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Satellite-based data for agricultural index insurance: a systematic quantitative literature review

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Abstract. Index-based insurance (IBI) is an effective tool for managing climate risk and promoting sustainable development. It provides payouts based on a measurable index. Remote sensing data obtained from satellites, planes, UAVs, or drones can be used to design index-based insurance products. However, the extent to which satellite-based data has been used for different crop types and geographical regions has not been systematically explored. To bridge this gap, a systematic quantitative literature review was conducted to examine the use of satellite-based datasets in designing index-based insurance products. The review analysed 86 global studies and found that NDVI was the most commonly used satellite-based index, accounting for approximately 77% of all studies using satellite data. The number of studies conducted after 2010 has sharply increased and almost doubled between 2016 and 2021. The studies have shown that satellite-based vegetation indices are effective in designing and developing index-based insurance for various crops. They have also found that satellite-based vegetation health indices outperform weather indices. Most studies have focused on cereal crops, with fewer studies focusing on perennial crops. The number of studies conducted in Africa, Asia and Europe is balanced. However, the research has focused on specific countries and has not been adequately spread across different regions, especially developing countries. The review suggests that satellite-based datasets will become increasingly important in designing crop index-based insurance products. This is due to their potential to reduce basis risk by providing high-resolution with adequately long and consistent datasets for data-sparse environments. The review recommends using high spatial and temporal resolution satellite datasets to further assess their capability to reduce basis risk.

Keywords: remote sensing, satellite data, satellite-derived index, index-based insurance, basis risk

1 Introduction

Agricultural insurance plays a crucial role in managing risks and building resilience against natural disasters. It is a vital part of major global initiatives such as the Sendai Framework for Disaster Risk Reduction, the COP21 Paris Agreement, and the

https://doi.org/10.5194/egusphere-2024-1527
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G7 InsuResilience. The goal of the G7 InsuResilience initiative is to offer insurance coverage to an additional 500 million households worldwide by 2025 (Fisher et al., 2019). Index-based insurance is a type of agricultural insurance with payouts generally based on external easy-to-measure indices that are correlated with individual losses or outcomes (Carter et al., 2016). The payouts in index-based insurance are triggered when the actual measurement of the index exceeds or falls below a pre-defined threshold. It can aid smallholder farmers in strengthening their resilience to the impacts of weather extremes, such as drought or flood, while also stimulating investments in productivity in favorable years to optimize profitability (Stoeffler et al., 2022).

Agricultural index-based insurance can be classified into three broad groups: (i) area-yield index insurance, which is based on an average yield of the crop over a specific area; (ii) weather-based index insurance, which is based on a specific weather parameter (such as rainfall, temperature, etc.), measured using data from weather stations, gridded climate information from satellites or reanalysis climate data; and (iii) vegetation-based or satellite-based index insurance with indices developed using time series dataset from satellite imagery (What are the different types of "crop" index insurance?, 2024).

Index-based insurance can overcome two significant problems associated with traditional indemnity-based insurance, namely adverse selection and moral hazard, as these indices are beyond the control of any individual (Adeyinka et al., 2022; Mushtaq et al., 2020). Furthermore, index-based insurance is a cost-effective and efficient option for farmers to transfer climate risk as they only need to monitor the index. In contrast, traditional multi-peril options require expensive loss assessment (Carter et al., 2017; De Leeuw et al., 2014; Miranda and Farrin, 2012).

However, the adoption of index-based insurance is often constrained by several factors, such as being restricted to certain measurable perils, insufficient technical capacity, lack of expertise, limited data availability, and basis risk, one of the most commonly cited limitations (Carter et al., 2017; Lichtenberg and Iglesias, 2022; Miranda and Farrin, 2012). Basis risk refers to the difference between an index's estimate of an individual farmer's losses and actual losses, the situation that payouts may occur when no losses happen or vice versa.

There are three common sources of basis risks, including (i) design basis risk, which occurs when the index poorly correlates with losses; (ii) spatial basis risk, which arises when the loss estimated by the index at the measured location is unlikely to occur at the insured farm location, which is geographically far away; and (iii) temporal basis risk, which results from imperfect choices of the time window for the index measurement (Boyd et al., 2019; Dalhaus and Finger, 2016; Dalhaus et al., 2018; Nieto et al., 2010; Woodard and Garcia, 2008). Despite its potential advantages, these limitations can make it challenging for farmers to access and benefit from index insurance (Kath et al., 2018, 2019).

The use of remote sensing (RS) data, acquired from satellites, planes, UAVs, or drones, has been identified as a way to reduce basis risk when developing index-based insurance products. These products require reliable, broad coverage and long historical data archives (De Leeuw et al., 2014). Over the years, researchers have focused on developing highly correlated indices that can accurately predict individual losses at lower costs. In several studies, satellite-based vegetation indices have been used to create effective index-based insurance for crops such as maize, wheat, cotton, and others. This has been successfully implemented in countries such as Canada, India, Mali, Kenya, Kazakhstan, Syria, and Zimbabwe (Bobojonov et al., 2014; Bokusheva et al., 2016; Makaudze and Miranda, 2010; Miranda and Farrin, 2012; Turvey and Mclaurin, 2012). Normalized difference vegetation index (NDVI) extracted from satellite images have also been employed to design index-based livestock insurance in Kenya (Chantarat et al., 2013), and have shown their potential to develop an insurance index for drought risk under limited or even absent weather data (Bobojonov et al., 2014). Brock Porth et al. (2020) developed Pasture Production Indices (PPI) using multiple data sources. The results showed that these indices had stronger correlations with ground truth forage yield data than the weather-based indices that relied on ground weather station data. The satellite-derived vegetation and biophysical parameter indices, such as NDVI, green NDVI (GNDVI), enhanced vegetation index (EVI), leaf area index (LAI), or fraction of absorbed photosynthetically active radiation (FPAR), used in PPI showed a maximum correlation of 62% and a minimum correlation of 43.8%. In some years, the best-performing satellite-based PPIs reached almost 90% correlation with yield losses. In demonstrating crop index-based insurance, remote sensing-based vegetation health indices (e.g., Vegetation Condition Index (VCI), Vegetation Health Index (VHI), and Temperature Condition Index (TCI), etc.) outperformed weather indices (e.g., temperature, precipitation, etc.) (Kölle et al., 2021; Möllmann et al., 2019).

Satellite-based indices are gaining popularity, but their potential applications in cropping systems, especially in developing countries, need to be further investigated. This involves identifying challenges and opportunities, particularly with the availability of new high-resolution satellite-retrieved indices that better address the issue of basis risk. More importantly, it is essential to conduct a comprehensive review to determine the crops and locations where satellite-retrieved data have been utilized as the primary inputs to create index-based insurance solutions. Additionally, it is important to identify the commonly used satellite-based time series datasets in such solutions.

We conducted a systematic quantitative literature review (SQLR) to identify gaps in index-based insurance research and build a comprehensive understanding of the potential use of satellite-based data for index-based insurance. The goal is to examine the current use of satellite-based data in developing crop-specific index-based insurance and identify gaps where future research is most needed. The review also aims to evaluate the potential role of satellite-based data in reducing basis risk and improving the index-based insurance solution. As a global scale systematic review, we believe the findings will help identify future priorities of study regions and crops to promote crop-specific index insurance solutions.

The focus of the paper is on four key areas: (1) the locations where index-based insurance studies have been conducted and the crops targeted in those studies, (2) the trends in using satellite-based data to directly develop index-based insurance products, (3) the most commonly used satellite-based datasets for the development of the index, and (4) a discussion of the advantages and disadvantages of using satellite data in index insurance and the future research directions.

2 Materials and methods

The SQLR has been carried out following the method by (Pickering and Byrne, 2014). The keywords used in the review are identified from two fields of study: remote sensing and index insurance. For the field of utilizing remotely sensed satellite-

https://doi.org/10.5194/egusphere-2024-1527
Preprint. Discussion started: 8 July 2024

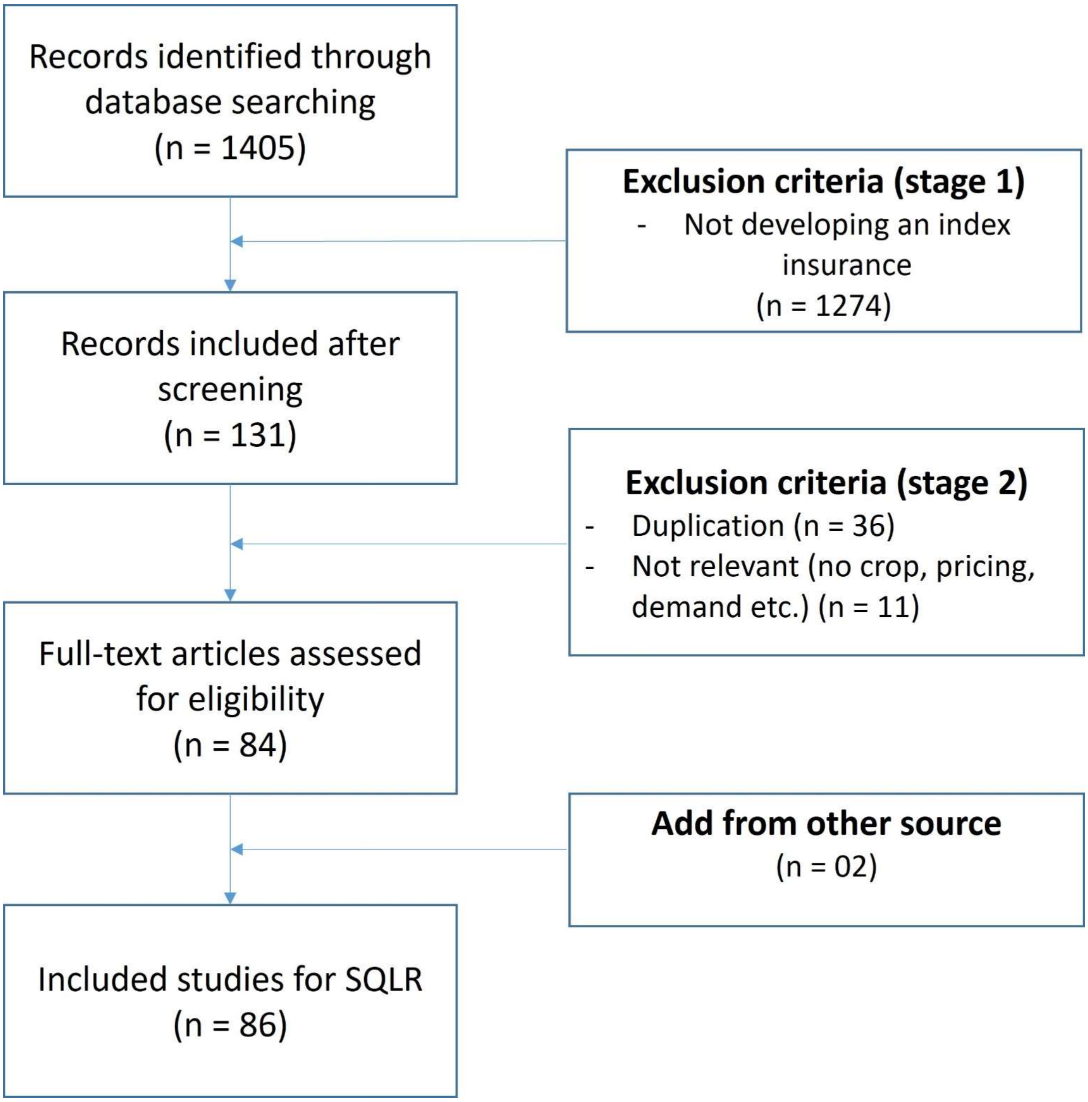
based data, the keywords included "remote sensing" and "satellite-based", while for the field of index insurance, the keywords included "index-based insurance", "index insurance", "agricultural insurance", "crop insurance", and "basis risk". The logical function "OR" was used to link the searched keywords in each field and the logical function "AND" was used to link keywords from both fields; parentheses were used to separate two groups of keywords corresponding to two fields of study. The searched terms were: ("index insurance" OR "index-based insurance" OR "crop insurance" OR "agricultural insurance" OR "basis risk" OR "satellite-based insurance") AND ("remote sensing" OR "satellite-based").

The keywords were searched over all fields of journal articles, including title, abstract, keywords, and main text. There was no limitation in publishing year and type of articles. Non-English publications and book reviews were excluded. The searched terms were used consistently over multiple databases: Science Direct, Springer Link, Scopus, Taylor & Francis, and MDPI. The below results were as of July 2023.

The studies from searched results were screened in a three-stage process with the number of papers to be included and excluded as shown in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flowchart (Figure 1).

- Stage one: Abstracts from the identified records through database search were screened. A paper was excluded if it did not develop any index insurance.
- Stage two: After the first stage of screening, all papers from different databases were combined to scan for duplication and relevant topics. Papers were excluded if (i) there was a duplication from other databases, (ii) the study was on irrelevant topics such as pricing, demand or willingness-to-pay for an index insurance product, or crop insurance was not the focus of the study. The full texts of the remaining papers after exclusion were obtained for further steps.
- Stage three: Papers that met the searching criteria but were not indexed in the selected database but from other sources were added to the final list to be included in the SQLR.

https://doi.org/10.5194/egusphere-2024-1527
Preprint. Discussion started: 8 July 2024



120 **Figure 1: PRISMA flowchart showing steps for conducting a systematic quantitative literature review, where n is the number of research papers (adapted from Moher et al., 2009).**

A structured table with categories and sub-categories was developed to present information from selected articles that were used to complete tasks (1) and (2) above. A subset of papers that directly used satellite-retrieved data to develop the index-

https://doi.org/10.5194/egusphere-2024-1527
Preprint. Discussion started: 8 July 2024

based insurance was used to complete tasks (3) and (4) with data on the Earth observation satellite (EOS) datasets, extracted index, the spatial and temporal resolution of satellite images (please see Supplementary Table S1 for a complete data table). These review tasks only focused on data from satellites that were used to observe the Earth from orbits for the purposes of environmental monitoring, such as vegetation cover, atmospheric content, ocean color, sea state and ice fields. These review tasks did not include other satellites for communication, navigation, or weather purposes. The indices, especially vegetation indices such as NDVI, EVI, LAI and so on, were computed from spectral bands collected by sensors onboard the satellites.

To identify the types of crops in our studies, we divided them into four main categories, based on the FAO Crop Classification System (ESS: Crops Statistics - Concepts, Definitions and Classifications, 2024). These categories were Cereals (including grain crops like rice, wheat, maize, sorghum, millets, etc.), Pasture and Forages (crops grown mainly for animal feed), Perennial crops (permanent crops as defined by FAO, such as coffee, cocoa, olive, sugar cane, etc.), and Others (including vegetables, oilseed crops, fruits, and nuts, etc.).

There are several types of insurance indices available, which are categorized into five main categories: area-yield index, weather-based index, satellite-based index, hybrid index, and other indices. The area-yield index calculates the average crop yield over a specific area. The weather-based index collects weather parameters from weather stations, gridded climate information, and reanalysis climate data. The satellite-based index calculates the index directly from spectral bands of satellite images. The hybrid index is developed from a combination of weather parameters and vegetation indicators that are retrieved directly from satellite images. Finally, other indices use soil information to determine the insurance coverage.

The satellite-based datasets that were used directly in the studies to develop the index for insurance were classified into medium and high-resolution groups based on their spatial resolution: medium spatial resolution datasets including AVHRR, MODIS, SPOT-VGT/Proba-V and GRASS LAI, and high spatial resolution datasets including Landsat, Sentinel, SPOT and Formosat-2.

3 Results

3.1. African, Asian, and European countries are where index-based insurance is focused

The global distribution of the studies in index-based insurance is shown in Figure 2a**Error! Reference source not found.**. At the continental scale, African countries have gained the most interest with 26 total number of studies. Asia and Europe are almost equal, with 22 and 21 studies, respectively. North American region follows next with a total of 13 studies. There are a smaller number of studies in South American countries (n=5) and Australia (n=3) in this review. In Southeast Asia, there are only a few (n=5) studies included in the review, with three of them in Indonesia, while Myanmar and Lao PDR were the subjects of one study each.

There are 34 countries presented within this SQLR; among them, countries that attract the most interest are the United States (n=9), China (n=9), Kenya (n=9), and Germany (n=8). Twenty other countries appear only once, while ten others appear in 2-6 papers.

https://doi.org/10.5194/egusphere-2024-1527
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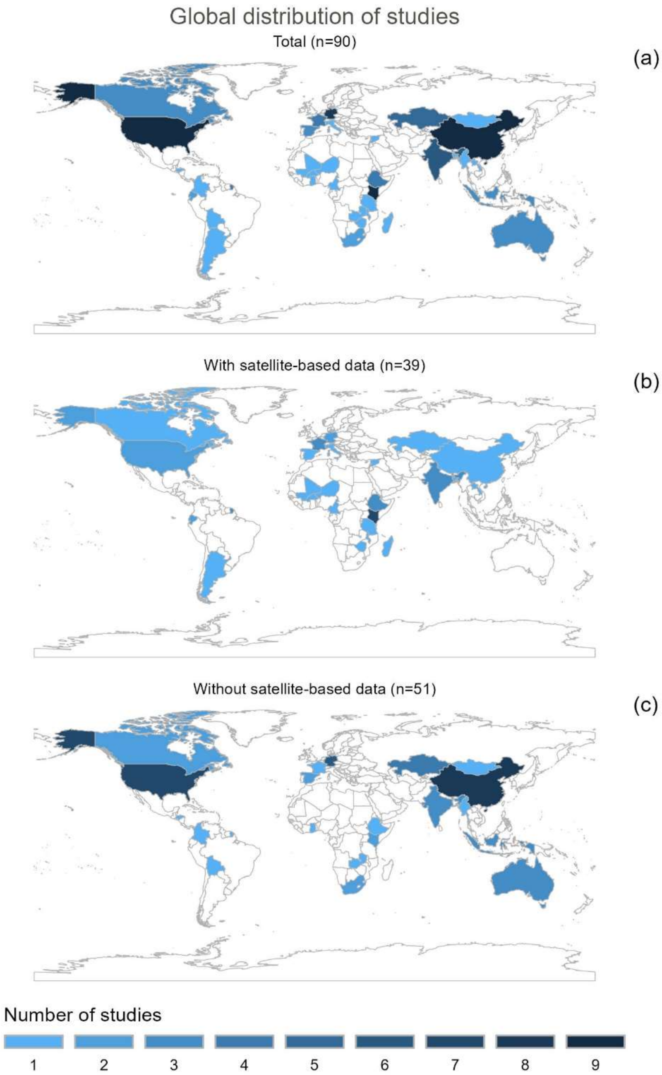

Figure 2: The distribution of studies on index-based insurance across the globe from 2007 to July 2023. a) Total number of studies (n=90), b) Number of studies using satellite data (n= 39), c) Number of studies not using satellite data (n= 51). Note: There is one study conducted in three countries and two studies conducted in two countries; so the total number of studies (n=90), counted on the number of countries that the studies were conducted, is larger than the total papers in the review (n=86).

From the global distribution (Figure 2b), Africa is the region with the highest number of studies that used satellite data, with 19 out of 26 studies in Africa (accounting for 73.1%). South America is the second region with a high percentage of satellite data used in the analysis (60% of total studies in the region). On the other hand, Asia, Europe, and North America show a low share of studies with satellite data, with percentages of 27.3%, 38.1% and 23.1% of total studies of the region, respectively. In Australia, there is not yet any study using satellite data directly in developing index-based insurance solutions.

Out of the total 39 studies that used satellite data, almost half of them (n=19, 48.72%) were conducted in African countries. European countries accounted for 20.51% (n=8), while Asian countries accounted for 15.38% (n=6) of the satellite-based studies. On the other hand, North and South American countries had the lowest number of studies using satellite data, with only three studies (7.69% of the total satellite-based studies) in each region.

Out of 24 countries where satellite data studies have been used, Kenya has the highest number of studies using satellite data. In fact, seven out of nine studies conducted in Kenya make use of satellite data, which accounts for 36.8% of all such studies conducted in Africa. The remaining satellite-based studies are spreading over the world, with 70.83% of the countries (n=17) having only one study that used satellite data. Among the six remaining countries with studies using satellite data, half of them (n=3) have two studies and the other half (n=3) have three studies in each country.

China and the United States are among the top three countries with the highest number of studies in total. However, most studies did not utilize satellite data, with only one study in China and two in the United States.

3.2. Grain cereal crops are the most studied type of index-based insurance

When exploring insured crop types, the results show that Cereals have gained the most attention, with more than half of the total studies (64.5%) focused on them. Pasture and Forages come in second with approximately 19% of the papers (Figure 3). Perennial crops, however, have the lowest share of 4.7%, with only four studies conducted on four different crops in three countries. These crops include sugar cane in Australia, coffee in Colombia, and grape and olive in Spain.

https://doi.org/10.5194/egusphere-2024-1527
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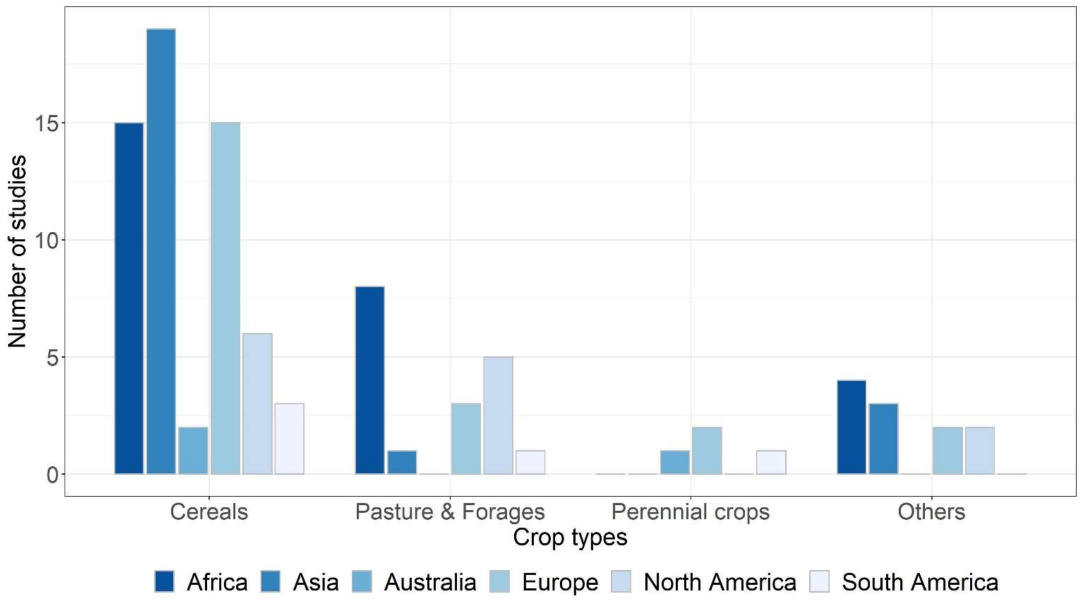

Figure 3: Types of insured crops to be studied in different continents. Crops are categorized into four major groups: Cereals, Pasture and Forages, Perennial crops and Others (such as vegetables, oilseed crops, fruits, nuts, etc.)

In terms of geographical distribution, Cereals are still the most studied among all continents. Most of these studies, accounting for 82.6%, are conducted in Asia (n=19). North America is the only region where Cereals account for less than half of the studies (46.2%). On the other hand, in the remaining continents, over half of the total studies are focused on Cereals, with the proportion ranging from 55.6% in Africa to 68.2% in Europe (Figure 3), especially in Asia (n=19, accounting for 82.6% of all studies in Asia). In contrast to the other continents, North America is the only region with less than half of studies in Cereals (46.2%).

The studies in Pasture and Forages are highest in Africa, with eight studies taking 44.4% of total studies globally. North American countries have five studies (27.8%), followed by European countries with three studies (16.7%). In Asia and South America, there is only one study on Pasture and Forages in each continent.

Among studies that employed satellite-based data to develop the index for insured crops directly Figure 4), Cereals have the highest number of studies (n=20), accounting for more than half (52.6%) of total studies using satellite-based data. Pasture and Forages show the second share with 34.2% (n=13). Perennial crops and Others share a total of 13.2% (n=5). Compared with the number of studies without satellite data for each type of crop, only Pasture and Forages have a higher count, even triple, of studies using satellite-based data (n=13) than those without any source of satellite images (n=4). All other crops

https://doi.org/10.5194/egusphere-2024-1527
Preprint. Discussion started: 8 July 2024

share a similar pattern of having approximately one-third of total studies using at least one source of satellite-based data to develop index insurance.

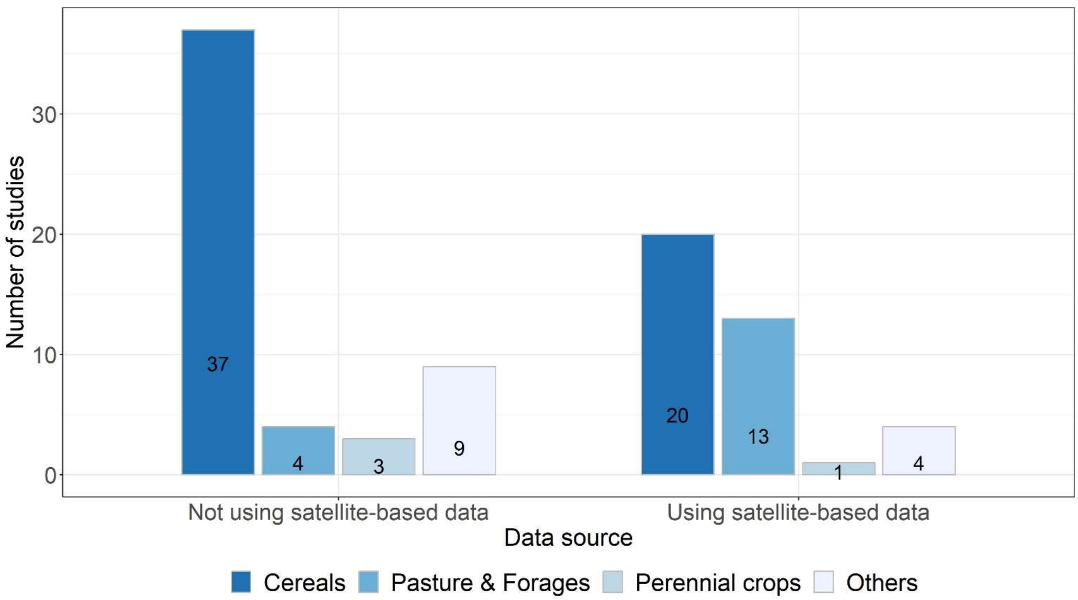

Figure 4: Use of satellite data for different types of insured crops. Crops are categorized into four major groups: Cereals, Pasture and Forages, Perennial crops and Others (such as vegetables, oilseed crops, fruits, nuts, etc.)

3.3. The number of studies is increasing over time

The total number of studies over time shows a sharp increase after 2010 (Figure 5). Between 2016 and 2021, they almost doubled the number of studies in the previous six-year period 2010-2015. A closer look by year shows a sharp increase in 2016 and 2019, while there's a big drop in 2017. Over the period from 2010 to 2022, the total number of studies in developing index insurance has shown a linear increasing trend. The two most popular indices, Weather and Satellite-based, also follow a similar trend.

https://doi.org/10.5194/egusphere-2024-1527
Preprint. Discussion started: 8 July 2024

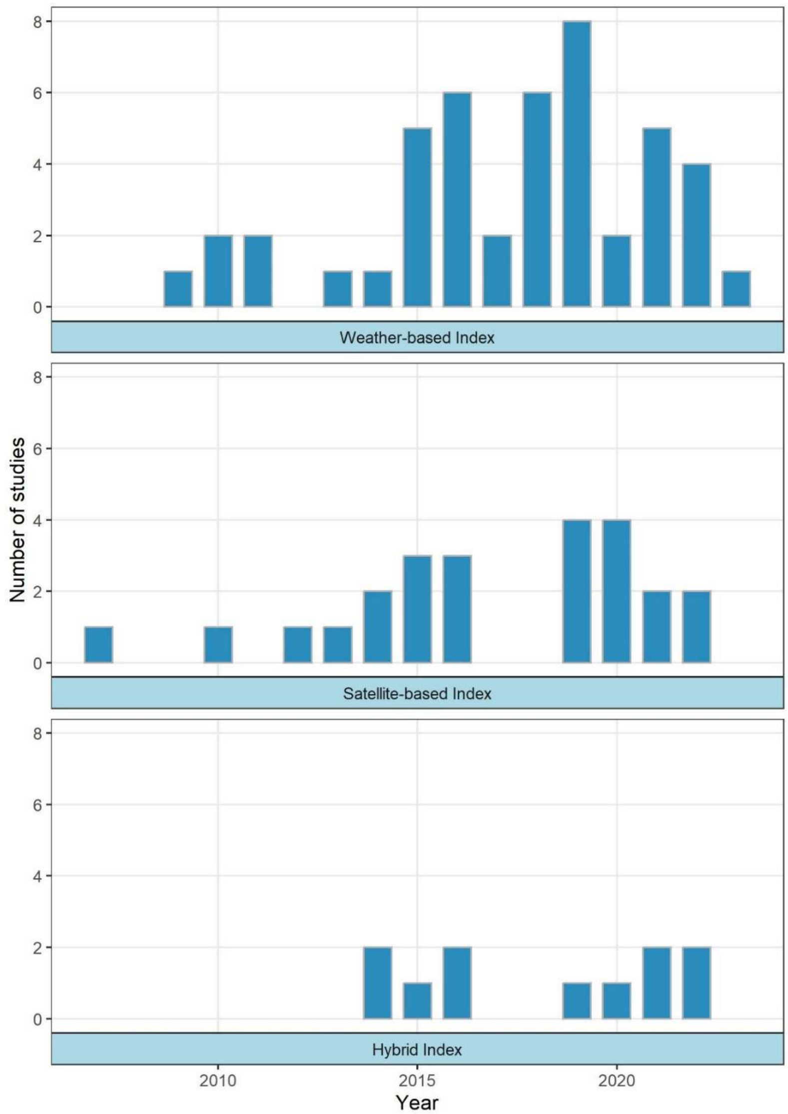

Figure 5: Number of studies that developed index-based insurance through time from 2007 to 2023, divided by types of index insurance: Weather-based index, Satellite-based index, and Hybrid index (combination of satellite-based vegetation indices and weather parameters). Note: Three studies on Area-yield index (in 2011, 2020 and 2021) and two studies developing Other indices using soil information (in 2016 and 2021) are not included in this figure.

https://doi.org/10.5194/egusphere-2024-1527
Preprint. Discussion started: 8 July 2024

3.4. Weather-based index has always been the most popular while satellite-based index and hybrid index are gaining more interest

The analysis indicates that the number of studies developing Weather-based index insurance has been increasing consistently in the periods of 2014-2016, 2018-2019, and 2020-2021. The use of Satellite-based indices for insurance also follows a similar pattern during these periods, while there is no clear trend for other types of index insurance solutions. Throughout the entire review period, more than half (52.94%) of the studies focused on Weather-based index insurance (n=46).

The Satellite-based index holds the second place with 24 studies (approximately 28.24%), slightly more than half of the number for the Weather-based index. The combination of weather and vegetation parameters makes up the Hybrid type (n=11), accounting for 14.12% of all the studies. There are three studies (3.49%) on Area-yield index and two studies (2.33%) developing Other indices (using soil information).

Among the satellite-based indices, NDVI is the most used vegetation index in satellite-based research. It accounts for 83.3% (n=20) of the studies that were conducted using satellite images. Other vegetation indices such as EVI, LAI, FAPAR, VCI, VHI, and TCI have also been utilized in other studies involving satellite-derived datasets.

In studies developing hybrid indices where satellite-based vegetation indices are combined with weather parameters (temperature, precipitation), NDVI is also the most popular vegetation index, appearing in 63.6% (n=7) of the studies. The remaining studies of the hybrid index have utilized FAPAR (n=2) and a group of VCI, TCI and VHI (n=2).

Combining Satellite-based and Hybrid indices, NDVI is still the most commonly used index extracted from satellite data with a total of 27 studies, accounting for approximately 77% of all studies using Satellite-based data.

3.5. Biweekly medium spatial resolution dataset is more preferred, high spatial resolution dataset is gaining more favour in recent years

During the period covered by this review from 2007-2023, satellite datasets have been employed in 39 studies with 49 times in total in different studies with medium spatial resolution Earth observation satellites (EOS), including AVHRR, MODIS, SPOT VGT/Proba-V and GRASS LAI, taking the dominance (81.6%). Among the medium spatial resolution EOS, AVHRR (with a varied spatial resolution of 1km, 4km and 8km) and MODIS (different products with a spatial resolution of 250m and 500m) are the most popular datasets that have been used for 15 and 21 times respectively, accounting for 37.5% and 52.5% of all medium spatial resolution datasets, with a relatively steady increase over time from 2007 to 2023 (Figure 6 and Table 1). SPOT VGT/Proba-V has been used three times, while GRASS LAI has been employed once.

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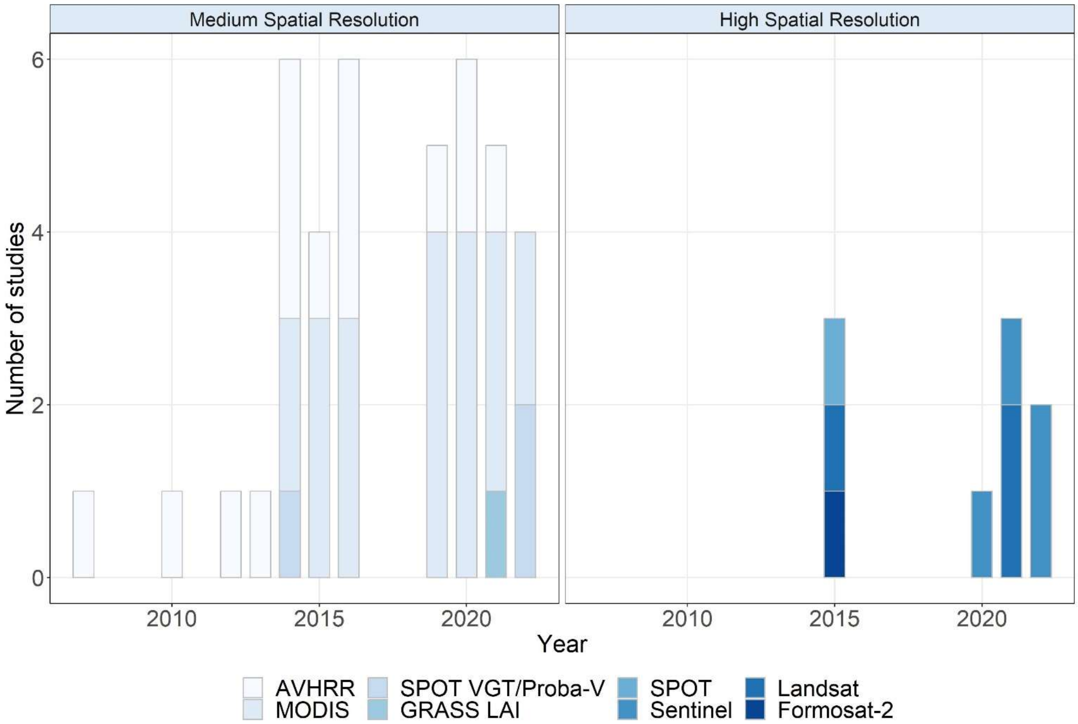

Figure 6: The use of medium and high spatial resolution datasets over years

Table 1: The use of satellite-based datasets with different spatial resolutions

		One dataset only	In combination with other datasets	Total number of usages	Average length of time series (years)
Medium spatial resolution	AVHRR	10	5	15	21.8
	MODIS	13	8	21	14.6
	SPOT VGT/Proba-V	0	3	3	8.0
	GRASS LAI	1	0	1	16.0
High spatial resolution	Landsat-8	0	3	3	7.7
	Sentinel-2	0	4	4	2.8
	Formosat-2	0	1	1	2.0
	SPOT-4 and SPOT-6	0	1	1	2.0

https://doi.org/10.5194/egusphere-2024-1527
Preprint. Discussion started: 8 July 2024

Since 2015, high spatial resolution satellite datasets like Landsat 8, Sentinel 2, SPOT 4 and SPOT 6, and Formosat-2 have been used either alone or paired with medium spatial resolution data nine times, accounting for 18.4% of all studies. The use of high spatial resolution datasets has been increasing since 2020 with the availability of the Sentinel constellation together with Landsat. SPOT 4 and SPOT 6 and Formosat-2 have been used together only once in a study in 2015.

In each of the studies, depending on the data preparation process, the satellite datasets were kept in their original spatial resolution or resampled to a certain resolution to ensure consistency with other datasets used in the analysis. Two studies utilized high spatial resolution satellite data (such as Landsat 8, Sentinel 2, SPOT 4 and SPOT 6, and Formosat-2) without any spatial aggregation, directly calculating the index for insurance at the plot level. In other studies, high spatial resolution datasets were resampled to coarser resolution to match with other datasets in the analysis, or aggregated to the insurance unit, whose size varies from farm level to village, division, district, county to zone, agro-ecological homogeneous zones (AHZ) and country levels.

In terms of temporal dimension, satellite data have been employed in the studies as a time series with varied length and temporal resolution. Studies using medium spatial resolution have much longer time series than those with high spatial resolution (Table 1). AVHRR datasets, available from 1981 until present, have been employed with the highest average length of the time series (21.8 years) with a maximum length of 32 years in two studies. MODIS datasets, available from 2000 until present, have also been used with long time series with an average of 14.6 years. The Landsat dataset, a high spatial resolution with the longest archive, also shows the appearance of the most extended time series among high spatial resolution datasets with an average of 7.7 years. The Sentinel-2 dataset, available since 2015, has been employed with a shorter time series, averaging 2.8 years.

Different temporal resolutions have been used in the various datasets analysed. The popular temporal resolutions that have been employed are biweekly (n=19), 10-day (n=11) and weekly (n=9), while daily and monthly datasets have been used much less with two times each (Figure 7). Besides, six datasets have been used in undefined temporal resolution, which are the cases of high spatial resolution datasets (Landsat, Sentinel and Formosat-2) when only some satellite images have been selected per year with specific criteria of cloud cover and time coverage over growing seasons.

Figure 7 illustrates the average length of datasets at different temporal resolutions. The average length of the monthly time series (18 years) is slightly longer than that of weekly (16.56 years), 10-day (16 years) and biweekly (15.68 years) datasets, while daily time series have a bit shorter length (12.5 years). The shortest time series with an average of 4.67 years are the high spatial resolution datasets. Overall, the average length of datasets employed in all studies is 14.53 years, much longer than that of high spatial resolution datasets (Table 1).

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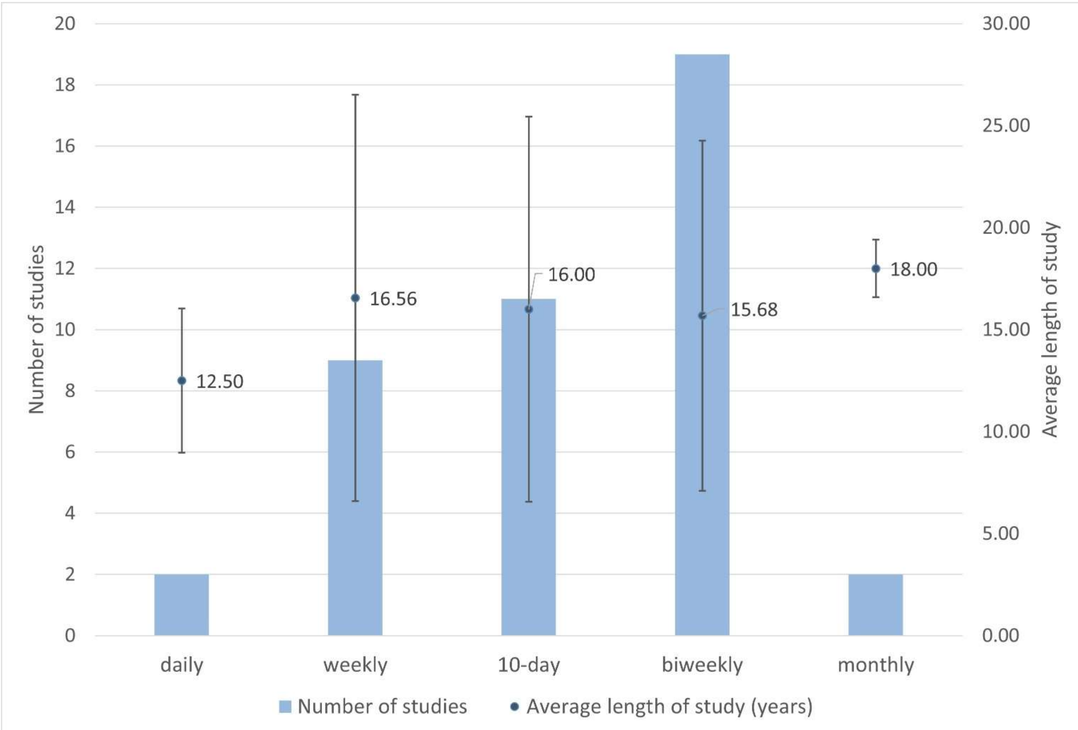

Figure 7: Average length of study (years) and temporal resolution of EOS satellite data. Blue columns show the number of studies using datasets with different temporal resolutions such as daily, weekly, 10-day, biweekly, and monthly. Blue dots and error bars represent the average length and standard deviation of the study period (number of years) of the corresponding temporal resolution. Note: There are six studies that are not included in this figure because they used the datasets containing satellite images at different points in time through the study period without a fixed frequency. The average length among the six studies is 4.67 years.

However, the temporal resolution of the time series might be different from that of the index insurance, which is based on crop phenology or general calendar. Therefore, approximately 66% of the raw time series data is processed to generate statistics such as average, maximum, minimum, anomaly, etc. over a specified period, such as a month or a crop growing phase or season. In some other cases where the studies employed time series with different temporal resolutions, satellite-derived datasets are resampled to a specific temporal resolution to have consistent datasets for analysis.

4. Discussion

The objective of the systematic quantitative literature review (SQLR) was to investigate the usage and scope, especially for smallholder farmers in developing countries, of satellite data in agricultural index-based insurance. The review comprises 86 peer-reviewed journal articles from 34 countries, covering four major types of crops. Cereals were the most frequently studied crop, likely because of their global extent and essential role in food security. Perennial crops were underrepresented with only four studies, accounting for 4.7% of all studies.

Academic research in index-based insurance using satellite data is primarily focused on developing countries in Africa and Asia. However, this research is not uniformly distributed, as it tends to concentrate on a few specific countries like Kenya and Ethiopia in Africa, and China in Asia. This could be because international donor agencies have historically focused on these countries to manage climate risks; thus, leaving a gap in multiple important agricultural production regions such as Southeast Asia, South America, and other countries in Africa.

The use of satellite imagery is increasing over time, mostly leveraging freely available datasets with long historical archives and medium spatial resolution. Since 2020, there has been an increase in studies using high spatial resolution satellite data, which are often combined with medium spatial resolution datasets and aggregated to coarser resolution, depending on the desired insurance solutions.

To develop an index insurance solution, the employed datasets have an average length of approximately 15 years, which is much longer than that of high spatial resolution datasets. Biweekly frequency is the most favoured over other temporal resolutions, although satellite images are usually accumulated over a specific period of time or corresponding to crop-specific growth phases.

The review suggests that only a few studies have developed index-based insurance for perennial crops. This may be due to the fact that these crops are not included in government subsidy programs, and growers have substantial equity to manage financial risks, making insurance unnecessary. However, as the climate becomes more variable, there could be an opportunity to develop index-based insurance for perennial crops in developing countries, especially where these crops are crucial to economic values and food security.

To develop suitable satellite-based insurance solutions that provide targeted coverage, more attention is required to assess the capability of satellite-based data in reducing basis risk at multiple spatial and temporal resolutions.

4.1. African, Asian, and European countries are where index-based insurance is focused

There is a moderate balance in the total number of studies in Africa, Asia and Europe. However, the studies are focused on some specific countries such as China in Asia, Ethiopia and Kenya in Africa, Germany in Europe, and the United States in North America. Developing countries, especially in Southeast Asia and South America, on the other hand, have not been attracting interest from academia to develop index-based insurance solutions despite their important role in global agriculture production, especially various cash crops with high economic values.

Input data is the crucial part of any model to develop an effective index-based insurance. However, weather ground station densities in developing countries in general are usually low, and thus not sufficient for insurance purposes. Current studies in this review have shown promising results in using satellite data to design index-based insurance contracts in developing

https://doi.org/10.5194/egusphere-2024-1527
Preprint. Discussion started: 8 July 2024

countries, especially in the Africa region (Chantarat et al., 2013; Eze et al., 2020; Makaudze and Miranda, 2010; Turvey and Mclaurin, 2012). Hence, satellite-based data provides an alternative solution to overcome the weather data constraint.

4.2. Grain cereal crops are the most studied type of index-based insurance

Cereals, the group of annual grain crops, are the most studied globally. This result is well aligned with their vital role in human diets, global food security and economics. According to production data from FAOSTAT in 2021, the global harvested areas for cereals reached 739.4 million hectares with a production of over three billion tons (FAOSTAT). There is greater interest in Pasture and Forages in Africa than in other continents. Livestock plays a significant role in Africa, accounting for one-third of the global livestock population and producing 40% of the agricultural GDP of African countries (Balehegn et al., 2021). Severe drought from 2008 to 2011 resulted in the total loss of livestock deaths worth billions of US dollars, with thousands of pastoralists losing their herds, which is their primary source of livelihood. Consequently, several programs have been implemented in African countries to develop livestock insurance, especially in Ethiopia and Kenya.

Perennial crops have not received as much attention as other crops, possibly due to the complexity of their crop cycles. These crops are often cash crops, which means they may not be eligible for government subsidies and may have enough equity to recover from climate disasters. Any existing studies on perennial crops may only be found in private sector-specific programs, making them inaccessible to the public and out of the scope of this review.

Despite the limited studies available, a recent study on Perennial crops shows promising results. The study developed an index-based insurance using satellite data for non-irrigated olives in Spain. Three satellite indices related to vegetation conditions (VCI, VHI, and TCI), derived from MODIS with meteorological indices as benchmarks, were used to develop different index insurance contracts. The hedging effectiveness result shows that VCI- and VHI-based index insurance contracts outperformed the traditional weather index with only weather variables (Kölle et al., 2021). Besides, the applications of satellite-based indices for annual crops also show that such data are suitable for developing index insurance (Bokusheva et al., 2016), and even outperformed weather-based IBI options (Brock Porth et al., 2020; Möllmann et al., 2019). As climate change results in increased variability and financial losses, and with the availability of high-resolution satellite data, it will become increasingly important to develop insurance solutions appropriate for perennial crops, in addition to traditional crops.

4.3. Satellite-based datasets show potential to reduce basis risk

4.3.1. High-resolution satellite data can reduce basis risk, but longer time series are needed

The analysis shows that medium spatial resolution satellite datasets are favoured over high spatial resolution (Figure 6), which might be due to a lack of evidence on the effectiveness of high spatial resolution on reducing spatial basis risk, and adequately long time series. To the best of the author's knowledge, there are only two studies exploring the potential to reduce basis risk of high-resolution data by comparing hedging effectiveness of insurance contracts developed using data at different spatial resolutions. Results from these studies by Kölle et al. (2021) comparing MODIS (at two spatial resolutions) and Landsat 5/8, and Eltazarov et al. (2023) comparing original and downscaled gridded climate data, show that increasing the spatial resolution of the datasets can increase the hedging effectiveness of index-based insurance contracts, resulting in a lower basis risk. However, the two studies only considered wheat. Therefore, further research is required to assess the effectiveness of index-based insurance contracts with distinct datasets for different crops, regions, and spatial resolutions.

The review also shows that high-resolution satellite datasets were not used alone, but in combination with other medium-resolution datasets (Table 1). The reason for this might be the effect of cloud cover resulting in limited high-resolution satellite images available over a specific time period (Kölle et al., 2021). To overcome cloud cover, (Kölle et al., 2021) selected only Landsat 5/8 without cloud and corresponding MODIS images. However, this solution limited the study within some selected years as there are trade-offs regarding spatial and temporal resolutions of satellite imagery (Warner et al., 2009). Utilizing a fusion of different datasets from multiple sensors might be a promising solution to gain a high spatial resolution with adequately long historical time series. Furthermore, data fusion is not restricted to optical sensors but can also include radar data, which is available throughout any weather condition, either day or night, ensuring continuous and gap-free time series. Besides, commitments from the United States Geological Survey (USGS) and the European Space Agency (ESA) to provide long-term satellite constellations free of charge will maintain the long historical archive of high-resolution satellite data for public access for multiple purposes. This presents an opportunity for further exploration into the use of such data to develop index-based insurance solutions in developing countries.

Additionally, high-resolution satellite images can also contribute indirectly to reducing spatial basis risk by capturing commodity dissimilarities within a complex and heterogeneous landscape or diversified crop rotations that were put together within an insurance unit, especially at higher levels such as district than provincial or regional levels (Eltazarov et al., 2023; Möllmann et al., 2019). Hence, a precise commodity map, possibly developed from high-resolution satellite images, would be considered in data preparation to ensure consistent information on specific commodity delineation for model inputs.

4.3.2. Biweekly dataset is the most preferred, more frequent data might be useful to map crop phenology to adjust time period of index insurance

The results presented in Figure 7 indicate that satellite-based data with biweekly, weekly and 10-day frequency resolution are more preferred as compared to daily data. This is because daily data is usually composited to a lower frequency to remove cloud cover. Additionally, input data is accumulated over a specific time window corresponding to a normal calendar or a crop growth phase, which is usually a few months long. Thus, the temporal resolutions from weekly to biweekly might be adequate. However, the effectiveness of using data at higher temporal resolution in developing index-based insurance still needs to be further explored. This is because such high frequency data can capture temporal fluctuations and outliers that might be reduced after aggregation.

To link with spatial resolution, it is necessary to note that all datasets with favoured temporal frequency are at medium spatial resolution. Because of cloud cover, high spatial resolution satellite data can only be acquired at certain periods. Thus, it is challenging to obtain a consistent, no-gap time series of sufficient length for insurance purposes. The issue of data availability has limited the use of high spatial resolution datasets with much shorter lengths of study (Table 1). Again, the fusion of different datasets is proposed to create longer historical time series as inputs to models to better capture temporal variations in developing the index for insurance (Vrieling et al., 2014).

Moreover, studies have shown the potential to reduce temporal basis risk with crop phenological phases or flexible index design at different time windows compared to using fixed-period accumulated data (Conradt et al., 2015; Dalhaus et al., 2018; Leblois et al., 2014). However, traditional crop phenological data collection methods involve field observations, which are costly and site-specific and can lead to spatial basis risk when applied to other locations over long distances. To overcome this data limitation, high-frequency satellite data with the capability to map crop key growth phases, even in near real-time, can contribute indirectly to reducing temporal basis risk by identifying crop phenology, especially anomalies of early or late start of the growth phases with impacts on crop production (Gao and Zhang, 2021). Furthermore, phenological information extracted from satellite-based data can also capture the heterogeneity in the timing of specific crop growth stages, which are used not only to disaggregate predictor values to improve crop yield estimation but also to adjust the time period of index insurance contracts (Afshar et al., 2021; Gao et al., 2017).

4.4. Satellite data-based index crop insurance solutions are expected to be prevalent in developing countries

While weather driver index-based insurance is an affordable and transparent method of providing insurance coverage, the widespread adoption has been limited due to the lack of available data, particularly in developing countries, and risks associated with the policy. Satellite-based index insurance can help solve these issues by providing datasets with appropriate length and spatial resolution, leading to the increased adoption of index-based insurance in developing countries. Given the availability of satellite data and the fact that many datasets are freely available, satellite-based data will become increasingly important in designing crop insurance, especially in data-sparse environments in developing countries.

The insurance industry is increasingly relying on satellite data to assess and manage risks more effectively. However, to fully leverage satellite datasets, some challenges need to be addressed. One of the most significant challenges is to ensure that the data remains continuously available. Without this, the practical and enhanced use of satellite data will be limited. Therefore, besides making free datasets available, ensuring the data's accessibility will be a crucial task for the industry to overcome.

4.5 Limitations of the study

As already mentioned in the Methodology section, the review only includes peer-reviewed papers that are accessible through the abovementioned databases. Materials from grey literature, including working papers, project reports, and so on, are not included, especially those that are under commercial property and are not accessible for research purposes. Given the importance of such materials, the results of this systematic quantitative literature review can be improved with different points of view and discussion from such limited-access literature.

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5 Conclusion

Our analyses have indicated the increasing trend in developing index-based insurance since 2010, especially from 2016-2021 with almost double the number of studies in the previous period from 2010-2015. There is a balance in the number of studies in Africa, Asia and Europe. However, attention has been placed on specific countries and not adequately spread across different regions, especially developing countries. Most studies have focused on cereal crops, with fewer studies focusing on perennial crops.

Satellite-based data have been employed and shown their effectiveness in designing index-based insurance for diverse crops. Among them, satellite datasets at a biweekly frequency and medium spatial resolution are the most favoured. NDVI is the most commonly used satellite-retrieved vegetation index while some vegetation health indices even outperformed weather variables.

The review suggests that satellite-based datasets will become increasingly important in designing and developing crop index-based insurance products. This is due to their potential to reduce basis risk by providing high-resolution with adequately long and consistent datasets for data-sparse conditions. The review recommends using high spatial and temporal resolution satellite-based datasets to further assess their capability to reduce basis risk.

Supplementary material

Supplementary Table S1: Systematic Quantitative Literature Review (SQLR) table

Author contribution

TN, SM, JK, TNH and LR: Conceptualization; TN performed the Data curation, Methodology, Formal analysis, Visualization, Writing - original draft; TN, SM, JK, TNH and LR: Writing - review and editing; SM: Funding acquisition.

Competing interests

The authors declare that they have no conflict of interest.

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