Use of space technology and Earth observation (EO) data to develop an agricultural insurance product to de-risk smallholder farmers.

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1 Introduction

In order to create more inclusive insurance for smallholder farmers, [6] identified three immediate priorities. Firstly, to attract insurance companies into the market, it is crucial to establish a task force comprising of public sector champions who can lead the insurance efforts and create a regulatory environment that is conducive to the insurance industry. Secondly, a public-private partnership should be developed to incentivize and support companies to create innovative products and services for agriculture. As initial setup costs for new products and distribution channels can be high, the private sector will need support in the early stages of development. Thirdly, a phased approach to developing agricultural insurance is recommended. This implementation should be designed in a way that progressively builds the capacity of all relevant stakeholders and strengthens the knowledge and evidence base for scaling up.

The objective of our study is to gain insights into the product design phase, particularly the Base Index design process. To achieve this goal, we will carry out a practical evaluation of the process and construct a Base Index for the purpose of developing a weather-based insurance product. Moreover, we will investigate the potential of earth observation data to supplement the available information in order to enhance the Base Index design.

2 Literature Review

In this section, we will review the literature on insurance in general, the key concepts surrounding this theory in particular index insurance, its strategies, opportunities and challenges and finally remote sensing and earth observation data.

2.1 Background

Insurance is a service that provides a benefit upon the occurrence of an uncertain and random event often referred to as a "risk". The benefit, usually financial, may be provided to an individual, an association or a company, in exchange for a contribution or premium. Thus the purpose of insurance is to transfer a specific type of risk from an individual or group to a third party who can manage the financial impact of the loss.

The key stakeholders in the risk transfer process are the regulator, the insured party, the policyholder, the insurer and the reinsurer [7]. In some cases credit banks may include as a stakeholder. In fact, they make loans to the insured and receive them in return for the insurers compensation when a risk occurs.

There are two types of insurance: traditional insurance and index insurance. Traditional insurance determines payout by means of loss assessment during individual policyholder visits. It is expensive and time-consuming. This price level is explained by the high administrative costs associated with assessing the risk, selling the product and, in the case of claims, assessing losses. The costs associated with these types of assessments can be even higher, due to the small size of the farms and the state of the transport infrastructure. The payment of claims takes time because the assessment of losses suffered by policyholders is done individually and differs from one policyholder to another

The risk involved in traditional insurance is the covariant risk which occurs when the risk affects a large population all at the same time. Often in difficult on-the-ground circumstances, assessing the losses of each individual insured party that is affected is not feasible. The insurer will not have the resources to assess each claim individually in a short period even in the best conditions. Unlike traditional insurance, Index insurance determines the payout on the basis of a predefined index. Its payment is quicker and does not require an individual assessment of the insured's loss. Thus agricultural insurance is more advantageous for large commercial farms. Thus there are remarkable differences between these two types of insurance.

These differences are mentioned in the table below:

Traditional insurance	Index insurance
Determines payout by means of loss assessment during individual policyholder visits	Does not need to assess individually
Expensive and time-consuming	Less expensive and payment is quicker
No basis risk	Has a basis risk
Has a covariant risk	No covariant risk

2.2 Index-based insurance

In recent years, index insurance has been presented as an important tool that can allow smallholder farmers to better manage climate risk, enabling investment and growth in the agricultural sector [5]. With this type of insurance, farmers can purchase coverage based on an index that is correlated with those losses, such as wind speed, the amount of rain during a certain window of time (weather-based indices), or average yield losses over a larger region (area yield indices). Subscribing to index insurance can help smallholder farmers enhance their resilience by providing them with financial compensation in the event of losses caused by weather-related events. Additionally, this insurance can assist them in taking advantage of opportunities to increase their productivity during years when they do not receive compensation, which could help them escape poverty. Moreover, insurance can facilitate access to credit for investing in agricultural technologies and inputs, allowing farmers to use their profits to pay for their insurance premiums and repay their loans in the event of losses.

This necessitates a need for a base index constructed with reference to historical data on that index [7]. That is why we add to the stakeholders in the risk process the product design team, the Data processing team, and the data provider for risk insurance who have the following different responsibilities:

- **Product design team**—The team working on product design is composed of professionals who have specific skills in developing products that allow for risk identification. These products are called "peril indexers."
- **Data processing team**— For processing of claims related to indexed insurance products,

it is essential to have access to real-time risk data, which can be collected from public or private weather stations, remote sensing equipment, or satellites. However, these data often need to be processed and adapted beforehand to be usable in the analysis conducted by the insurer. As a result, many companies offering product design services have developed expertise in data processing specifically to meet the needs of insurance.

- **Data provider**—The sources of data vary by country, they can be government agencies, private companies, or a combination of both. Data is collected from ground-based or satellite instruments. The data provider supplies historical data needed for product design and pricing, as well as real-time data for claim settlement

3 Product design

Index insurance contracts are designed using historical hazard and inventory damage data to trigger payouts at specific frequency and severity levels. The index insurance product design process occurs in two phases [7]. In the first phase, the product design team develops a product based mainly on input from local subject specialists (for example, agronomists), and evaluates and prices this initial product. This guide calls this product the Base Index. The Base Index is designed with the goal of providing maximum transfer of the risk of the named peril. It provides the highest level of coverage possible against damage to the farmer's inventory. The Base Index triggers a payment when the proxy's behavior indicates that any damage to inventory no matter how small is expected. In some cases, the policyholder will purchase the Base Index. The Base Index Design and Evaluation Process consists of 8 steps as shown in figure 11.

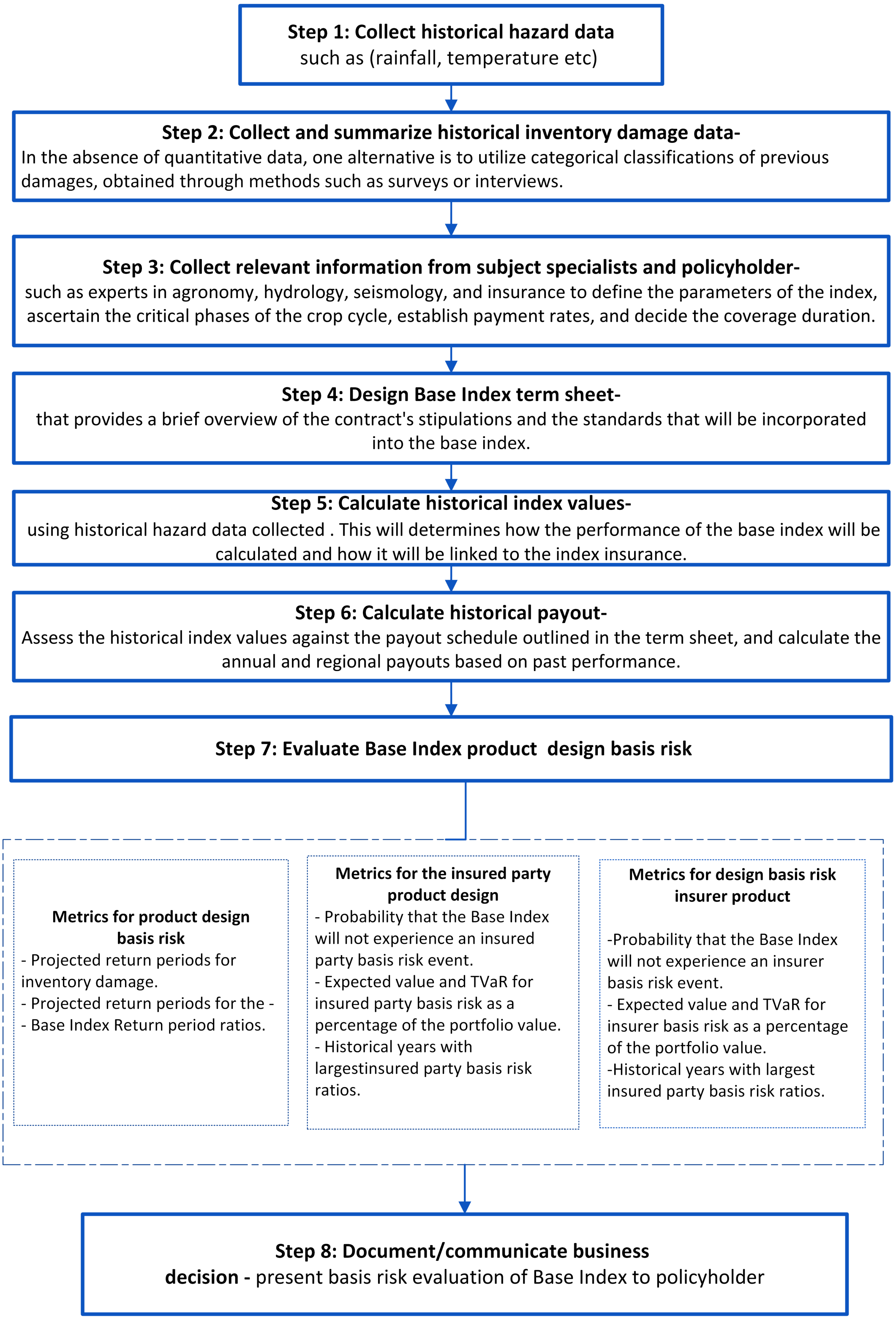

Figure 1: Base Index Design and Evaluation Process.

The primary obstacle in designing the Base Index is the issue of basis risk, which refers to the discrepancy between the payout amount triggered by the index insurance product and the actual losses suffered by the insured party due to the specific peril [3]. Basis risk for the insured party occurs when the payout is less than the actual losses incurred by the farmer because of the named peril. In this situation, the farmer suffers an economic loss due to the peril, but the claim payout is insufficient to compensate for it adequately. Basis risk for the insurer arises when the payout is more than the actual losses experienced by the insured party due to the named peril. In such a case, the insurer faces an economic loss due to unnecessary claim payments.

It occurs when the data or information used to develop the base index is unreliable and fails to reflect the ground realities of the area. Basis risk can be classified into three categories. The first is geographical or spatial basis risk, which is determined by the distance between the farmer's plot and the measurement point. The second is design basis risk, which arises from the models and variables utilized in constructing an index. The third category is temporal basis risk, which is linked to the time frame during which the index is measured. Clearly, imperfect insurance products characterized by high basis risk are typically associated with very low [8]

There are several approaches to reducing basis risk in insurance products. Firstly, some recommend that insurance products cover all possible losses related to the insured peril, rather than just a single dimension of losses. This approach is called "insured peril basis risk." Secondly, insurance can cover losses in agricultural production that are not caused by the insured peril, which is called "production smoothing basis risk." To reduce basis risk as a whole, insurance product designers can use multiple sources and types of data to better understand production risk and the various dimensions of possible losses. However, the base index can often cost more than the policyholder is willing or able to pay. In this case, the second phase of product design begins. The design team uses feedback from the policyholder on price to redesign and improve the product with new parameters to reduce the cost. This new version of the product is called the "redesigned index", which transfers less named peril risk from the policyholder to the insurance company.

The data used to design the base index are obtained from space technologies including space vehicles such as spacecraft, satellites, space stations and orbital launchers, deep space communications, space propulsion, and a wide variety of other technologies including supporting infrastructure equipment and process.

3.1 Collecting historical hazard data

In order to trigger payouts based on specific frequency and severity levels, index insurance contracts make use of historical data on hazards and inventory damages. Real-time hazard data can be obtained from various sources, including publicly or privately owned weather stations, remote sensing equipment, or satellites. However, such data often requires processing and conversion into a suitable format for analysis by the insurer. This section will cover the crops that are insured in Senegal, their corresponding climate trends, and potential trigger approaches for payout. All these factors will determine the historical hazard data.

An observable index built upon meteorological data solves any moral hazard issue [1], reduces transaction costs, and allows for quick payment of the indemnity [4]. Additionally, indices enable a focus on a specific risk independently of other conditions. When there is a single index for a particular disaster and multiple contracts (rather than a specified risk for a specific location), transaction costs and insurance premiums are reduced.

3.2 Trigger approaches in index-based insurance

In index-based insurance, triggers are used to determine if a payout should be made to the policyholder. There are two main trigger approaches used in index-based insurance: single trigger approach and multiple trigger approach. The trigger approach used in index-based insurance depends on the specific needs of the policyholder and the level of complexity that they are willing to accept.

The trigger approach is important because it will be used in the indemnity schedule. The schedule can be defined by three parameters according to the framework designed by [2]. The strike S is the threshold level of the index that triggers payoffs for insured forest owners. The slope-related parameter λ ($0 < \lambda < 1$) determines the exit level $(\lambda.S)$ from which payoffs are capped to a maximum M.

- **The single trigger approach** is the most common trigger approach used in index-based insurance. Under this approach, a single index is used as a trigger for the payout. If the value of the index falls below a pre-determined threshold, the policyholder receives a payout. The threshold is set based on historical data and is meant to reflect the point at which the policyholder is likely to incur losses. The advantage of the single-trigger approach is its simplicity, which makes it easier to understand and administer. However, it may not accurately reflect the losses incurred by the policyholder as it relies on a single index.
- **The multiple-trigger approach** is a more complex trigger approach used in index-based insurance. Under this approach, multiple indices are used as triggers for the payout. Each index represents a different aspect of the risk being insured, and if any of the indices fall below their respective thresholds, the policyholder receives a payout. The advantage of the multiple-trigger approach is that it provides a more accurate reflection of the losses incurred by the policyholder as it takes into account multiple indices. However, it is more complex to understand and administer.

4 Challenges and opportunities

Insurance as a risk management tool provides many benefits to stakeholders ranging from regions, national governments and communities, to households and individuals. These include:

- Incentives for loss reduction and resilience.
- Decision-making support.
- Provision of protection to take risks and pursue opportunities building behavior.

In addition to the opportunities and potential benefits, there are a number of challenges that need to be considered in the design and implementation of insurance solutions in the context of climate risk management including:

- Reducing the base risk in the insurance contract
- Costs for insurance and complexity
- Asymmetric information
- Establishment of cost-effective distribution channels

  Creating affordable ways to distribute a pilot program, which can later be expanded nationally, is a crucial challenge that must be tackled. Nonetheless, utilizing current networks, like insurance or banking company branches, input supplier branches, large farmer organization member networks, or public extension services, for sales could maintain transaction costs at a manageable level. Additionally, employing cutting-edge technologies like mobile-based payment systems may help to keep expenses low and access a greater number of people.

- Scaling-up of small pilot projects

  The diversity of risks, livelihoods, geographical areas, microclimates, coping mechanisms, and other variables by region makes it difficult to generalize and replicate the same insurance product on a large scale.

5 Remote Sensing and Earth Observation ((EO) Use in Index based Insurance

Remote sensing is the science of collecting and analyzing information about the Earth from sensors mounted on satellites, aircraft, drones, and ground sensors. Earth observation data is the information collected from these sensors. Therefore, remote sensing is closely related to Earth observation data.

Earth observation data collected through remote sensing can be used to monitor climate change, land use, air and water quality, mapping, natural disaster monitoring, etc. Remote sensing data can also be used to monitor human activities such as agriculture, forestry, fisheries, urbanization, mining, road construction, etc.

Remote sensing provides high-resolution data over large areas in a relatively short time. It is therefore a valuable tool for long-term monitoring of the Earth and for making informed decisions on natural resource management and urban planning. Remote sensing data are also used in fields such as meteorology, oceanography, geology, seismology, insurance, etc.

Remote sensing and earth observation data are increasingly used in agricultural insurance to assess risk and crop losses.

Remote sensing data can be used to monitor weather conditions, crop growing conditions, land use, rainfall levels, temperatures, etc. These data can be combined with historical data and crop growth models to assess the risk of crop loss.

Agricultural insurers can use remote sensing data to identify high-risk areas and adjust premiums accordingly. Remote sensing data can also be used to monitor crops for signs of stress or disease, allowing farmers to take preventive measures to reduce crop losses.

By using remote sensing data, agricultural insurers can also process claims more quickly and accurately, avoiding costly and time-consuming site visits. Satellite images can be used to verify claims and crop losses reported by farmers.
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6 Agricutural insurance products

There are several types of agricultural insurance products such as area yield index insurance (AYII), weather index insurance (WII), remote sensing/ satellite index insurance. Each product is characterized by its features, benefits, and limitations.

6.1 Yield index insurance (AYII)

Yield index insurance works by using the average yield of a specific geographic area, such as a region or district. The amount of compensation paid out depends on the percentage of the long-term historical average yield of the area that is guaranteed (usually between 50% and 90% of the average yield). Farmers are grouped into homogeneous units for this insurance. If the actual average yield of the area is lower than the insured yield, then compensation is paid out regardless of the actual yield of the farm covered by the policy. This insurance is based on a reference index, and it is possible for a farmer to be compensated even if they have not suffered a loss, while another farmer may not be compensated even if they have suffered a loss.

- Advantages of the AYII
  - Covers multiple business risks/losses - Multirisk
  - Easy to understand and explain to farmers
  - Useful for covering a large number of farmers
  - Reduced administrative costs for insurance companies
  - Premium is cheaper than other products
  - Easy registration process for farmers
  - Ability to cope with disasters - perils affecting groups or vast areas.
- Inconveniences of the AYII

  - Possibility of paying a farmer who does not deserve to be paid or not paying a farmer who deserves to be paid in the insured area.
  - Creation of non-homogeneous zones.
  - Localized perils (such as hail, wild animals, or flooding from a nearby river) that do not have an impact on average yield.

6.2 Weather index insurance (WII)

Weather index insurance is a form of insurance based on meteorological indices. The idea is to use a meteorological parameter, such as precipitation or temperature, which is related to losses suffered by farmers, to calculate indemnity payments in the event of losses. Generally, the insured amount is calculated based on the production cost or a predetermined value, and payments are made based on a pre-established scale in the insurance policy.

For the meteorological index to be a good indicator of losses, it must be based on an objective measure that has a strong correlation with crop yields. It must be easily measurable, transparent, independently verifiable, reported in a timely manner, consistent over time, and tested over a wide area. Additionally, it must be designed in such a way that farmers can easily understand how it is calculated and how it is used to determine indemnity payments.

- Advantages of the WII

  Weather index insurance has the following advantages:

  - Reducing moral hazard.
  - Elimination of on-site loss assessment.
  - Reduction of information requirements and bureaucracy.
  - Facilitation of reinsurance.
  - Transparency.
  - Facilitation of access to financial services.
  - Adaptability to disasters - perils affecting groups or vast areas.

- WII challenges:

  Weather index insurance has the following challenges:

  - Availability of data (valid, accurate, and complete data sets).
  - Integrity of meteorological stations.
  - Need to strengthen the capacity and education of farmers, insurers, and regulators.

6.3 Remote sensing/ satellite index insurance

- Normalized Difference Vegetation Index (NDVI)

  This is a simple product based on the combination of reflectance measured in the red and near-infrared parts of the spectrum. The NDVI is calculated by subtracting the reflectance in the near-infrared spectral band from that in the visible spectral band, and then dividing this difference by the sum of these two measurements. The NDVI ranges from -1 to 1, where higher values indicate denser and healthier vegetation, while lower values may indicate bare soil or stressed vegetation. It is a good indicator of the amount and condition of vegetation. The indices are constructed using time-series remote sensing imagery where payment is based on a Normalized Difference Vegetation Index, which relates moisture deficit to pasture degradation. Since it is a good indicator of vegetation vigor (or health) and yield, NDVI is suitable for index-based insurance to provide coverage against drought or other perils that impact crop yields. However, the relationship between NDVI and crop yield varies greatly depending on the crops and regions.

7 Agriculture insurance in Bougouni

Bougouni, a city located in southern Mali, in the Sikasso region, is situated approximately 250 kilometers southeast of Bamako. This area is characterized by a transition between the Mandingue Plateau and the southern plains, offering a hilly landscape composed of hills and plains. Bougouni has a tropical savanna climate, with a rainy season from June to October, followed by a dry season from November to May. Temperatures generally remain high throughout the year. In addition to its favorable climate, Bougouni is renowned for its thriving agricultural activity. The fertile lands of the region allow for the cultivation of a variety of crops such as cotton, corn, millet, peanuts, and vegetables.

7.1 Maize calendar in Bougouni

In Bougouni, the cultivation of maize relies heavily on the rainy season, which typically starts in May and ends in October. The agricultural calendar for maize cultivation can be divided into three phases. Due to abundant rainfall since June, favorable moisture conditions have facilitated the germination and establishment of maize crops. Therefore, the sowing stage for maize takes place from June to July, the growth stage occurs in August, and the maturation and harvest are expected to take place from September to October. However, the period when the crop is particularly exposed to climate risks, including precipitation, is from June to September.

7.2 Single trigger approach

7.2.1 Description of the data set

The data used in this study are monthly and daily precipitation data from 1990 to 2015 obtained from the Mali Synoptic meteorological station. We will also use monthly precipitation data from the Naza website. Additionally, we will use maize yield data for Bougouni for each year.

7.2.2 Key concepts

- **Strike**: refers to the predetermined trigger value in an insurance contract. It is the specific threshold or level at which the insurance coverage is triggered, and benefits are payable to the policyholder.

- **Exit**: typically refers to the termination or cancellation of an insurance policy. It signifies the point at which the policy coverage ceases to be in effect.
- **Previous 7 Year Avg Yield (kg/ha)**: refers to the average yield taken for the past seven years that we will be using.
- **Crop Price (Franc/kg)**: refers to the price of maize per kilogram in the market that we will be using.
- **Total Sum Insured**: refers to the maximum amount of coverage or compensation that an insurance policy provides in the event of a covered loss or damage.

  Total Sum Insured= Previous 7 Year Avg Yield * Crop Price
- **Sum Insured for Deficit Rain**= maximum Loss * Total Sum Insured /100
- **Loss rate**: refers to the frequency and severity of losses experienced by an insured.

  Loss rate=Sum Insured for Deficit Rain/(rain zero loss - rain max loss)
- **Franchise**: It serves to define the threshold from which the insurer assumes responsibility for the insured's claims.

  Franchise= 0,05 * Sum Insured for Deficit Rain
- **Actual payout**: refers to the amount actually paid by the insurer to the insured in the event of a loss or claim.

  The actual payout is calculated as follows: we compare the cumulative precipitation of each year to the "rain zero loss" value. If it is lower than this value, the actual payout is set to 0. Otherwise, we calculate the next value as "(rain zero loss - annual precipitation) * loss rate". Then, we compare it to the "franchise" value, and if it is higher, the actual payout is set to the previously calculated value; otherwise, the payout is set to 0.
- **Required payout** refers to the minimum or specified amount that the insurer is obligated to pay to the insured party in the event of a covered loss, according to the terms and conditions of the insurance policy.

  Required payout= Loss * Sum Insured for Deficit Rain/100.
- **claim frequency**: refers to the number of claims filed by policyholders over a given period, typically expressed in terms of an annual frequency. It measures the probability that an insured individual will experience a loss and file a claim with their insurance company. Claim frequency is a key indicator used to assess risks and determine insurance premiums.
- **Payout Difference** is the absolute difference between the expected payout and the actual payout.
- **satisfaction index** is a quantitative measure used to assess the level of satisfaction of policyholders regarding their insurance experience.

$$\text{Satisfaction Index} = (1 - \text{Payout Difference}) * 10$$

$$\text{claim frequency} = (\text{nombre de réclamations} / \text{nombre total d'assurés}) * 100$$

- **risk premium (or premium)**: refers to the amount of money that the insured must pay to the insurer in order to obtain insurance coverage.

7.2.3 Methodology

Regarding the strategy for designing weather index insurance contracts based on a single trigger approach, the crop calendar considered spans from June to September.
Firstly, for the time series plots, we show the evolution of monthly precipitation and yield over the years under consideration. We also present the annual evolution of precipitation.
Secondly, a linear regression model for yield loss - rainfall is designed, and trigger values (exit and strike) are calculated using the parameters of the yield loss linear regression model. The exit value is determined by the rainfall value corresponding to maximum yield loss, while the strike value is set at zero yield loss according to the linear yield loss model.
Thirdly and finally, the evaluation of the contract is conducted by calculating the correlation between actual payouts and yield loss, as well as the farmer satisfaction index to measure basic risk.

7.3 Designing single-trigger index insurance products for maize crop in Bougouni

In this section, we will delve into an in-depth exploratory analysis of the data, focusing on studying their interrelationships and identifying trends. Furthermore, we will proceed to evaluate the contract by calculating the different payouts, satisfaction indices, and exploring the correlation between yield loss and precipitation.We will simultaneously conduct the analysis using both the Mali Synoptic meteorological station data and NASA data.

7.3.1 Monthly average rainfall from 1990 to 2015

Upon analysis of both the Mali Synoptic meteorological station data and the NASA data, a consistent pattern emerges: the month of August consistently exhibits the highest average rainfall, followed by July, September, and June. Furthermore, it is worth noting that there are variations in the average monthly precipitation between the two datasets.

7.3.2 Variation of Rainfall per Year

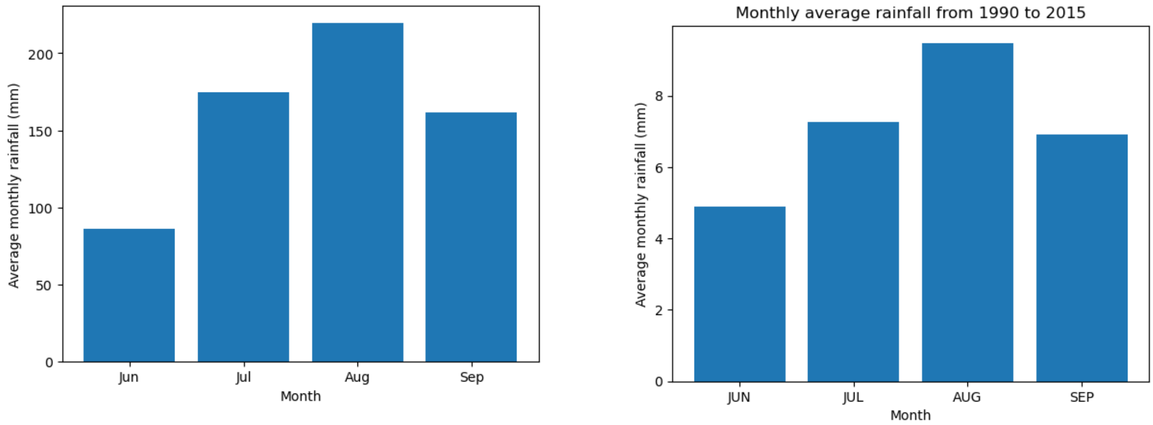


Figure 2: Monthly average rainfall from 1990 to 2015.

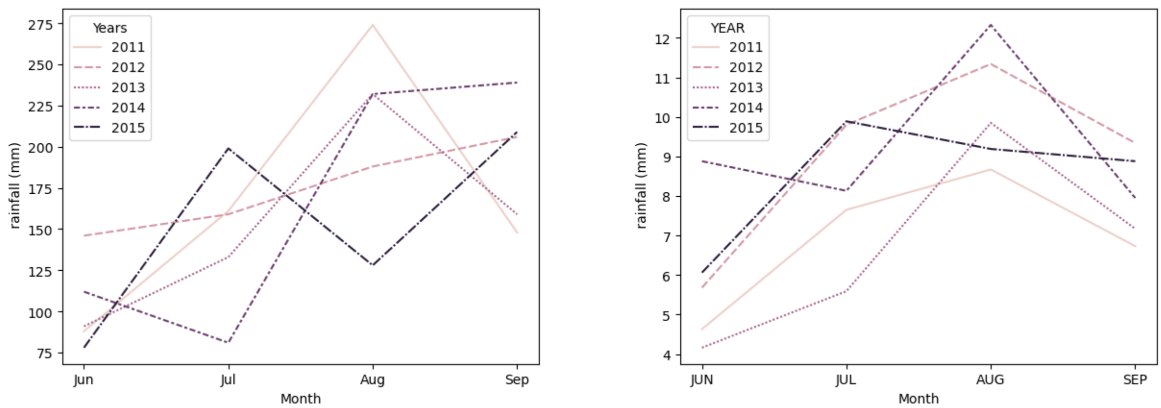


Figure 3: Variation of rainfall per year.

Based on the analysis of the past five years, it is evident that the month of August consistently witnessed the highest precipitation levels, with one exception in the year 2015 when the highest precipitation occurred in July. These findings reinforce our earlier analysis, confirming that August continues to be the rainiest month in Bougouni.

7.3.3 Yearly time series of rainfall and yield

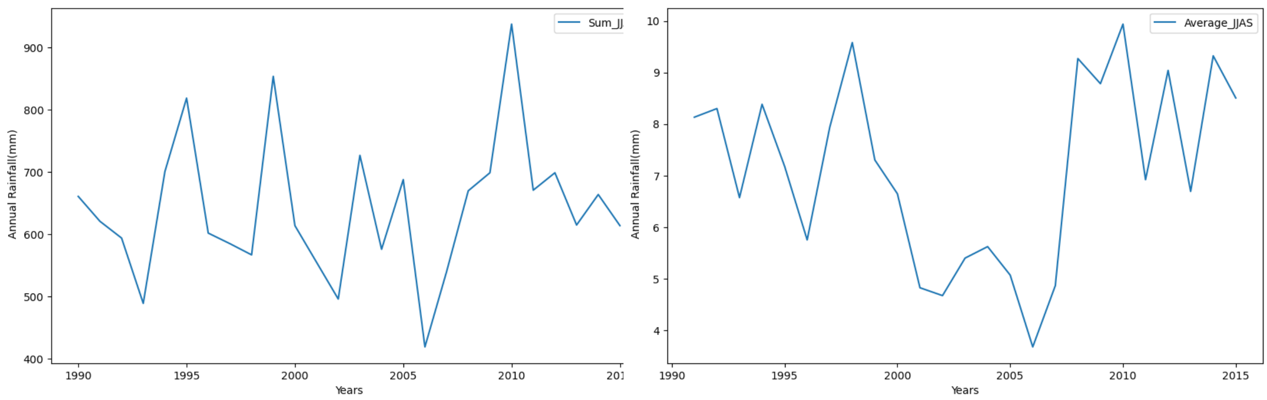
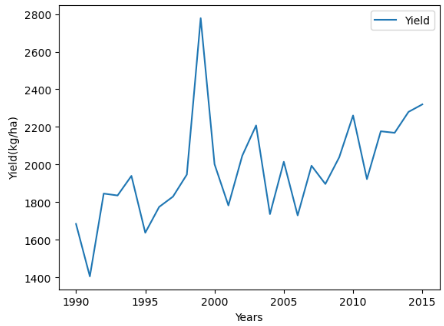


Figure 4: Yearly time series of rainfall from 1990 to 2015.

The analysis reveals that the year 2006 stands out as the least rainy year in Bougouni between 1990 and 2015. Furthermore, both graphs indicate that the years 1998 and 2010 experienced higher levels of precipitation. Notably, there are disparities between the data obtained from NASA and the Mali Synoptic meteorological station for specific years.



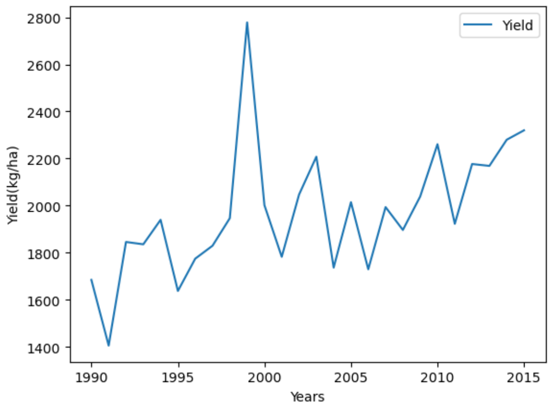
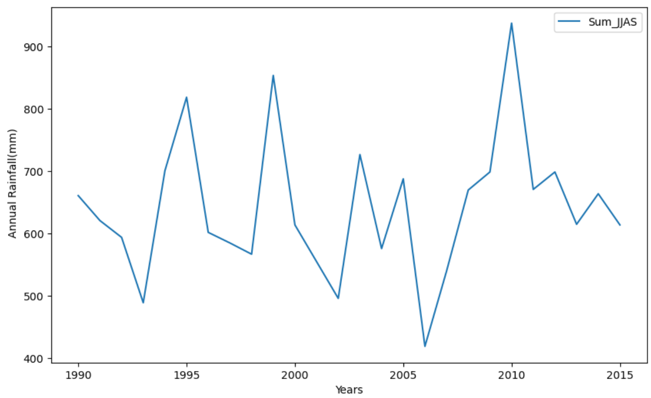


Figure 5: Yearly time series of rainfall from 1990 to 2015.

We observe significant irregularity in the yield between 1990 and 2015 in Bougouni. The yield exhibits considerable variation from year to year, with certain years yielding higher results than others. The highest yield is recorded in 2010, reaching approximately 2800 kg/ha, whereas the lowest yield is estimated to be around 1400 kg/ha in 1992.

7.3.4 comparaison yearly time series of Rainfall and yield loss



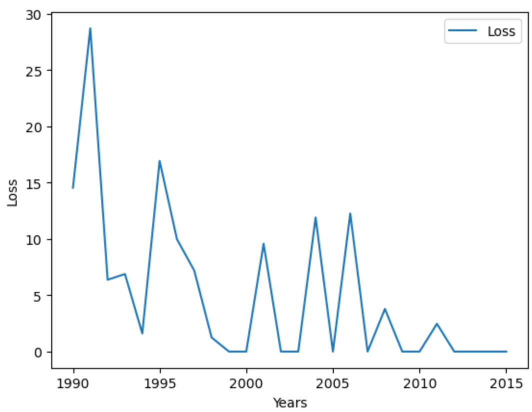


Figure 6: Yearly time series of yield and loss from 1990 to 2015 with Mali Synoptic meteorological station data .

It is evident from the Mali Synoptic meteorological station data that there is no perfect correlation between yield loss and precipitation. Specifically, it is observed that in the year 2010, when the highest precipitation is recorded, there is also a low yield loss. Conversely, in the year 2006, when the lowest precipitation is observed, the highest yield loss is not observed during that period.

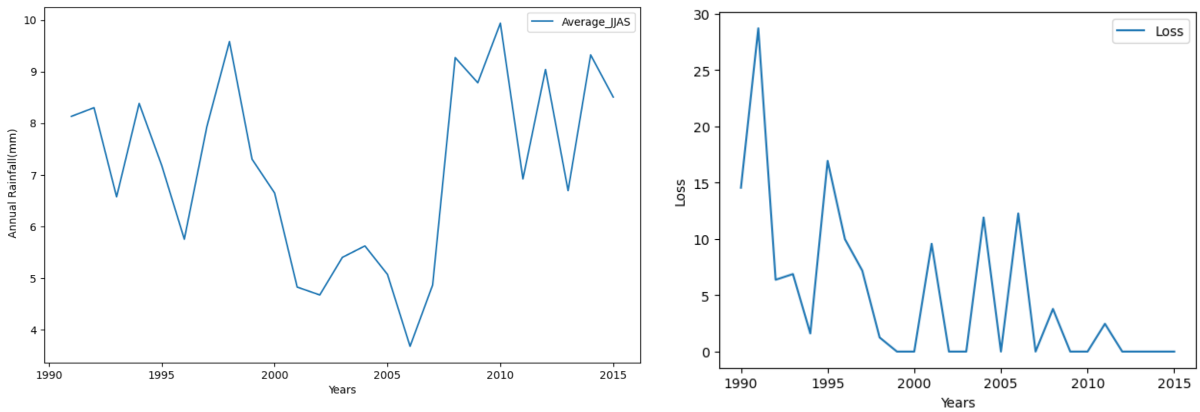


Figure 7: Yearly time series of yield from 1990 to 2015 with NASA data.

It is evident from the NASA data that there is no perfect correlation between yield loss and precipitation. Specifically, the highest precipitation recorded in 2009 and 1997 does not align with the highest or lowest yield loss, which are observed in 1996 and 2005 respectively.

7.3.5 Index insurance results with the Mali synoptic meteorological station data

We present the results of the index insurance obtained using data from the Mali Synoptic meteorological station, and finally provide an analysis of these results.

- **Linear regression**

  After calculating the yield losses for each year, we establish a linear regression between the variable Loss and the annual precipitation variable, which is the sum of the precipitation for the four months of maize cultivation. Through this regression, we obtain the rain zero loss (strike) and the rain maximum loss (exit).

Slope	-0.011
Intercept	12.39
Rain zero loss (exit)	1094.78
Rain max loss (strike)	621

- **Contract evaluation**

  In this section, our focus will be on the evaluation of the contract, where we will perform calculations for the actual payout, required payout, difference payout, and the satisfaction index (refer to the two tables presented below for detailed information).

	Years	Jun	Jul	Aug	Sep	Yield	Sum_JJAS	Loss	Actual_payout	Req_payout	Payout_diff	Sat_index
0	1990	98	222	169	172	1685	661	14.538751	31917.122067	5068.242976	0.770186	2.298136
1	1991	72	266	161	122	1406	621	28.689308	34860.236107	10001.160533	0.713107	2.868931
2	1992	84	157	230	123	1846	594	6.373018	34860.236107	2221.648974	0.936270	0.637302
3	1993	37	236	130	86	1836	489	6.880206	34860.236107	2398.456055	0.931198	0.688021
4	1994	90	227	176	208	1940	701	1.605446	28974.008027	559.662414	0.815093	1.849067
5	1995	67	189	383	180	1638	819	16.922537	20291.821610	5899.236257	0.412865	5.871346
6	1996	81	180	158	183	1775	602	9.974055	34860.236107	3476.979248	0.900259	0.997406
7	1997	101	182	195	107	1830	585	7.184519	34860.236107	2504.540304	0.928155	0.718452
8	1998	92	110	233	132	1947	567	1.250415	34860.236107	435.897457	0.987496	0.125041
9	1999	34	281	430	109	2778	854	0.000000	17716.596825	0.000000	0.508218	4.917821
10	2000	126	182	194	112	2002	614	0.000000	34860.236107	0.000000	1.000000	0.000000
11	2001	104	166	175	110	1783	555	9.568305	34860.236107	3335.533584	0.904317	0.956830
12	2002	63	107	243	83	2047	496	0.000000	34860.236107	0.000000	1.000000	0.000000
13	2003	110	178	208	231	2208	727	0.000000	27060.983901	0.000000	0.776271	2.237292
14	2004	75	208	177	116	1737	576	11.901371	34860.236107	4148.846156	0.880986	1.190137
15	2005	105	186	233	164	2015	688	0.000000	29930.520090	0.000000	0.858586	1.414137
16	2006	52	85	169	113	1730	419	12.256403	34860.236107	4272.611112	0.877436	1.225640
17	2007	44	163	219	114	1994	540	0.000000	34860.236107	0.000000	1.000000	0.000000
18	2008	98	138	268	166	1897	670	3.786357	31254.921408	1319.932862	0.858714	1.412855
19	2009	69	155	207	268	2039	699	0.000000	29121.163729	0.000000	0.835369	1.646309
20	2010	111	184	303	340	2261	938	0.000000	11536.057342	0.000000	0.330923	6.690769
21	2011	88	161	274	148	1923	671	2.467667	31181.343557	860.234451	0.869791	1.302093
22	2012	146	159	188	206	2177	699	0.000000	29121.163729	0.000000	0.835369	1.646309
23	2013	91	133	232	159	2169	615	0.000000	34860.236107	0.000000	1.000000	0.000000
24	2014	112	81	232	239	2280	664	0.000000	31696.388514	0.000000	0.909242	0.907581
25	2015	78	199	128	209	2320	614	0.000000	34860.236107	0.000000	1.000000	0.000000

Figure 8: Contract evaluation.

total sum insured	650100
Sum Insured for Deficit Rain	34860
Loss rate	73.57
franchise	1743.01
Claim frequency	100
Risk premium	31070.97

- **correlation between yield loss and actual payout**

$$\begin{bmatrix} 1 & 0.17 \\ 0.17 & 1 \end{bmatrix}$$

We note a correlation of 0.17 between the loss of yield and the actual payout.

- **interpretation of results**

The conclusions of this data study conducted between the period from June to September from 1990 to 2015 lead to the following observations: rainfall did not have a significant influence on yield or yield loss (high value of the payout difference, weak correlation between Yield loss and Actual payout, low values of the satisfaction index).

In order to confirm whether it is due to poor data quality or if meteorological risks do not have a significant impact on the losses suffered by farmers, or if a single trigger is not the right way to assess meteorological risks, we will also redo the same study using NASA's rainfall data.

7.3.6 Index insurance results with the NASA data

We present the results of the index insurance obtained using data from the Mali Synoptic meteorological station, and finally provide an analysis of these results.

- **Linear regression**

After calculating the yield losses for each year, we establish a linear regression between the variable Loss and the annual precipitation variable, which is the sum of the precipitation for the four months of maize cultivation. Through this regression, we obtain the rain zero loss (strike) and the rain maximum loss (exit).

Slope	-0.14
Intercept	5.99
Rain zero loss (exit)	41.87
average rain max loss (strike)	8.3

- **Contract evaluation**

In this section, our focus will be on the evaluation of the contract, where we will perform calculations for the actual payout, required payout, difference payout, and the satisfaction index (refer to the two tables presented below for detailed information).

	YEAR	JUN	JUL	AUG	SEP	Average_JJAS	Yield	Loss	Actual_payout	Req_payout	Payout_diff	Sat_index
0	1991	6.82	9.58	9.86	6.27	8.1325	1685	13.930491	30388.843406	4233.314965	0.860695	1.393049
1	1992	4.24	10.43	11.11	7.42	8.3000	1406	28.181762	30388.843406	8564.111662	0.718182	2.818176
2	1993	4.23	8.62	7.03	6.41	6.5725	1846	5.706638	30388.843406	1734.181387	0.942934	0.570664
3	1994	6.32	6.24	11.45	9.52	8.3825	1836	6.217437	30314.180701	1889.407075	0.935369	0.646313
4	1995	3.55	4.67	11.27	9.23	7.1800	1940	0.905135	30388.843406	275.059919	0.990949	0.090513
5	1996	4.11	5.21	7.59	6.10	5.7525	1638	16.331242	30388.843406	4962.875699	0.836688	1.633124
6	1997	7.54	7.58	10.72	5.90	7.9350	1775	9.333306	30388.843406	2836.283773	0.906667	0.933331
7	1998	5.01	9.37	14.80	9.14	9.5800	1830	6.523916	29230.440223	1982.542488	0.896641	1.033585
8	1999	4.00	6.24	13.78	5.19	7.3025	1947	0.547576	30388.843406	166.401938	0.994524	0.054758
9	2000	3.78	7.88	10.61	4.32	6.6475	2778	0.000000	30388.843406	0.000000	1.000000	0.000000
10	2001	3.79	4.67	5.72	5.12	4.8250	2002	0.000000	30388.843406	0.000000	1.000000	0.000000
11	2002	2.48	6.56	6.21	3.44	4.6725	1783	8.924667	30388.843406	2712.103222	0.910753	0.892467
12	2003	4.48	4.89	6.08	6.15	5.4000	2047	0.000000	30388.843406	0.000000	1.000000	0.000000
13	2004	2.79	7.33	7.94	4.43	5.6225	2208	0.000000	30388.843406	0.000000	1.000000	0.000000
14	2005	4.05	4.54	6.58	5.11	5.0700	1737	11.274340	30388.843406	3426.141387	0.887257	1.127434
15	2006	2.45	2.62	4.29	5.35	3.6775	2015	0.000000	30388.843406	0.000000	1.000000	0.000000
16	2007	3.46	6.66	6.40	2.94	4.8650	1730	11.631898	30388.843406	3534.799369	0.883681	1.163190
17	2008	7.04	9.45	12.25	8.34	9.2700	1994	0.000000	29510.990994	0.000000	0.971113	0.288873
18	2009	6.41	6.78	10.54	11.40	8.7825	1897	3.101567	29952.179706	942.530378	0.954615	0.453849
19	2010	6.21	11.17	11.30	11.07	9.9375	2039	0.000000	28906.901835	0.000000	0.951234	0.487660
20	2011	4.63	7.65	8.67	6.73	6.9200	2261	0.000000	30388.843406	0.000000	1.000000	0.000000
21	2012	5.68	9.80	11.34	9.34	9.0400	1923	1.773492	29719.141566	538.943589	0.960227	0.397727
22	2013	4.16	5.59	9.85	7.17	6.6925	2177	0.000000	30388.843406	0.000000	1.000000	0.000000
23	2014	8.88	8.13	12.33	7.95	9.3225	2169	0.000000	29463.478364	0.000000	0.969549	0.304508
24	2015	6.06	9.89	9.19	8.88	8.5050	2280	0.000000	30203.317896	0.000000	0.993895	0.061051

Figure 9: Contract evaluation.

total sum insured	631971.42
Sum Insured for Deficit Rain	30388.84
Loss rate	905
franchise	1743.01
Claim frequency	100
Risk premium	30156.43

- **correlation between Yield loss and Actual payout**

$$\begin{bmatrix} 1 & 0.25 \\ 0.25 & 1 \end{bmatrix}$$

  We observe a correlation of 0.25 between yield loss and actual payout.

- **Interpretation of results**

  The conclusions of this data study conducted between the period from June to September from 1990 to 2015 lead to the following observations: rainfall did not have a significant influence on yield or yield loss (high value of the payout difference, weak correlation between Yield loss and Actual payout, low values of the satisfaction index).

  On the one hand, it can be thought that the non-significant influence of rainfall on the yield loss suffered by farmers is due to poor data quality because the correlation between these two variables differs depending on the data used. There is a higher correlation between the NASA data and the yield loss (0.25) compared to the data from the synoptic station in Mali (0.17). On the other hand, this could be due to the fact that rainfall alone does not explain the yield losses suffered by farmers. Furthermore, the single trigger approach may also be unsuitable. We will redo the same study using the multi-trigger approach.

7.4 Designing multi-trigger index insurance products for maize crop in Bougouni using meteorological data from the synoptic station in Mali.

7.4.1 data description

The data we are using consists of daily rainfall data from the synoptic station in Mali, covering the period from 1990 to 2013. We will only use the data that corresponds to the months of June to September, which correspond to the maize growing season.

7.4.2 Methodology

For the multi-trigger approach, we will first divide the growing season into three periods:

- Initial phase: corresponding to germination or sowing and vegetative phase or Sowing period (du 15 juin au 15 juillet).
- Intermediary phase: corresponding roughly to flowering or growing period (from July 16th to August 15th).
- Final phase: corresponding to seed formation and ripening (mature) or harvesting period (from July 16th to September 15th).

For each phase, we have specific conditions on precipitation, which is how we identify three types of payment triggers: the required amount of rainfall per phase, the consecutive number of dry days, and the excessive amount of rainfall.Thus, we use the values from the Climate Change, Agriculture and Food Security (CCAFS) model as default values.

Parameters	phase 1	Phase 2	Phase 3	Consecutive dry day	excessive rainfall
Start date	15/06	16/07	16/08	15/07	15/08
End date	15/07	15/08	15/09	15/08	15/09
Strike	50	40	30	Strike1=10, strike2=22	80
Exit	0	0	0	32	130
Rate 1	80	75	100	35	70
Rate 2	-	125	150	98	-
Max payout 1	4000	3000	3000	1500	3500
Max payout 2	-	5000	4500	-	-

Somme insured = 15000
franchise = 500
NB: A day is considered a drought day if the rainfall is less than 5mm, including the previous day.

- **Calculation methodology of the differences payouts.**
  - To calculate Payout 1 (the payment linked to the amount of rainfall received during phase 1, which extends from 15/06 to 15/07), the following steps are followed:
    - If the rainfall amount is greater than the strike value defined in the previous table for this phase, then there is no payout for this phase (Payout 1 = 0).
    - If the rainfall amount is between the exit and strike values, the payout is calculated as follows:

      Payout 1 = (Strike - Rain) * rate

      Here, "Rain" represents the amount of rainfall during this phase.
    - If the rainfall amount is less than the exit value, the payout is calculated as follows:

      Payout 1 = (Strike - Exit) * rate
  - To calculate Payout 2 and Payout 3 (the payments for phases 2 and 3, respectively), the following steps are followed:
    - If there was a payment in the previous phase, the calculations are as follows:
    - If the rainfall amount is greater than the strike value, there is no payout, so it returns 0.
    - If the rainfall amount is less than the strike and greater than or equal to the exit value, the payout is calculated as follows:

      Payout = (Strike - Rain) * rate
    - If the rainfall amount is less than the exit value, the payout is calculated as follows:

      Payout 1 = (Strike - Exit) * rate.
    - If there was no payment in the previous phase, the calculations are similar but using the rate2 instead of rate1.
  - To calculate payouts based on the number of consecutive dry days (CDD). The payouts are determined according to the following conditions:
    - If the number of consecutive dry days (CDD) is less than the strike1 value, no payment is made.
    - If the CDD value is greater than or equal to strike1 and less than strike2, the payment is calculated as follows:

      Payout= (strike2 - CDD) * rate1
    - If the CDD value is greater than or equal to strike2 but less than the exit value, it indicates that the CDD exceeds the threshold for the second payout calculation. The payout is determined by:

      Payout= (strike2 - strike1) * rate1 + (exit - CDD) * rate2
    - If the CDD value is greater than or equal to the exit value, indicating a prolonged period of consecutive dry days, the payout is calculated as follows:

      Payout= (strike2 - strike1) * rate1 + (exit - strike2) * rate2

- To calculate the payout related to excessive rainfall, the following steps are followed:
  - If the amount of rainfall is greater than the strike value and less than or equal to the exit value, the payout is calculated by:
    (rain - strike) * rate
  - If the amount of rainfall exceeds the exit value, indicating excessive rainfall, the payout is calculated by:
    (exit - strike) * rate
  - If the amount of rainfall does not meet any of the above conditions, indicating insufficient rainfall, the payout is set to 0.
- To calculate the total payout, we first sum up the five individual payouts: payout for phase 1, payout for phase 2, payout for phase 3, payout for consecutive dry days (CDD), and payout for excessive rainfall.

  Next, we compare this total payout amount to the predefined franchise specified in the previous table. If the total payout is less than the deductible, the Total payout remains equal to the sum of the individual payouts. However, if the Total payout exceeds franchise , the Total payout is set to zero.

7.5 Results Multi-triggers

In this section, we will provide the results related to consecutive dry days, excessive rainfall, payment in each phase, and the total payout. Then, we will analyze the correlation between the total payout and yield loss.

	years	01/06	02/06	03/06	04/06	05/06	06/06	07/06	08/06	09/06	...	p1_payout	p2_payout	p3_payout	ds_payout	er_payout	Total_payout
0	1990	3.5	4.5	0.0	0.0	9.9	0.6	0.0	23.1	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0
1	1991	6.6	0.0	2.2	0.0	0.0	0.0	0.0	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0
2	1992	0.0	0.0	0.0	7.8	35.4	0.0	0.3	0.2	0.0	...	0.0	0.0	0.0	0.0	77.0	0.0
3	1993	0.0	0.0	0.0	0.0	30.8	0.0	0.0	1.4	18.5	...	0.0	0.0	0.0	0.0	0.0	0.0
4	1994	0.0	0.9	0.0	0.0	9.0	0.0	51.3	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0
5	1995	0.0	13.1	0.0	0.0	37.8	0.0	0.0	16.2	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0
6	1996	0.0	0.0	0.0	0.0	1.7	0.0	1.1	1.4	7.9	...	0.0	0.0	0.0	0.0	0.0	0.0
7	1997	0.0	0.0	0.0	0.7	0.6	0.0	0.0	0.0	21.1	...	0.0	0.0	0.0	0.0	0.0	0.0
8	1998	10.9	0.0	4.5	0.0	0.0	3.5	55.4	0.0	2.5	...	0.0	0.0	0.0	0.0	0.0	0.0
9	1999	0.0	0.0	3.3	0.0	0.0	0.0	0.0	20.5	0.0	...	0.0	0.0	0.0	0.0	1421.0	1421.0
10	2000	0.0	0.0	85.7	4.5	0.0	8.8	0.0	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0
11	2001	5.2	17.9	0.0	3.1	0.0	23.8	0.0	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0
12	2002	0.0	0.0	10.1	0.0	0.0	22.2	4.3	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0
13	2003	23.7	8.3	0.0	0.0	36.1	7.4	0.0	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0
14	2004	18.6	20.6	0.0	0.0	0.0	0.0	2.4	0.0	20.5	...	0.0	0.0	0.0	0.0	721.0	721.0
15	2005	0.0	2.0	0.6	28.7	5.6	0.0	0.0	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0
16	2006	14.9	5.6	0.0	0.0	2.2	0.0	8.5	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0
17	2007	0.0	0.2	0.0	0.0	20.3	0.0	0.0	0.0	0.0	...	0.0	0.0	0.0	0.0	2366.0	2366.0
18	2008	33.7	0.5	11.5	0.0	0.0	0.0	0.0	0.0	0.0	...	0.0	0.0	0.0	0.0	2492.0	2492.0
19	2009	0.0	2.4	3.0	0.0	0.0	0.3	0.0	5.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0
20	2010	0.2	0.0	2.6	0.0	0.0	0.0	12.9	0.0	0.0	...	0.0	0.0	0.0	0.0	2408.0	2408.0
21	2011	5.6	5.1	3.1	0.0	0.0	0.0	6.4	0.2	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0
22	2012	0.0	73.8	0.5	0.0	0.0	0.0	17.8	15.7	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0
23	2013	0.0	0.0	0.0	18.3	0.6	0.0	0.0	4.7	11.9	...	0.0	0.0	0.0	0.0	0.0	0.0

Figure 10: Contract evaluation.

06/06	07/06	08/06	09/06	...	p1_payout	p2_payout	p3_payout	ds_payout	er_payout	Total_payout	Total_payout_perc	Payout_sum	Yield	Loss
0.6	0.0	23.1	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0	0.000000	0.0	1685	13.336048
0.0	0.0	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0	0.000000	0.0	1406	27.685747
0.0	0.3	0.2	0.0	...	0.0	0.0	0.0	0.0	77.0	0.0	0.000000	0.0	1846	5.055397
0.0	0.0	1.4	18.5	...	0.0	0.0	0.0	0.0	0.0	0.0	0.000000	0.0	1836	5.569723
0.0	51.3	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0	0.000000	0.0	1940	0.220732
0.0	0.0	16.2	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0	0.000000	0.0	1638	15.753381
0.0	1.1	1.4	7.9	...	0.0	0.0	0.0	0.0	0.0	0.0	0.000000	0.0	1775	8.707113
0.0	0.0	0.0	21.1	...	0.0	0.0	0.0	0.0	0.0	0.0	0.000000	0.0	1830	5.878319
3.5	55.4	0.0	2.5	...	0.0	0.0	0.0	0.0	0.0	0.0	0.000000	0.0	1947	0.000000
0.0	0.0	20.5	0.0	...	0.0	0.0	0.0	0.0	1421.0	1421.0	9.473333	1421.0	2778	0.000000
8.8	0.0	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0	0.000000	1421.0	2002	0.000000
23.8	0.0	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0	0.000000	1421.0	1783	8.295652
22.2	4.3	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0	0.000000	1421.0	2047	0.000000
7.4	0.0	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0	0.000000	1421.0	2208	0.000000
0.0	2.4	0.0	20.5	...	0.0	0.0	0.0	0.0	721.0	721.0	4.806667	2142.0	1737	10.661552
0.0	0.0	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0	0.000000	2142.0	2015	0.000000
0.0	8.5	0.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0	0.000000	2142.0	1730	11.021580
0.0	0.0	0.0	0.0	...	0.0	0.0	0.0	0.0	2366.0	2366.0	15.773333	4508.0	1994	0.000000
0.0	0.0	0.0	0.0	...	0.0	0.0	0.0	0.0	2492.0	2492.0	16.613333	7000.0	1897	2.432334
0.3	0.0	5.0	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0	0.000000	7000.0	2039	0.000000
0.0	12.9	0.0	0.0	...	0.0	0.0	0.0	0.0	2408.0	2408.0	16.053333	9408.0	2261	0.000000
0.0	6.4	0.2	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0	0.000000	9408.0	1923	1.095086
0.0	17.8	15.7	0.0	...	0.0	0.0	0.0	0.0	0.0	0.0	0.000000	9408.0	2177	0.000000
0.0	0.0	4.7	11.9	...	0.0	0.0	0.0	0.0	0.0	0.0	0.000000	9408.0	2169	0.000000

Figure 11: Valuation of contracts (continued).

7.5.1 correlation between Yield loss and Total payout

$$\begin{bmatrix} 1 & -0.23 \\ -0.23 & 1 \end{bmatrix}$$

We observe a correlation of -0.23 between yield loss and actual payout.

7.5.2 Interpretation of results

The conclusions of this study of data using the multiple trigger approach carried out between June and September from 1990 to 2013 lead to the following observations: rainfall had no significant influence on yield or yield loss (weak correlation between yield loss and total payment).
This could be explained by the fact that the yield losses suffered by farmers are not solely caused by rainfall or poor data quality.

8 Conclusion

It is observed that with both approaches (Single trigger and multi triggers), precipitation alone does not explain the yield or yield losses with the different data used. Therefore, it can be suggested that climatic factors such as wind, temperature, humidity, and light also play a crucial role in yield or yield losses. By using these different types of climatic data, it is possible to reconstruct a more comprehensive and suitable baseline index for assessing agricultural risks. Additionally, one can attempt to use the Normalized Difference Vegetation Index (NDVI) to reconstruct a more appropriate index considering crop losses.

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