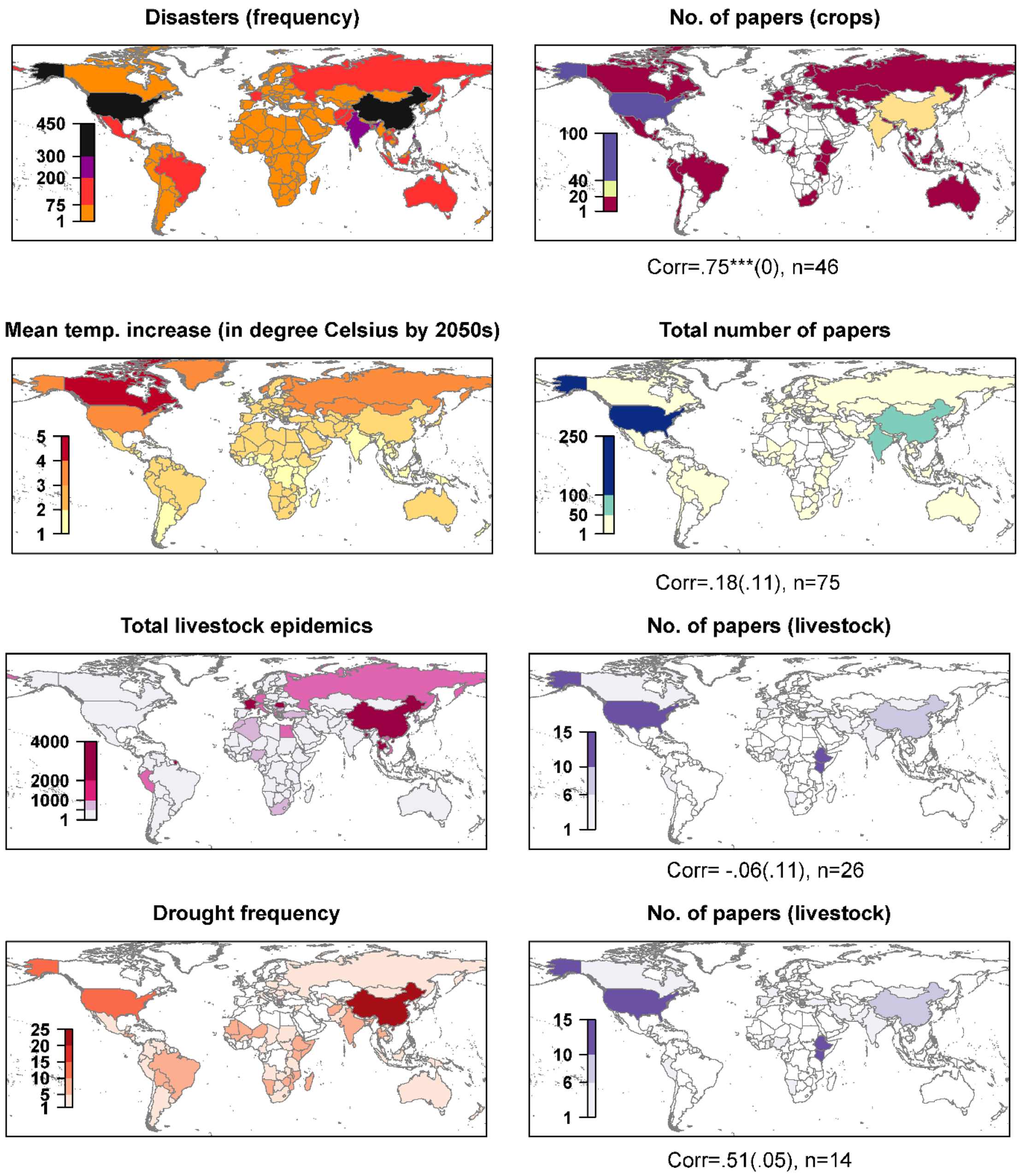

Figure 7. Research intensity of papers on agricultural insurance with four risk indicators. Correlation (with corresponding risk indicator), standard error (in brackets) and *n* (number of countries) are provided below each map. The significance-level are shown by stars (p-value $\leqslant$ .05 is denoted with one star, p-value $\leqslant$ .01 with two stars and p-value $\leqslant$ .001 with three stars).

4. Discussion and conclusion

This review synthesized agricultural insurance research since the year 2000 and identified key research themes, along with their geographical focus, agricultural product insured, insurance product type and the hazards covered. The results were mapped and compared with historical and future risks. Overall, we find that case studies in the US and China dominate agricultural insurance research, calling for future research to focus more on areas most affected by climate change. Regarding the research themes, insurance financing has been most commonly studied, including topics such as insurance pricing, revenue plans and reinsurance. So far, climate change has attracted little attention in agricultural insurance research.

There is a clear research focus on crops, especially cereals. Other crops like fruits and vegetables, millets, pulses, oilseeds and roots-tubers have an important role to play in promoting sustainable diets and nutritional security across the world (Willett *et al* 2019). Notably, we do not find significant insurance research on these agricultural products. For example, large fruits and vegetable producing countries in Southern America (Brazil and Mexico) and non-cereal producers (small grains including pulses and millets) in Africa (Ethiopia, Nigeria) are missing in recent literature. These production systems are also vulnerable to extreme weather yet receive less focus in agricultural insurance research (Park *et al* 2019). Among livestock, cattle insurance has the highest research intensity, as compared to swine, poultry, sheep and goats. Fisheries and aquaculture receive the least attention. Incidentally, no studies on fisheries and aquaculture insurance were retrieved for the top fish producing countries like Indonesia, India, Russia and Japan.

Index insurance was the most prominent among insurance product types found in the review, followed by indemnity insurance, while research intensity was lowest for revenue insurance. Literature on index insurance focused on different developing countries, that are often characterized by poor infrastructural resources and data scarcity, which limits the scope of indemnity-based products in these regions. This has led to considerable policy and donor-driven investments to develop index insurance in low and lower-middle income countries (Barnett and Mahul 2007, Skees 2008). Further, advances in remote sensing and data science have opened new opportunities to integrate satellite-based data with agricultural risk management (Enenkel *et al* 2019, Vroege *et al* 2021). This may also be the reason for the low correlation between drought disasters hotspots (China, the US and India), and papers in the review focusing on drought (correlation coefficient of .32), since a significant proportion of index insurance literature (found in the developing countries) is on droughts. Recent literature highlights the need to further improve index-based insurance and disaster risk management tools for drought protection (Belasco *et al* 2020, Bucheli *et al* 2021, Leppert *et al* 2021). Here synergies between research on index insurance in developing and developed countries might advance products in both regions.

Apart from drought, most of the studies in the review address multiple perils and few are focused on single perils, especially flood, hail and pests and diseases of crops. Pests and diseases significantly undermine the sustainability of food systems, causing 17%–30% productivity losses globally among major crops (Savary *et al* 2019) and are expected to cause further damage in temperate regions due to global warming (Chaloner *et al* 2021). Similarly, livestock diseases cause a significant loss in animal production systems. While the role of insurance in agricultural pest and disease management is found to be limited in this review, it can become an important future research topic to incentivize risk prevention and insure losses wherever feasible (Möhring *et al* 2020). The Covid-19 pandemic has brought forth the need for risk prevention measures for global epidemics (Gu and Wang 2020), and such crisis events are expected to become more frequent in the future due to ongoing biodiversity loss (Morand 2020, McElwee *et al* 2020) and climate change. Targeting livestock insurance and other risk management strategies to epidemic hotspots is, therefore, an important area for future research.

We also find a mismatch (low correlation) between the spatial patterns of insurance research and future climate change risk hotspots. Very few papers in the review (4.5%) focus on the role of insurance in addressing challenges arising from climate change. The importance of insurance (among many agricultural risk management strategies) in addressing climate extremes is increasingly being realized because of the potential 'double-role' of insurance, i.e. as a tool to provide incentives for risk prevention and adaptation, and as an instrument to cover severe losses. However, limited evidence is found in this review for the role of insurance in scaling climate adaptation and mitigation. It remains an empirical question whether insurance, when combined with climate action (adaptation and mitigation activities), can reduce risks and encourage climate-smart pathways among farmers (Loboguerrero *et al* 2020). Climate change is projected to impact various regions differently, due to diverse agro-ecological conditions, adaptive capacities and vulnerability. Yield gains and shifts in favorable growing conditions are expected to occur in many temperature regions (King *et al* 2018, Aggarwal *et al* 2019). With limited climate and disaster finance available (especially in developing countries), aligning insurance with the identified research gaps can help to ensure risk protection for the most vulnerable groups. Findings from insurance research in developed countries also have a significant potential for application in developing countries, keeping into consideration the location and region-specific issues and challenges. At the same time, improving the insurability of currently under-represented regions is another important pathway for future work.

Agricultural research is increasingly focused on strategies to transition towards more sustainable food production pathways (Herrero *et al* 2020). Some of these innovations include protein-based production systems, sustainable animal feed techniques like insect farming, land-saving technologies like vertical farming and glasshouse cultivation, as well as circular farm models (Chia *et al* 2019). They have become an important part of the food systems narrative and future insurance research can focus on some of these promising technologies. The mapping exercise conducted in this review can help to set targets, recognize potential research topics and areas, and streamline research with current and potential risks. Finally, it is important to recognize the role of agricultural insurance in the larger risk management agenda, as a complement to other farm management tools. Risk hotspots based on weather and related crisis events, imply important policy decisions—a scoping analysis of the feasibility of agricultural insurance (when other farm risk management strategies do not work or are costly) is needed to offer adequate risk coverage. Linking risk management strategies (like agricultural insurance) with risk exposure, context-specific vulnerabilities and resilience capacities of the food systems, can offer important lessons for policy design and prioritization. As countries strive to achieve SDGs and transform food systems along sustainable pathways, agricultural insurance will play an important role in risk management. The research gaps highlighted in this review can help stakeholders, including donors, policymakers and researchers, in planning and aligning future action.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Conflict of interest

The authors declare no competing interests.

ORCID iDs

Shalika Vyas https://orcid.org/0000-0002-9933-1269
Tobias Dalhaus https://orcid.org/0000-0001-5853-0942
Martin Kropff https://orcid.org/0000-0001-9598-9824
Pramod Aggarwal https://orcid.org/0000-0002-1060-7602
Miranda P M Meuwissen https://orcid.org/0000-0001-6929-3743

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