

Review

The Potential and Uptake of Remote Sensing in Insurance: A Review

Jan de Leeuw ^{1,*}, Anton Vrieling ², Apurba Shee ³, Clement Atzberger ⁴, Kiros M. Hadgu ⁵,
Chandrashekhar M. Biradar ⁶, Humphrey Keah ⁷ and Calum Turvey ⁸

¹ World Agroforestry Center (ICRAF), Eastern and Southern African Region, P.O. Box 30677-00100 Nairobi, Kenya; E-Mail: j.leeuw@cgiar.org

² Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, P.O. Box 217 7500 AE Enschede, The Netherlands; E-Mail: a.vrieling@utwente.nl

³ International Livestock Research Institute (ILRI), P.O. Box 30709-00100 Nairobi, Kenya; E-Mail: a.shee@cgiar.org

⁴ Institute of Surveying, Remote Sensing & Land Information (IVFL), University of Natural Resources and Life Sciences (BOKU), Peter Jordanstrasse 82, 1190 Vienna, Austria; E-Mail: clement.atzberger@boku.ac.at

⁵ World Agroforestry Center (ICRAF), Eastern and Southern African Region, P.O. Box 5689 Addis Ababa, Ethiopia; E-Mail: k.hadgu@cgiar.org

⁶ International Center for Agricultural Research in Dry Areas (ICARDA), P.O. Box 950764 Amman, Jordan; E-Mail: c.biradar@cgiar.org

⁷ World Agroforestry Center (ICRAF), P.O. Box 30677-00100 Nairobi, Kenya; E-Mail: h.keah@cgiar.org

⁸ Charles H. Dyson School of Applied Economics and Management, Cornell University, Ithaca, NY 14853-7801, USA; E-Mail: cgt6@cornell.edu

* Author to whom correspondence should be addressed; E-Mail: j.leeuw@cgiar.org; Tel.: +254-737-223-157.

External Editors: Bingfang Wu and Prasad S. Thenkabail

Received: 25 May 2014; in revised form: 28 October 2014 / Accepted: 28 October 2014 /

Published: 7 November 2014

Abstract: Global insurance markets are vast and diverse, and may offer many opportunities for remote sensing. To date, however, few operational applications of remote sensing for insurance exist. Papers claiming potential application of remote sensing typically stress the technical possibilities, without considering its contribution to customer value for the insured

or to the profitability of the insurance industry. Based on a systematic search of available literature, this review investigates the potential and actual support of remote sensing to the insurance industry. The review reveals that research on remote sensing in classical claim-based insurance described in the literature revolve around crop damage and flood and fire risk assessment. Surprisingly, the use of remote sensing in claim-based insurance appears to be instigated by government rather than the insurance industry. In contrast, insurance companies are offering various index insurance products that are based on remote sensing. For example, remotely sensed index insurance for rangelands and livestock are operational, while various applications in crop index insurance are being considered or under development. The paper discusses these differences and concludes that there is particular scope for application of remote sensing by the insurance industry in index insurance because (1) indices can be constructed that correlate well with what is insured; (2) these indices can be delivered at low cost; and (3) it opens up new markets that are not served by claim-based insurance. The paper finally suggests that limited adoption of remote sensing in insurance results from a lack of mutual understanding and calls for greater cooperation between the insurance industry and the remote sensing community.

Keywords: insurance; remote sensing; index insurance; agriculture; flood risk management

1. Introduction

Remote sensing has the potential to support the insurance industry. This suggestion has been repeated since 1975 when Towery described the potential of aerial photography and remote sensing in crop hail damage assessment [1,2]. The remote sensing literature offers numerous other examples proposing earth observation techniques to support insurance, for example in assessment of damage from fire [3], hail [4], and drought [5]. The insurance industry represents a large market of USD 4.3 trillion or 6.4 percent of global GDP [6], while worldwide agricultural insurance markets have a collective premium pool worth €12.5 billion [7]. Because of the size of these markets insurance may constitute an important application field for remote sensing. So far, however, operational applications of remote sensing in the insurance industry appear to be few, notwithstanding the size of the market and the potential and recent progress of the technology.

Why does the insurance industry have reservations about adopting remote sensing? The insurance industry is among the most information intensive of all service enterprises [8] so at first glance the detailed information from remote sensing would appear to be attractive to insurance companies. Yet, a 2008 review of the value-added from spatial information ranked the insurance sector among the lowest intensity users in Australia [9]. The same study suggested that the insurance sector had potential for increased use of spatial information, particularly in better risk assessment.

The discrepancy between the perceived potential and the actual uptake by the industry is probably the result of over-optimistic assumptions by the remote sensing community regarding the industry's readiness to adopt the information that remote sensing could provide. One factor hindering the uptake of remote sensing might be its appropriateness for the purpose, because of the indirect relation

between remote sensing information and the insured damage as well as the limited duration of available time series. However, the adoption of a new technology by an industry depends not only on the appropriateness of the technique to support business processes, but also on its impact on customer value and the industry's productivity and profitability. Proper assessment of the potential of remote sensing in insurance therefore requires consideration of the technology from the perspective of the industry's business processes and profitability.

In this paper, we review relevant literature on remote sensing and insurance to investigate the potential and actual use of earth observation in support of the insurance industry. The review is based on a search of the literature that was accessible in Scopus (Elsevier) using the keywords "Remote Sensing AND Insurance" and searching the title, abstract, keywords and references (date of access 24 March 2014). The retrieved publications were further examined to select those publications with applications of remote sensing in insurance as their core subject matter. This sample was complemented with additional professional reports found on the web or referred to in the peer-reviewed literature. The assembled compilation of relevant literature reveals that papers on the application of remote sensing in insurance have for long been dominated by examples in classical claim-based insurance in agriculture and flood and fire risk management, while a smaller but rapidly growing number of papers describe its potential in so-called index insurance in agriculture. This paper reviews the actual and potential contribution of remotely sensed information in support of conventional claim-based insurance and index insurance.

The remainder of the paper is structured as follows. Section two provides an introduction about the basic working principles of insurance. The use and potential of remote sensing in classical (claim-based) insurance is presented in section three. Section four reviews the application of remote sensing in index insurance. Section five discusses the findings of the reviews while section six provides concluding comments and recommendations.

2. An Overview of Insurance

Insurance is a financial instrument, which allows exposed individuals to pool resources to spread their risk. They do so by contributing premium to an insurance fund, which will indemnify those who suffer insured loss. This procedure reduces the risk for an individual by spreading his risk among the multiple fund contributors. Insurance can be designed to protect many types of individuals and assets against single or multiple perils and buffer insured parties against sudden and dramatic income or asset loss.

2.1. Classification of Insurance

Insurance varies based on a number of characteristics, two of which are particularly relevant for this review. The first is the geographical distribution of the shock causing the risk. Risks vary between idiosyncratic risk, the situation where an individual's exposure does not concur with that of its neighbors and covariate or systemic risk where a single shock affects neighboring individuals at the same time [10]. Drought and floods can affect many people concurrently over larger areas and are thus examples of covariate risks. Covariate risk, by definition, captures the degree of correlation between a peril (event) and economic loss. It is the degree of co-variation between an event and a loss that determines an insurable event; not all droughts or floods result in economic loss, and not all losses are insurable. Insurance can be further differentiated according to the criterion used for indemnification.

Classical claim-based insurance pays an indemnity following a claim of loss by the insured customer. Index insurance in contrast indemnifies the insured customer based on an index related to such losses rather than the claimed loss.

Table 1 provides a classification of insurance according to these two criteria. Classical claim-based insurance covers both idiosyncratic (Table 1, class a) and covariate risks (Table 1, class b). From a business perspective, idiosyncratic risk insurance is relatively easy to manage because the administration can be optimized to a regular and continuous flow of incoming claims. The management of covariate risk is a challenge to insurance companies in several ways. First, in case of a covariate shock, insurers are often at unpredictable moments confronted with a huge number of claims, thus stressing their ability to handle all claims properly. In such situations, it becomes a challenge to verify claims in time and particularly before verifiable signs of damage and loss have disappeared. Second, covariate shocks expose the insurer to the risky obligation of making massive indemnity payments that may exceed their solvability. Insurers mitigate this threat by dispersing their policyholders beyond the geographical distribution of covariate shocks, or transferring the risk to reinsurers who can absorb covariate shocks at local levels through a global spread of their portfolios.

Table 1. Classification of insurance according to indemnification and distribution of risk.

Indemnification	Geographical Distribution of Risk	
	Idiosyncratic	Covariate
Claim	a	b
Index	--	c

Index insurance is appropriate to address covariate risk (Table 1, class c), but not idiosyncratic risk because it is the covariate nature of a hazard that allows the insurer to predict losses and determine indemnity payments for a large number of policyholders over a wide geographical area. Unlike classical insurance, it indemnifies policyholders on the basis of an index correlated with the insured losses. In fact, index insurance establishes a trigger point below or above which an indemnity payment is made. An example of such an index is rainfall during the growing season used in index-based crop insurance. The contract pays the same amount per unit premium to each policyholder within the spatial domain for which the index value is valid, regardless of the actual losses they face. Similar to classical insurance, the index insurer also needs to take precautions to spread their business risk imposed by covariate shocks among a wider group of policyholders or reinsurers.

2.2. Advantages and Disadvantages of Claim and Index-Insurance

The two insurance types have advantages and disadvantages. An advantage of index insurance is that it can potentially be delivered at lower cost. A significant barrier that hinders uptake of claim-based insurance is the high transaction cost for searching for prospective policyholders, negotiating and administering contracts, verifying losses and determining payouts. Index insurance eliminates the loss verification step, thereby mitigating a significant transaction cost. However, the administration, contract design, client search, premium collection, and claims disbursement processes remain labor- and cost-intensive in index insurance, which has additional initial cost related to the development of an index

that has good relation with insured losses and recurrent costs for the acquisition and processing information on the state of the index [11].

A second advantage of index insurance is that, because it pays an indemnity based on the reading of an index rather than individual losses or individual risk profiles, it eliminates much of the fraud, moral hazard and adverse selection, which are common in classical claim-based insurance. Moral hazard is the situation where a policyholder engages in risky behavior, increasing his actual risk profile beyond that originally considered by the insurer. Adverse selection is the situation where people exposed to higher risk seek insurance more frequently than those exposed to lower risk. This occurs when the insured has more information about his “risk profile” than the insurer, a case of information asymmetry. Raised premiums are a consequence of fraud, moral hazard and adverse selection. Index insurance avoids this, provided that an index is used that cannot be manipulated by the parties involved. A further advantage of index insurance is that payments based on a standardized and indisputable index also allow for a fast indemnity payment [12] that could be automated, further reducing transaction costs.

Basis risk is a major disadvantage of index insurance. It is the situation where an individual experiences a loss without receiving payment or *vice versa* [13]. Basis risk is a direct result of the strength of the relation between the index that estimates the average loss by the insured group and the loss of insured assets by an individual. The weaker this relation the higher the basis risk. It is obvious that high basis risk undermines the willingness of potential clients to purchase insurance. It thus challenges insurance companies to design insurances such as to minimize basis risk.

The described advantages can allow delivery of index insurance at lower cost than claim-based insurance. This makes index insurance potentially affordable in remote areas, and thus opens up markets for insurance in areas where it has not previously been offered. Examples of this are insurance for crops and livestock in drylands, where the insurer’s costs of writing individual insurance contracts and verifying individual claims would be prohibitive.

Reduced cost also makes index insurance more affordable to smallholder farmers in the developing world. These smallholder farmers rely for their livelihoods, to a large extent, on their farm products while facing major risks that can profoundly affect their livelihoods, such as crop failure or loss of livestock during drought. Until recently insurance companies did not, or would not offer agricultural insurance products for smallholder farmers in the developing world because of the associated costs. Instead, smallholder farmers traditionally reduce adverse effects of risks through transferring these risks within their community [14]. This is particularly effective in covering idiosyncratic risk, when the non-affected fraction of a community remains capable of covering and absorbing the losses of those affected. Traditional arrangements are less effective in insuring covariate risk. The ubiquity of damage and loss caused by covariate hazards erodes the ability of one community member to cover the loss of others. Traditional arrangements thus lack the desirable robustness to cover people against systemic risk imposed, for example, by drought or floods. Insurers capable of spreading risk beyond the geographical region affected by the covariate shock may however insure against this risk. This insight spurred a recent interest in the possibility of index-based micro-insurance for smallholder farmers in the developing world.

2.3. Social Security Nets and Subsidies

Thus far, insurance has been presented from a private enterprise perspective, focusing on the transactions between the insured and the private enterprise delivering the insurance product. In many countries, government plays an important regulatory and facilitating role; they provide legal frameworks within which the insurance industry operates and subsidizes various forms of insurance to keep them affordable. The latter is a common practice in agricultural insurance, which is subsidized or supported in other ways by governments in many developed countries to ensure sufficient uptake of the insurance product. The government support to agricultural insurances varies from virtually nil in Australia and Africa to 73% of all costs in the USA [15,16]. An important reason motivating governments to subsidize agricultural insurance is the realization that fully commercial insurance would be too expensive, resulting in limited adoption. Yet, many governments also subsidize agricultural insurance because of the importance of the agricultural sector from electoral, employment, food security and social security net perspectives. In the developing world where governments may not have the financial strength to prioritize subsidizing agricultural risk, donors supporting relief and development are increasingly interested in supporting the development of agricultural insurance. A proper perspective of the role of government and other parties supporting insurance is important to understand the latter parts of this paper where we will see that these parties play an important role in supporting the development of applications of remote sensing in insurance.

3. Claim-Based Insurance and Remote Sensing

3.1. Business Processes in Claim-Based Insurance

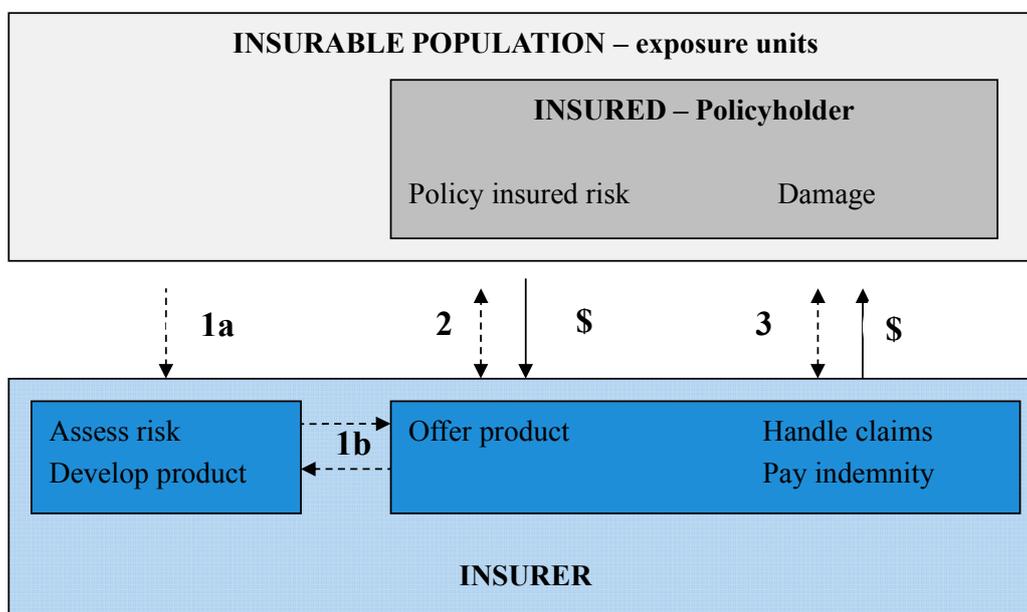
The literature describes various examples of how earth observation and GIS might support the insurance industry in managing its business operations in claim-based insurance. Below we first describe claim based insurance in some more detail and next review the possibilities and actual use of remote sensing to contribute to insurance business processes related to risk assessment and the handling of claims.

Figure 1 provides a scheme of the transactions and information flows in classical loss-based insurance and shows distinct groups of information flows. The first information flow (number 1) is between the insurer and the insurable population as a whole while the second and third information flows (number 2 and 3) are between the insurer and the individual client. The first information flow relates to the risks to which the insurable population is exposed. To the insurer this is critical information because it allows for an estimation of the risk and the probability of future claims and payouts, and to set an insurance premium with sufficient margin. When introducing new products, an insurer develops and offers these products, with the premium based on an assessment (1a) of the frequency and severity of the insured risk and the expected average payout that would result from this peril. Thereafter insurance companies continuously re-evaluate their risk and re-adjust their premium based on the information accumulated while handling claims and making payouts (1b). This process brings their risk assessment from one pertaining to the potentially insurable population to the risk for the exposure units insured by the insurer.

The second flow of information relates to the interaction between the insurer and the clients. Information is exchanged (number 2) between the client and insurer, allowing the client to assess the

product and the insurer to assess (underwrite) the risks of that particular client. Further information is exchanged (number 3) when the insured makes his claims seeking indemnity for insured damage.

Figure 1. Business processes (blue) including financial transactions (\$) and information flows (numbered) between insurers and their clients in claim-based insurance.



3.2.1. Underwriting of Risk

Retrospective Underwriting

Traditionally, insurers establish premiums while assessing risk based on claims made in the past. This retrospective underwriting works well for insurance products that have been in the market long enough to develop a historic record of claims and payments. This approach does not work in case of new products for new populations, for which such historic records are absent. In such cases insurers use other sources of information, such as *in situ* measurements of the hazard rather than the claims, to underwrite their risk.

However, accurate *in situ* monitoring of hazard-related variables is costly, and thus it has been suggested that remote sensing has a potential for more cost effective risk assessment [17]. The underlying idea is that satellite imagery allows analysis of the historical recurrence of a hazard when the record from other sources captures the exposure insufficiently. For example, in areas where a historic record of drought recurrence is missing, rainfall estimates from satellites could potentially be used to construct a historic drought record. However, data mining of remotely sensed archives to retrospectively underwrite insurance risk is not straightforward. For the example mentioned, remote sensing rainfall records have their intrinsic errors [18] and in addition the rainfall estimates need to be translated to agricultural and economic losses. Utilizing remote sensing systems to reconstruct a reliable record on hail damage or vegetation production anomalies would pose similar problems. For this reason, it is perhaps not surprising that we did not find any references to feasibility studies or operational applications of remote sensing in the underwriting of risk in claim-based insurance. In contrast, historical remote sensing records are the basis of the underwriting of risk in index insurance as described in Section 4.2.

Geographic Stratification of Risk Exposure

Risk is not uniformly distributed among the insured, and insurers vary insurance premiums accordingly. An example is a life insurance premium, which varies with age and individual mortality enhancing behavior like smoking. The risk of exposure to hazards often varies geographically; for example, real estate in wooded peri-urban areas might be more frequently affected by fire than property downtown and flood risks are higher in coastal or flood plain areas than in well-drained uplands. Insurance companies use this spatial variation in exposure to differentiate their insurance rates geographically. To do so they may use their historical record of claims and payments made. They may also opt to use geo-spatial data related to the hazard to identify areas with increased risk to justify a higher premium.

The geographical underwriting of risk has in fact been studied and operationalized in flood risk insurance. Several publications describe the potential and use of remote sensing in establishing a spatial stratification of flood risk [19,20]. Flood damage in Europe accounts for 75 percent of all insurance payments attributable to natural disasters [21]. For example, the 2002 flood damage in Central and Eastern Europe led to claims of several billion Euros [20] and insurers increasingly use geo-spatial information to assess flood risk in order to realistically price their insurance products. While detailed local hydrological models supply such information for smaller areas, it has been argued that insurers require models at regional and national scale rather than sophisticated models for small areas and that detailed information on the elevation of the terrain is generally the component with the highest uncertainty in the flood risk models [20].

In reality flood risk may vary over relatively short horizontal distance and a vertical gradient of a few decimeters may make the difference between safe areas and those areas exposed to risk. Not considering this fine scale variability in the underwriting might under- or over-estimate the risk, with significant consequences to the insurer and the insured customer or asset. Insurance companies are thus facing a challenge to improve the vertical accuracy of the geo-spatial models, which they are using in underwriting the risk of flooding. In the UK use of airborne laser altimetry data as an input into flood risk modeling allowed assessing of risk and calculating insurance premiums at much finer resolution (postcode basis, approx. 15 households) than risk models used by the insurance industry, which had spatial units with over 2000 households [22]. Based on this, it was advised to acquire laser altimetry data for urban areas susceptible to storm surges.

The examples above are feasibility studies. The Flood Insurance Rate Maps (FIRMs) produced by FEMA, the Federal Emergency Management Authority in Southern USA are an example of an operational utilization of remote sensing in stratification of flood risk exposure [19,23]. The FIRMs, which are used to assess flood risk, are based on remotely-sensed LiDAR (Light Detection And Ranging) data measuring terrain elevation with 15 cm vertical accuracy. The underwriting by insurance companies is based on this, with higher premiums in more flood-prone areas. The actual premium may be adjusted, depending on preventive action and best management practices taken by communities to avoid flood damage.

3.2.2. Handling of Claims

Damage Assessment

A second commonly proposed application of earth observation in claim-based insurance is related to the handling of claims. Ideally, the insurer would attempt to check every claim and verify the damage personally or obtain an independent damage assessment. In many cases, this is not possible. For example with claims of minor monetary value, the costs of on-site damage assessment may become too high. Insurers thus do not investigate each claim, but seek to balance customer satisfaction, handling expenses and leakage from insurance fraud. For this, they often use automated statistical procedures, identifying outliers from the normal pattern of claims, to identify suspicious cases for further investigation.

Earth observation imagery offers an alternative possibility to verify whether a claimant has been affected by an insured risk and to investigate suspicious claims. This possibility emerges from the well-established potential of remote sensing to detect damage on vegetation and crops by drought, fire, hail, frost and pests and diseases. Similarly, there is a rich literature describing applications of remote sensing in assessing damage to man-made objects and infrastructure.

Contrasting conclusions have been reported regarding the feasibility of remote sensing to support the insurance industry in crop hail damage assessment. Peters *et al.* [24] evaluated the suitability of airborne multispectral imagery to assess the effect of artificially induced hail damage in corn and soy-bean and of a Landsat TM image to assess true hailstorm effects on croplands. They considered the 30 m broadband imagery adequate for preliminary post storm hail damage assessment and 5 m resolution imagery adequate to confirm hail damage and consequently were confident that remote sensing would assess hail damage faster and more accurately than traditional field based verification. In contrast, coarser resolution MERIS (MEdium Resolution Imaging Spectrometer) data did not reliably estimate the area of crop damage, a finding which was based on imagery acquired a few days before and after a hail storm and field-based damage assessments of the Agriculture Financial Service Cooperation in Alberta, Canada [25]. Apan *et al.* [26] expressed further reservation while arguing that, although RS has potential to delineate areas of reduced biomass, it remains difficult to attribute such losses to hail damage as other confounding factors may have caused the biomass reduction. These two latter papers suggested that remote sensing could at best be deployed in a supportive and cost-saving role targeting areas for further field verification. However, the plausibility of attributing remotely-sensed evidence of crop damage to hail could possibly be enhanced by combining the optical remote sensing with verification of the hail event with polarimetric radar imagery [27].

The United States Department of Agriculture (USDA) Risk Management Agency (RMA) subsidizes the US crop insurance program, with insurance policies covering a liability of USD 55 billion in 2007 being sold by 16 private insurance companies. The program initially included crop insurance that covered risk from drought and hail, but has broadened in scope over the years and now includes a broad array of damages and a wide variety of agricultural commodities. The system is, like any insurance system, not free of fraud. Utilization of data mining techniques of the remote sensing record to seek for anomalies and suspect cases resulted in a cost reduction of USD 450 million over a six-year period [28]. Remote sensing derived crop classification was used, for example, to verify whether farmers had planted the crop for which losses were claimed [29].

There seems to be ample scope for further use of remote sensing in crop damage assessment, as field-based assessment is costly. However, satellites with relatively long (>20 days) revisit times that carry optical sensors whose imaging capability is affected by clouds (e.g., Landsat) are not very suitable if assessment is required within a few days after a peril. Several new satellite missions exist that significantly reduce revisit times while mapping the Earth at very high spatial resolution (approx. 1 m). For example, the German Rapid Eye AG developed a series of five satellites that can cover any area on earth once per day, and aims with this potential for more timely delivery to service the crop insurance industry among others [30]. Competitors like Digital Globe (WorldView-2 satellite with 8 spectral bands) and SPOT IMAGE (Pleiades satellite) offer the same revisit frequency. Similarly, SarMap is developing applications of radar imagery, unaffected by cloud cover and acquired at a spatial resolution of approx. 20 m as an input in a crop damage insurance system [31]. A common problem of the mentioned new missions relates to the fact that imagery is usually only acquired through tasking and not regularly, such as by Landsat and other 10–30 m resolution sensors. Hence, suitable imagery depicting the situation before the damage event may not be available. In this respect, the increase of public-domain high resolution optical and radar imagery with short revisit times such as the European Sentinel-1 and -2 missions are highly welcome, as they will monitor the Earth surface continuously. The first Sentinel-1 satellite was launched in April 2014 and the first Sentinel-2 will be launched towards the end of 2015.

Apart from applications in crop insurance, remote sensing has also been explored for usage in forest fire damage assessment. Canaseva and Dagonne [32] suggested in 1985 that airborne color infrared remote sensing imagery could be used to delineate forest area affected by fire for insurance purposes. Since that time, much development has taken place in the remote sensing based assessment of active fires, fire intensities, and burned areas [33], and various coarse-resolution operational products exist [34]. The suggestion of operational use of airborne multi-spectral imagery in assessment of fire damage by the Safire Insurance Company in South Africa [35] was however not confirmed when requesting the company for further information and confirmation of its operational use.

Verification of Conditions in Insurance Contracts

Another potential application of earth observation is in verifying whether claimants complied with specific conditions stipulated in the insurance contract. The presence of well-maintained firebreaks, for example, is a condition included in most forest fire insurance policies. Remote sensing might offer insurance companies the possibility to verify whether and how well firebreaks were maintained before the outbreak of a forest fire. The temporal resolution of the sensor and its ability to detect the condition of the firebreak would be critical in verifying compliance in this particular case. We were however, unable to find examples of the use of remote sensing in verifying compliance to contractual obligations.

4. Index Insurance

4.1. Development of Index Insurance

Halcrow [36] introduced the concept of index insurance in 1949 when arguing that the Federal Crop Insurance in the United States should offer an insurance product based on the yield over a wider area to eliminate adverse selection among insured farmers. The idea of area-yield insurance was taken up

in India where the Indian National Agricultural Insurance Scheme (NAIS) is an area yield insurance that is based on yield estimates made in so called insurance units covering hundreds to thousands of farmers. With 25 million insured farmers it is the largest agricultural insurance scheme in the world offering crop insurance to smallholder farmers that could otherwise not be insured [37]. In the United States of America (USA), the Group Risk Plan (GRP) uses yield at county level for calculating indemnities to insured farmers [38].

Around the same time the idea of weather-based index insurance was developed in Australia [39,40]. Weather index insurance differs from area-yield insurance in that it uses an index related to the yield rather than an estimate of the yield based on field measurement. Weather index insurance avoids the cost of estimating yield, but requires the availability of a historic record of weather and yield data to calibrate a model to design the insurance scheme. In the late 1990s the World Bank supported the piloting of index insurance in the developing world and since then there has been an increase of index insurance in developing countries [41]. Initially projects focused on weather-index-insurance based on rainfall, and recently IFAD [42] published a technical guide to support the development of weather-based index-insurance. Potentially, there is a much wider array of indicators including Richter values used in earthquake insurance in Mexico, reservoir levels used as an indicator for insurance for insufficient irrigation water supply in Mexico, area livestock mortality rates for livestock insurance in Mongolia and the El Niño Southern Oscillation (ENSO) index for flood insurance in Peru [43]. A recent publication of the EU Joint Research Centre provides a comprehensive overview of the challenges of index insurance in developing countries [44].

Vrieling *et al.* [45] suggested that the information underpinning index insurance requires four criteria, which are not always easy to meet. First, the information should be trustworthy and independently verifiable, *i.e.*, derived from impartial data providers who use well-described data collection and processing methods. For weather-based index insurance that uses rain gauges the condition of impartiality is sometimes impractical in remote areas when farmers with interest in insurance also maintain the rainfall stations. Second, the index should correlate strongly with what is insured, such as livestock or crop losses. The weaker the relation between the index and the loss of insured assets, the higher the likelihood of households experiencing a loss without receiving payment or *vice versa*, a situation referred to as “basis risk” [13] described in Section 2.2.1. Basis risk is inherent to index insurance. It is a genuine problem because the strength of the correlations between the yield of agricultural commodities and indices is variable [41]. For instance, basis risk tends to increase with increasing distance between the location of the insured assets and where information for an index is gathered, a situation complicating weather index-insurance based on observations from weather stations in data scarce areas. The third condition is that the information required for the index can reliably be delivered into the future, at least for the duration of the insurance contract, and is available in near real-time, so that payments can be made in due time. The fourth condition is that the record of the index is sufficiently long to properly underwrite the risk and accurately price the insurance product. This can be conceived as a major limitation of index insurance based on remote sensing inputs, even if coarse resolution NDVI time series exist now for more than thirty years (starting with the launch of the first AVHRR in 1979). In addition, a number of initiatives exist to combine observations from various sensors to increase consistency between time series [45]. From the insurer point of view one may add as a fifth condition, *i.e.*, that gathering of information should not be too expensive.

4.2. Remote Sensing in Index Insurance

Remote sensing offers opportunities to address some of the above described requirements of index insurance. If data are pre-processed properly, sensors onboard satellites provide cost-effective, reliable and impartial information on a wide variety of vegetation and hydrological parameters at various spatial resolutions. Moreover, operational satellites have the potential to provide a continuous flow of information and the remote sensing community has developed image-processing routines to generate long-term datasets with stable characteristics over time. Many efforts currently exist to create consistent long-term records based on a variety of satellite-based input source, for example the European Space Agency's Climate Change Initiative [46] and NASA's Land Long Term Data Record [47]. The continuously extending duration of the remotely sensed record is going to increase its value as a historic record of the variability of natural processes and hence its utility in index insurance.

Thanks to these advantages, it is not surprising that remote sensing indices have found their way into index insurance. One example of the application of remote sensing indices is in insurance that covers the risk of forage scarcity in rangelands, an application based on the well-established relation between rainfall, NDVI and forage scarcity. Strong correlations of NDVI and rangeland productivity have been documented for rangelands of central Australia [48], North America [49], the Middle East [50] and Africa [51–53].

Two separate applications of remotely sensed index-insurance have been developed based on this. The first is instigated by government in the United States where the USDA's Risk Management Agency (RMA) offers pasture and rangeland insurance, which are based on rainfall and NDVI time series [54]. The insurance is designed to protect farmers against a decline in forage where the indemnity payments are determined based on deviation from normal of the combined NDVI and rainfall index.

The second example is the Index-Based Livestock Insurance (IBLI) scheme that is offered by private insurance companies and insures Kenyan pastoralists against drought-related livestock mortality. The IBLI livestock insurance, which was developed by the International Livestock Research Institute (ILRI), uses an index based on seasonal and spatially-aggregated NDVI acquired from MODIS (Moderate Resolution Imaging Spectroradiometer) and statistically fitted (Figure 2A) with household-level livestock mortality data [55]. The insurance is offered twice a year, in the month before the onset of the long-rains (March–May) and the short-rains (October–December) respectively. A payout is made when the cumulative z-scored NDVI index (Figure 2B) falls below a threshold corresponding to a predicted livestock mortality of 15%.

Support from international donors allows the insurance to be offered at 30%–40% below full market price. During the pilot phase the insurance was designed based on the interest and demand among pastoral livestock keepers. The insurance was first introduced in Marsabit District in northern Kenya in 2011, where below normal dry conditions during the 2011 long rainy season triggered a first payout in October 2011.

Figure 3 illustrates the dry conditions during the long rains for 2011 (Figure 3A) with respect to the previous-year good long rains (Figure 3B) by displaying the NDVI at the moment when green vegetation cover is normally close to maximum (1–10 May). While Figure 3 does not display the seasonally aggregated index used (as in Figure 2, *i.e.*, seasonal z-scoring of each image, followed by spatial and temporal aggregation), it illustrates how NDVI time series capture the inter-annual differences in

vegetation conditions. Following the introduction of IBLI in Marsabit ILRI has implemented similar index insurance schemes in southern Ethiopia and other districts in northern Kenya.

Figure 2. (A) Relation between the cumulative z-scored NDVI index and livestock mortality used in design of IBLI livestock insurance and (B) Variation of the cumulative z-scored NDVI index over an eleven-year period for Laisamis division in Marsabit district (see Figure 3).

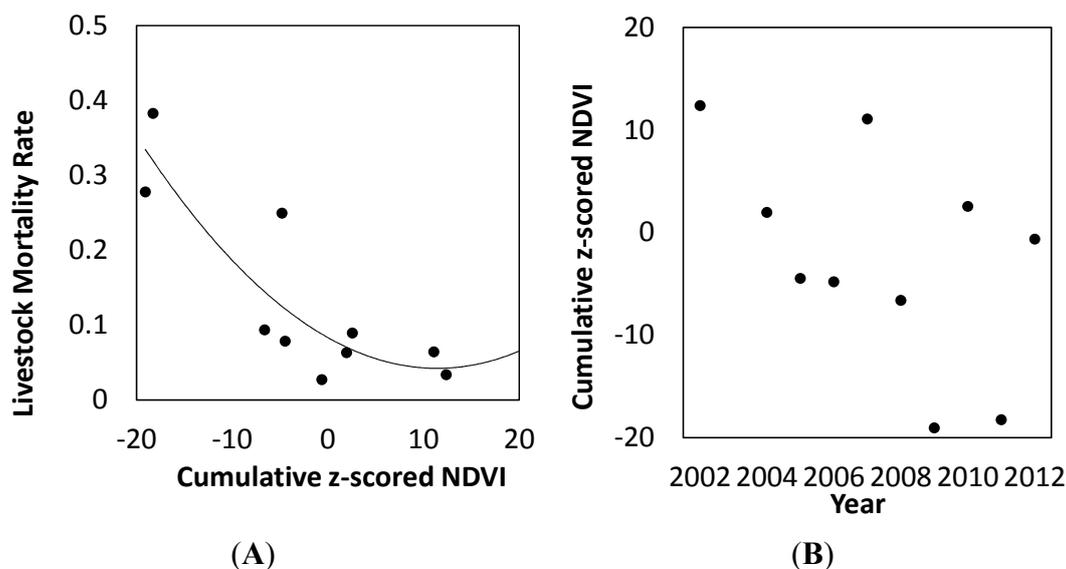
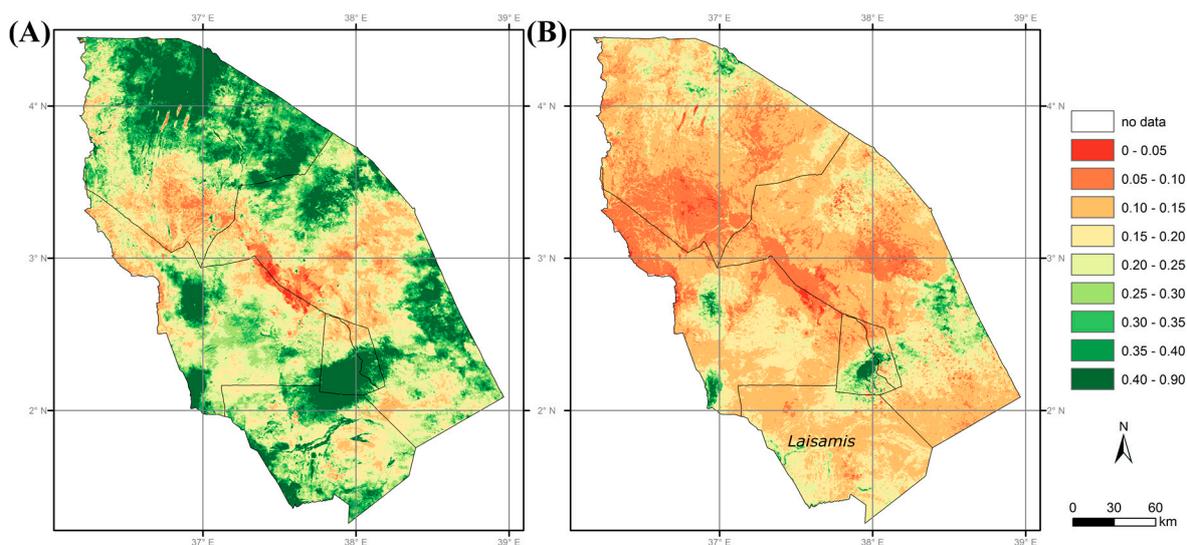


Figure 3. MODIS NDVI during the first decade of May during a good (2010, A) and a poor long rainy season (2011, B) in Marsabit District (now Marsabit County). The black lines show the boundaries of the six divisions that are contained in Marsabit District. The southern division Laisamis corresponds to Figure 2.



We are not aware of operational use of remotely sensed indices in crop insurance, but several studies have been carried out to explore the potential of such indices in crop insurance. Rao [56] reports on research of the Indian Insurance Company looking into the feasibility of NDVI based index insurance

for crops, while options for remotely sensed index insurance have also been reviewed for wheat in Kazakhstan [57] and Syria [58]. Pantakar [59] described a pilot study in Chhattisgarh and Andhra Pradesh states in India where a composite index insurance product based on NDVI and rainfall was designed and offered to farmers. Analysis of the relation between a rainfall index and an NDVI index with historical maize and cotton crop yield data from nine districts in Zimbabwe [60] led to the conclusion that NDVI was a better indicator because it exhibited higher correlations with yield than the rainfall index. Turvey and McLaurin [61] examined the potential of NDVI as an index in crop insurance. They reported that the relationship between NDVI, precipitation, extreme heat and crop yields is highly variable and location-specific, and consequently concluded that application of NDVI to index insurance product design requires site-specific calibration.

Besides index insurance based on remotely sensed vegetation productivity indices (e.g., NDVI), there is also potential for insurance based on remote sensing rainfall indices [14]. Johnson [62] describes that the automated weather stations, which form the backbone of the Kilimo Salama weather index insurance offered to over 150,000 farmers in Kenya and Uganda are too expensive to maintain, and this is the reason why research has been initiated to investigate the possibility of satellite rainfall estimates. Because rainfall has high spatial variability, particularly for short temporal time-scales, dense station networks are needed to generate an effective spatial representation of the rain field. When such networks are nonexistent or do not reliably deliver data, satellite data can partly fill this gap. These data consist of thermal infrared observations, mostly from geostationary satellites, and active and passive microwave observations from polar-orbiting satellites. Many satellite rainfall products exist that merge rainfall retrievals from various remote sensing sources [63]. Because quality of the rainfall products varies depending on climatic region, local calibration with ground-based rainfall measurements may be required to improve the estimates [64]. Nonetheless, satellite rainfall estimates provide a good alternative to interpolated station data, and large international efforts such as the Global Precipitation Measurement (GPM) mission will improve their accuracy further [18].

The above-mentioned remotely sensed index insurance programs deliver micro-insurance products that target and benefit individual households. Recently, there has been increasing interest in meso- and macro- level insurance products. Those products do not target individual farmers. They target relief agencies and regional and national governments that have an interest in financially supporting farmers affected by disasters. For example, in Argentina and Uruguay feasibility studies have been undertaken for meso-insurance based on NDVI index tracking pasture productivity [65,66] designed to cover loss of livestock. This meso-insurance would, when implemented, allow the government to make timely payouts to support livestock owners to maintain their herds in the event of severe drought.

5. Discussion

5.1. Adoption of Remote Sensing in Insurance

This review revealed an apparent contrast between the claimed potential of remote sensing in support of insurance, and the actual adoption of remote sensing by the insurance industry. Forty years of technical literature describing the potential of remote sensing is not backed by evidence for significant uptake by the insurance industry of remote sensing in classical claim-based insurance. In fact, we found reference

in the literature of application of remote sensing in claim-based insurance by the government but not by the insurance industry (Table 2). The adoption of remote sensing in claim-based insurance by government, which is surprising at first sight, is understandable when one realizes that both examples were from the United States where the government provides significant support to the insurance industry. In the case of flood risk management, government facilitates the insurance industry with information that allows better underwriting of flood risk. In the case of crop insurance, the application of remote sensing stems from the concern of government to control fraud in agricultural insurances, which when left uncontrolled inflates government expenditure on subsidies.

Table 2. Summary of papers describing operational application of remote sensing supporting the delivery of operational insurance products.

Type of Insurance	Insurance Application	Description	Reference
Claim	Crop damage assessment	USDA (United States Department of Agriculture) Risk Management Agency using medium resolution remote sensing imagery to verify cases suspect of fraud	[28,29]
	Flood risk stratification	Insurers using Flood Insurance Rate Maps produced by USA Federal Emergency Management Authority	[19,23]
Index	Rangeland productivity	USDA using rainfall and NDVI data to offer pasture and rangeland insurance	[54]
	Livestock loss	Insurers in Kenya using a composite NDVI index as a backbone of index based livestock insurance	[55]

These observations raise the question: why is the private industry reluctant to adopt remote sensing in claim-based insurance? One reason could be that insurers do not publicize the use of remote sensing, because sharing of this information would lead to understanding of the procedures used to verify compliance to contractual obligations, which might stimulate the development of approaches to avert detection. However, the use of such undisclosed information would contradict insurance contracts, which have verification and transparency at their basis. Further, even when applied discretely the use of remote sensing would be revealed sooner or later through the use of remotely sensing in court cases. We are not aware of the widespread use of remote sensing in the settling of disputes between insurers and insured customers and thus consider that private enterprises' uptake of remote sensing in claim-based insurance is low.

An alternative reason to explain this lack of adoption is that most proposed applications of remote sensing in classical insurance aim to automate the industry's existing business processes, for example, the assessment of damage or the underwriting of risk. One of the lessons learned from the introduction of information technology in the second half of the 20th century is the limited success of automation of existing business processes, which has been attributed by Hammer [67] to the fact that such effort frequently does not add value to the industry and its customers. Hammer went on to argue that information technology has much greater potential to add value when obliterating rather than automating existing business processes.

Eliminating existing business processes is exactly what remotely sensed indices and other indices are doing in index insurance. Impartial indices allow insurers to avoid the handling and verification of

claims and the costs imposed by fraud, moral hazard and adverse selection. Potentially, this would allow the industry to enlarge its market while delivering products at lower costs than claim-based insurance and in areas where classical insurance products could not be delivered.

Our review revealed several applications of remotely sensed indices in drought insurance aiming at rangelands and livestock, while several groups are exploring or developing proof of concept to cover the impact of drought on annual cereal crops. Exploring the potential of remote sensing index insurance for non-cereal annual crops like peanuts and cotton seems interesting. For the latter an *ex-ante* assessment of the feasibility for weather station based index insurance has recently been published [68]. Potentially index insurance could also be applied to perennial crops. For example, Lou *et al.* [69] describe an application of thermal remote sensing in monitoring frost damage to tea, and mention index insurance for tea frost damage as a possible application.

5.2. Economics and Financial Sustainability of Remote Sensing Applications in Insurance

The above argument that there are better opportunities for index insurance is based on the assumption that index insurance would be less costly than claim based insurance. While this assumption appears plausible there are to our knowledge no studies assessing and comparing the costs and benefits associated to the use of remote sensing in claim-based and index insurance. An interesting question would be to investigate the effect of adoption of remote sensing on the cost benefits of the insurance product. There appears to be specific potential for value of information approaches [70], which have only recently been explored in the geo-spatial sciences [71]. The costs to consider in such assessment and comparison include the cost of acquisition and processing of imagery, as well as the cost of developing and calibrating indices that relate the remote sensing imagery to the insured agricultural loss. The design of index insurance may be costly when sophisticated modeling is required for establishing relationships with the underlying loss, such as for example, Woodard *et al.* [72], who developed spatial models in an NDVI-based insurance framework to reduce design-related basis risk. Insurers will generally recover these development costs with additional loading, which is a non-recoverable cost to the insured. Benefits from remote sensing information in insurance to consider in cost benefit analysis include; (1) making insurance affordable to low income households; (2) reducing fraud, moral hazard and adverse selection; (3) eliminating the burden of costly verification of claims on-the-ground and (4) enabling faster and cheaper payouts to the insured. Another benefit is that remotely sensed index insurance can provide insurance to farmers in remote areas that conventional crop or livestock insurance cannot serve. Developing formal insurance markets to help manage weather-related risks faced by crop and livestock producers, if applied correctly comes with broader welfare benefits. For example, NDVI based index based livestock insurance in Kenya provides a 36% reduction in distress livestock sales and a 25% reduction in food shortage induced avoidance of meals among pastoralists [73].

Further, the promise of remote sensing in insurance industries depends largely on the financial sustainability of markets for various insurance products. Our research revealed a strong dependence of remote sensing applications in insurance on financial support from government or donors. For example, the uptake of index-insurance by the insurance industry was supported by government in case of the USDA pasture and rangeland insurance in the USA and by development donors in case of the Index Based Livestock Insurance (IBLI) in Kenya. In both cases the insurance premium is kept low with this

support, and markets and adoption of agricultural insurance are likely to reduce or disappear without such financial support.

In developing countries, where many index insurance initiatives emerge, it remains to be seen how sustainable the market for such products will be. This is partly due to the strong dependence on support from development donors, which might be an ephemeral source of funding in the longer run. Given this, there is a need for a dialogue on the role of government in supporting agricultural insurances in the developing world. Moreover, some suggest that farmer demand for insurance products could be low, as rich farmers are able to self-insure, and the poorest farmers that could best benefit from insurance may not be able to afford it [74]. For that reason, new initiatives are developed that incorporate the insurance with a credit scheme, where farmers receive a credit before the season, with the pay-back depending on the index-value of that season. For example, Shee and Turvey [75] reviewed the possibility to combine credit and insurance and applied this concept to loans for insuring pulse crops in India. Hence, the market sustainability for insurance using remote sensing will also depend on how the insurance is embedded in credit facilities that meet farmers' needs.

5.3. Challenges for Remote Sensing in Index Insurance

Notwithstanding the positive outlook for remotely sensed index insurance, we foresee a number of challenges because of technical factors constraining the uptake of remote sensing. The first is data continuity. The need for a steady flow of data that can be relied upon by the insurance industry might limit the widespread development of remote sensing based index insurance. This is because current low-resolution satellite imagery systems do not guarantee continuation of data delivery. For example, the discontinuation of the AVHRR 16 in January 2010 forced the IBLI (Index Based Livestock Insurance) team at ILRI to shift to MODIS. It is clear that regular recurrence of such calamities undermines the potential of remote sensing to serve the insurance industry, and it would be good to consider developing mechanisms to ensure more reliable data delivery in case the insurance industry would mainstream remotely sensed index insurance. Fortunately, the need for data continuity is recognized by the remote sensing community, as well as by space agencies. With current and approved missions such as the Sentinel 2 and 3, Proba-V and Suomi-NPP [76], data continuity is currently assured well beyond 2020. In addition, a number of initiatives exist to combine observations from various sensors to create long-term consistent time series [45–47].

A second challenge of index insurance relates to data quality. Indeed, as a direct result of the high altitude and low exposure time of earth observation sensors, the (raw) measurements obtained from satellite sensors are usually noisy. Noise in optical remote sensing systems stems mainly from undetected (sub-pixel) clouds and poor atmospheric conditions (e.g., haze). This further degrades the already low signal-to-noise ratio of currently employed large swath sensors. As observation conditions are highly variable in space and time, the effects are moreover space-time dependent [77]. Consequently, satellite observations often lack statistical stability prohibiting the conversion of data into usable probabilistic information. Non-stationary differences, if revealed in practice, would suggest that the measures are highly unstable for modeling (and pricing) purposes. This can be overcome in some contexts through a transformation of variables such as the cumulative NDVI metric used for the IBLI livestock insurance [55]. Yet, vegetation indices like NDVI are affected by factors such as soil humidity, and it

has been proposed [78] to use remote sensing products derived from radiative transfer techniques, such as FAPAR (Fraction of Absorbed Photosynthetically Active Radiation), which are less affected by such confounding factors. Nonetheless, should remote sensing and metrics such as NDVI or FAPAR become commonplace in the delivery of index insurance an extended effort into the continuous-time properties of the measure will become increasingly important. Only a few institutions around the world currently offer filtered and gap-filled NDVI time series going beyond very basic compositing techniques.

A third issue relates to the spatial resolution of the earth observation data used. Whereas it is clear that claim-based insurance profits from very high spatial resolution to properly assess damage, for index insurance the dependence of spatial resolution is less clear. For example, with respect to drought insurance, areas affected are large such that with low-resolution data such strong impacts can be readily mapped from space. Indeed, a number of international organizations build since many years successfully on this principle (e.g., in food security early warning). A finer spatial resolution would not necessarily bring additional information if the (meteorological) impact acts at meso-scale or larger. Reliance on lower resolution imagery may however ignore spatial variation within a low-resolution pixel, which could be picked up using finer spatial resolution imagery. For example, if an index-based insurance is provided for agriculture, one could limit the analysis to those (fine resolution) pixels falling within cropland. However, extreme cases ignored (e.g., irrigated crops), in our experience meso- to large-scale meteorological anomalies are usually well retrieved through a number of (observational) scales. Indeed, from our point of view, data quality—and hence the quality of the data pre-processing—as well the available archive, seem of higher importance for index insurance than the spatial detail. One should also not forget that the available rain gauge data used in index insurance are generally representative for areas much larger than a low-resolution satellite pixel.

The final and likely greatest challenge is whether the insurance scheme can effectively limit basis risk. A key requirement to achieve that is to have an index (or a set of complementary indices) that shows high correlation with the losses suffered by farmers or pastoralists. This challenge is composed of two main elements; index construction and calibration options.

Regarding index construction, this review showed that several data could be used, including, but not limited to, satellite-derived vegetation indices (e.g., NDVI) and rainfall estimates. However, even when an initial choice for a data source has been made, a large variety of approaches can be deployed to use that data source. For example Funk *et al.* [79] provide an overview of studies that found different time-integrations of NDVI optimal to predict agricultural yields. Besides temporal integration, choices can also be made regarding the spatial integration of the data source. The spatial integration refers to the size of the aggregation units used, in many cases determined by how data on asset losses for calibration are aggregated. In addition, within a spatial unit, decisions can also be made to limit the spatial integration to areas covered by a land use of interest [80]. These choices are often crucial for the performance of the index vis-à-vis induced losses. For this reason, while existing insurance schemes like IBLI (Section 4.2) have provided insurance following one specific temporal and spatial integration [55], they are continuing efforts to improve this integration further with the purpose to reduce basis risk. We therefore suggest that the choice and optimization of spatio-temporal design parameters is an important area for further research, very likely resulting in region-dependent designs.

Data on agricultural yields or livestock losses are needed for calibrating potential indices and to select an appropriate index (and its spatio-temporal integration) that reduces basis risk. The lack of reliable

crop statistics and long-term agricultural yield data in many developing countries is therefore a key constraint to the uptake of remote sensing in crop insurance. Equally, the lack of livestock loss data creates problems for livestock insurance. Although in some cases, logically relationships may be assumed between agricultural yields and reduced levels of an index like seasonal-integrated NDVI, the impossibility to effectively calibrate this index may result in poor performance of an insurance scheme. Particularly if this would result in no payout to farmers/pastoralists in seasons with high losses, this will have large negative effects on future insurance uptake.

6. Conclusions and Recommendation

The purpose of this paper was to review the state of the art in use of remote sensing in the insurance industry. While there are examples of insurance companies using remote sensing directly or in combination with other indices it remains a curiosity as to why remote sensing has not been adopted more widely by the insurance industry. The adoption of the technology in claim-based insurance is poor, an observation that we attribute to the limited impact of remote sensing techniques on the profitability of the industry. Our analysis suggests that index based insurance has a greater potential for uptake by the industry because the application of remote sensing in index insurance is an example of redesigning the way business is done. It allows for the development of insurance products in areas and to customers that could not be reached before. It thus allows the industry to develop new markets, which could not be serviced without remote sensing. Apart from this the technique also has potential to replace traditional agricultural insurances, because it might be provided at lower costs to the insured and subsidizing sponsors. Remote sensing also has potential to supply information to existing index insurances that currently use other information sources, such as rain gauges or area-averaged yield data, which could be an interesting market because markets for index insurances not using remote sensing are much larger than the current market for remotely sensed index insurance. For this reason—together with other advantages of index insurance—we expect a further growth of opportunities for remote sensing in index insurance.

The discussion identified several issues that need to be addressed to promote the adoption of remote sensing in index insurance. These include the creation or continuation of an enabling environment willing to subsidize the insurance as well as solving several technical challenges in the field of remote sensing. Apart from this, the slow adoption of remote sensing in insurance is also the result of a mutual lack of understanding of the opportunities offered by the remote sensing community and the insurance industry. During this review we realized that although there have been a number of workshops that brought these communities together [44,81,82], there have been very few papers comprehensively reviewing the potential of remote sensing in insurance synthesizing the perspectives in both worlds. We anticipate that this paper assists to fill this gap and support those interested in promoting the adoption of remote sensing in insurance. In this respect, we call for the remote sensing community to consider collaborating more closely with economists, agro-meteorologists and insurers in order to more effectively approach the challenge of developing successful applications of remote sensing in insurance.

Acknowledgments

We thank the four anonymous reviewers and the editor in chief for their constructive comments that helped to improve the article. We also wish to acknowledge the support of the CGIAR Research Programs for Drylands Systems (CRP 1.1) and for Water, Land and Ecosystems (CRP 5).

Author Contributions

Jan De Leeuw conceptualized and led the writing, Anton Vrieling, Apurba Shee, Kiros Hadgu, Chandrashekhara Biradar, Clement Atzberger; Calum Turvey contributed to the writing. Humphrey Keah managed the database and organized references and citations.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Towery, N.G.; Eyton, J.R.; Changnon, S.A.; Dailey, C.L. *Remote Sensing of Crop Hail Damage. Report of Research to the Country Companies* (Referred to in Towery, 1980); 1975; p. 29.
2. Towery, N.G. *Some Applications of Remote Sensing of Crop-Hail Damage in the Insurance Industry*; Circular 143/80 of the Illinois State Water Survey, Illinois Institute of Natural Resources: Urbana, IL, USA, 1980; p. 17.
3. Smith, K. *Environmental Hazards Assessing Risk and Reducing Disasters*, 6th ed.; Routledge: Abingdon, UK, 2013; p. 371.
4. Young, F.; Chandler, O.; Apan, A. Crop Hail Damage: Insurance Loss Assessment using Remote Sensing. In Proceedings of the Remote Sensing and Photogrammetry Society Conference, Aberdeen, UK, 7–10 September 2004.
5. Rojas, O.; Vrieling, A.; Rembold, F. Assessing drought probability for agricultural areas in Africa with coarse resolution remote sensing imagery. *Remote Sens. Environ.* **2011**, *115*, 343–352.
6. Wikipedia Insurance. Available online: <http://en.wikipedia.org/wiki/Insurance> (accessed on 5 November 2014).
7. Herbold, J. New approaches to agricultural insurance in developing economies. In *Finance for Food: Towards New Agricultural and Rural Finance*; Kohn, D., Ed.; Available online: http://link.springer.com/chapter/10.1007%2F978-3-642-54034-9_9#page-1 (accessed on 5 November 2014).
8. Triplet, J.E.; Bosworth, B.P. “Baumol’s disease” has been cured: IT and multifactor productivity in US service industries. In *The New Economy and Beyond, Past, Present and Future*; Jansen, D.W., Ed.; Edward Elgar Publishing: Cheltenham, UK, 2006; pp. 34–71.
9. ACIL Tasman. The value of spatial information: The impact of modern spatial information technologies on the Australian economy. In *A Report Prepared for the CRC for Spatial Information and ANZLIC—The Spatial Information Council*; ACIL Tasman: Melbourne, Australia, 2008; pp. 1–98.

10. Bhattamishra, R.; Barrett, C.B. Community-Based risk management arrangements: A review. *World Dev.* **2010**, *38*, 923–932.
11. Herbold, J. Index insurance in agriculture, the (re) insurers perspective. In *The Challenges of Index-Based Insurance for Food Security in Developing Countries*; Gommès, R., Kayitakire, F., Eds.; Joint Research Centre: Ispra, Italy, 2013; pp. 47–54.
12. Alderman, H.; Haque, T. Countercyclical safety nets for the poor and vulnerable. *Food Policy* **2006**, *31*, 372–383.
13. Barnett, B.J. Agricultural index insurance products: Strengths and limitations. In *Agricultural Outlook Forum*; United States Department of Agriculture: Arlington, VA, USA, 2004; p. 41.
14. World Bank. *Managing Agricultural Production Risk*; The World Bank, Agriculture and Rural Development Department: Washington, DC, USA, 2005; p. 129.
15. Mahul, O.C.; Stutley, C.J. *Government Support to Agricultural Insurance: Challenges and Options for Developing Countries*; World Bank: Washington, DC, USA, 2010.
16. Mahul, O. Agricultural insurance for developing countries—The role of governments. In Proceedings of the FARM—Pluriagri Conference on Insuring Agricultural Production, Paris, France, 18 December 2012.
17. Mathieu, P.P. Space for Insurance. *Environmental Finance*. Available online: http://www.eomd.esa.int/files/document/131-176-149-30_200562910165.pdf (accessed on 5 November 2014)
18. Tapiador, F.J.; Turk, F.J.; Petersen, W.; Hou, A.Y.; Garcia-Ortega, E.; Machado, L.A.T.; Angelis, C.F.; Salio, P.; Kidd, C.; Huffman, G.J. Global precipitation measurement: Methods, datasets and applications. *Atmos. Res.* **2012**, *104*, 70–97.
19. Damron, J.J. *Comparing Digital Flood Insurance Rate Maps (DFIRMS) to Interferometric Synthetic Aperture Radar (IFSAR) Products*; U.S. Army Engineer Research and Development Center: Alexandria, VA, USA, 2000.
20. Sanders, R.; Shaw, F.; MacKay, H.; Galy, H.; Foote, M. National flood modelling for insurance purposes: Using IFSAR for flood risk estimation in Europe. *Hydrol. Earth Syst. Sci.* **2005**, *9*, 449–456.
21. Bach, H.; Appel, F.; Fellah, K.; de Fraipont, P. Application of flood monitoring from satellite for insurance. In Proceedings of the International Geoscience and Remote Sensing Symposium (IGARSS), Seoul, Korea, 25–29 July 2005; Volume 1, pp. 63–66.
22. Murtach, J.; Cheesman, P. Laser altimetry and flood risk assessment: Practical application of laser altimeter data in the insurance industry. *Geomat. Info Mag.* **1999**, *13*, 6–9.
23. Flood Insurance Rate Map (FIRM). Available online: <http://www.fema.gov/floodplain-management/flood-insurance-rate-map-firm> (accessed on 21 April 2013).
24. Peters, A.J.; Griffin, S.C.; Vina, A.; Ji, L. Use of remotely sensed data for assessing crop hail damage. *Photogramm. Eng. Remote Sens.* **2000**, *66*, 1349–1355.
25. Smith, A.M.; Daub, N.; Nadeau, C. Assessing hail damage in agricultural crops using MERIS data. In Proceedings of the 26th Canadian Symposium on Remote Sensing, Wolfville, NS, Canada, 14–16 June 2005; pp. 365–371.
26. Apan, A.; Chandler, O.; Young, F.; Maraseni, T. Opportunities and limitations of remote sensing for crop loss (hail damage) assessment in the insurance industry. In Proceedings of the Spatial Sciences Institute Biennial Conference: Spatial Intelligence, Innovation and Praxis (SSC2005), Melbourne, Australia, 14–16 September 2005.

27. Felix, M.O.K.P. Correlation of polarimetric radar hail signature with MODIS satellite ground truth data. Colorado state university's chill radar REU program. In Proceedings of the 21st AMS Conference on Hydrology, San Antonio, TX, USA, 14–18 January 2007.
28. Little, B.; Schucking, M.; Gartrell, B.; Chen, B.; Olson, S.; Ross, K.; Jenkerson, C.; KcKellip, R. Remote sensing and US crop insurance program integrity: Data mining satellite and agricultural data. *WIT Trans. Inf. Commun. Technol.* **2007**, *30*, 151–159.
29. Burnett, J. *High Tech Methods Crack Farm Insurance Cheats*. Available online: <http://www.npr.org/templates/story/story.php?storyId=5013871> (accessed on 5 November 2014).
30. Capellades, M.A.; Reigber, S.; Kunze, M. Storm damage assessment support service in the US Corn belt using RapidEye satellite imagery. *Proc. SPIE* **2009**, *7472*, doi:10.1117/12.830393.
31. Radar-Based Remote Sensing Technology Revolutionizes Crop Insurance, 2011. Available online: https://www.allianz.com/en/press/news/business/insurance/news_2011-07-27.html (accessed on 28 April 2014).
32. Canaseva, A.; Dagorne, A. Assessment of forest fire zones by airborne colour infrared remote sensing. *Photo Interpret.* **1985**, *85*, 27–34.
33. Lentile, L.B.; Holden, Z.A.; Smith, A.M.S.; Falkowski, M.J.; Hudak, A.T.; Morgan, P.; Lewis, S.A.; Gessler, P.E.; Benson, N.C. Remote sensing techniques to assess active fire characteristics and post-fire effects. *Int. J. Wildland Fire* **2006**, *15*, 319–345.
34. Mouillot, F.; Schultz, M.G.; Yue, C.; Cadule, P.; Tansey, K.; Ciaï, P.; Chuvieco, E. Ten years of global burned area products from space borne remote sensing—A review: Analysis of user needs and recommendations for future developments. *Int. J. Appl. Earth Obs. Geoinf.* **2014**, *26*, 64–79.
35. Shacklock, R. Remote sensing aids fire damage assessment: Innovative digital imagery technology is used for speedy and effective responses to timber plantation fires in South Africa. *GEO Connex.* **2007**, *6*, 32–33.
36. Halcrow, H.G. *The Theory of Crop Insurance*. Ph.D. Dissertation, University of Chicago, Chicago, IL, USA, 1948.
37. GFDRR. National agricultural insurance scheme in India. In *Disaster Risk Financing and Insurance Case Study*; GFDRR: Washington, DC, USA, 2011; pp. 1–2.
38. Glauber, J.W. Crop insurance reconsidered. *Am. J. Agric. Econ.* **2004**, *86*, 1179–1195.
39. Bardsley, P.; Abey, A.; Davenport, S. The economics of insuring crops against drought. *Aust. J. Agric. Econ.* **1984**, *28*, 1–14.
40. Quiggin, J. A note on the viability of rainfall insurance. *Aust. J. Agric. Econ.* **1986**, *30*, 63–69.
41. Smith, V.H.; Watts, M. *Index Based Agricultural Insurance in Developing Countries: Feasibility, Scalability and Sustainability*; Department of Agricultural Economics and Economics, Montana State University: Bozeman, MT, USA, 2011; p. 40. Available online: <http://www.ibrarian.net/navon/page.jsp?paperid=17443900> (accessed 5 November 2014).
42. International Fund for Agricultural Development. *Weather Index-Based Insurance in Agricultural Development: A Technical Guide*; IFAD: Rome, Italy, 2011; p. 66.
43. Miranda, M.J.; Farrin, K. Index insurance for developing countries. *Appl. Econ. Perspect. Policy* **2012**, *34*, 391–427.

44. Gommès, R.; Kayitakire, F. The challenges of index-based insurance for food security in developing countries. In Proceedings of Technical Workshop Organised by the EC Joint Research Centre (JRC) and the International Research Institute for Climate and Society (IRI, Earth Institute, Columbia University), JRC, Ispra, Italy, 2–3 May 2012.
45. Vrieling, A.; Meroni, M.; Shee, A.; Mude, A.G.; Woodard, J.; de Bie, C.A.J.M. Historical extension of operational NDVI products for livestock insurance in Kenya. *Int. J. Appl. Earth Obs. Geoinf.* **2014**, *28*, 238–251.
46. Hollmann, R.; Merchant, C.J.; Saunders, R.; Downy, C.; Buchwitz, M.; Cazenave, A.; Chuvieco, E.; Defourny, P.; de Leeuw, G.; Forsberg, R. The ESA climate change initiative satellite data records for essential climate variables. *Bull. Am. Meteorol. Soc.* **2013**, *94*, 1541–1552.
47. Pedelty, J. Generating a long-term land data record from the AVHRR and MODIS instruments. In Proceedings of the IGARSS Conference “Sensing and Understanding our Planet”, Barcelona, Spain, 23–27 July 2007.
48. Hobbs, T.J. The use of NOAA-AVHRR NDVI data to assess herbage production in the arid rangelands of central Australia. *Int. J. Remote Sens.* **1995**, *16*, 1289–1302.
49. Goward, S.N.; Tucker, C.J.; Dye, D.G. North-American vegetation patterns observed with the NOAA-7 advanced very high-resolution radiometer. *Vegetatio* **1985**, *64*, 3–14.
50. Al-Bakri, J.T.; Taylor, J.C. Application of NOAA AVHRR for monitoring vegetation conditions and biomass in Jordan. *J. Arid Environ.* **2003**, *54*, 579–593.
51. Tucker, C.J.; Vanpraet, C.L.; Sharman, M.J.; Vanittersum, G. Satellite remote sensing of total herbaceous biomass production in the Senegalese Sahel: 1980–1984. *Remote Sens. Environ.* **1985**, *17*, 233–249.
52. Prince, S.D. Satellite remote-sensing of primary production—Comparison of results for Sahelian grasslands 1981–1988. *Int. J. Remote Sens.* **1991**, *12*, 1301–1311.
53. Fuller, D.O. Trends in NDVI time series and their relation to rangeland and crop production in Senegal, 1987–1993. *Int. J. Remote Sens.* **1998**, *19*, 2013–2018.
54. Hellmuth, M.E.; Osgood, D.E.; Hess, U.; Moorhead, A.; Bhojwani, H. *Index Insurance and Climate Risk: Prospects for Development and Disaster Management*; Climate and Society No 2; International Research Institute for Climate and Society (IRI): New York, NY, USA, 2009; p. 112.
55. Chantararat, S.; Mude, A.G.; Barrett, C.B.; Carter, M.R. Designing index-based livestock insurance for managing asset risk in northern Kenya. *J. Risk Insur.* **2013**, *80*, 205–237.
56. Rao, K.N. Index based crop insurance. *Agric. Sci. Proced.* **2010**, *1*, 193–203.
57. Bokusheva, R.; Spivak, L.; Vitkovskaya, I.; Kogan, F.; Batyrbayeva, M. Application of remote-sensing data in the index-based insurance design. In Proceedings of the 2012 IEEE International Geoscience and Remote Sensing Symposium (IGARSS), Munich, Germany, 22–27 July 2012.
58. Bobojonov, I.; Aw-Hassan, A.; Sommer, R. Index-based insurance for climate risk management and rural development in Syria. *Clim. Dev.* **2013**, *6*, 166–178.
59. Pantakar, M. *Comprehensive Risk Cover through Remote Sensing Techniques in Agriculture Insurance for Developing Countries: A Pilot Project*; Micro-Insurance Innovation Facility, International Labour Organization: Geneva, Switzerland, 2011; p. 34.

60. Makaudze, E.M.; Miranda, M.J. Catastrophic drought insurance based on the remotely sensed normalised difference vegetation index for smallholder farmers in Zimbabwe. *Agrekon* **2010**, *49*, 418–432.
61. Turvey, C.G.; McLaurin, M.K. Applicability of the Normalized Difference Vegetation Index (NDVI) in index-based crop insurance design. *Weather Clim. Soc.* **2012**, *4*, 271–284.
62. Johnson, L. Agricultural index insurance through remote sensing: Experiences from east Africa. In *Remote Sensing Beyond Images*; 2013. Available online: <http://www.slideshare.net/CIMMYT/l-johnson-sfsa-remote-sensing-public> (accessed on 5 November 2014).
63. Kidd, C.; Levizzani, V. Status of satellite precipitation retrievals. *Hydrol. Earth Syst. Sci.* **2011**, *15*, 1109–1116.
64. Dinku, T.; Ceccato, P.; Connor, S.J. Challenges of satellite rainfall estimation over mountainous and arid parts of east Africa. *Int. J. Remote Sens.* **2011**, *32*, 5965–5979.
65. World Bank. *NDVI Pasture Index-Based Insurance for Livestock Producers in South West Buenos Aires Province*; Feasibility Study: Final Report; World Bank: Washington, DC, USA, 2012.
66. World Bank. *NDVI Pasture Index-Based Insurance for Livestock Producers in URUGUAY*; Feasibility Study: Final Report; World Bank: Washington, DC, USA, 2013.
67. Hammer, M. Reengineering work: Don't automate, obliterate. *Har. Bus. Rev.* **1990**, *July/August*, 104–112.
68. Leblois, A.; Quirion, P.; Sultan, B. Weather index-based insurance in a cash crop regulated sector: *Ex-ante* evaluation for cotton producers in Cameroon. *Research Paper 21. Micro Insurance Innovation Facility, International Labour Office*, Geneva, 2013. Available online: <http://www.ilo.org/public/english/employment/mifacility/download/repaper21.pdf> (accessed on 5 November 2014).
69. Lou, W.P.; Ji, Z.W.; Sun, K.; Zhou, J.N. Application of remote sensing and GIS for assessing economic loss caused by frost damage to tea plantations. *Precis. Agric.* **2013**, *14*, 606–620.
70. Macauley, M. The value of information: Measuring the contribution of space-derived earth science data to resource management. *Space Policy* **2006**, *22*, 274–282.
71. Bouma, J.A.; Van Der Woerd, H.J; Kuik, O.J. Assessing the value of information for water quality management in the North Sea. *J. Env. Manag.* **2009**, *90*, 1280–1288.
72. Woodard, J.; Shee, A.; Mude, A.G. *A Spatial Econometric Approach to Scalable Index Insurance against Drought Related Livestock Mortality in Kenya*; International Livestock Research Institute: Nairobi, Kenya, 2014; p. 29.
73. Janzen, S.A.; Carter, M.R. *After the Drought: The Impact of Microinsurance on Consumption Smoothing and Asset Protection*; NBER Working Paper Series 19072; National Bureau of Economic Research: Cambridge, MA, USA, 2013; p. 27.
74. Binswanger-Mkhize, H.P. Is there too much hype about index-based agricultural insurance? *J. Dev. Stud.* **2012**, *48*, 187–200.
75. Shee, A.; Turvey, C.G. Collateral-free lending with risk-contingent credit for agricultural development: Indemnifying loans against pulse crop price risk in India. *Agric. Econ.* **2012**, *43*, 561–574.
76. Belward, A.S.; Skøien, J.O. Who launched what, when and why; trends in global land-cover observation capacity from civilian earth observation satellites. *ISPRS J. Photogramm. Remote Sens.* **2014**, in press.

77. Atzberger, C.; Eilers, P.H.C. Evaluating the effectiveness of smoothing algorithms in the absence of ground reference measurements. *Int. J. Remote Sens.* **2011**, *32*, 3689–3709.
78. Meroni, M.; Kayitakire, F.; Brown, M. Remote sensing of vegetation: Potential applications for index insurance. In *The Challenges of Index-Based Insurance for Food Security in Developing Countries*; Gommaes, R., Kayitakire, F., Eds. Joint Research Centre: Ispra, Italy, 2013; pp. 238–245.
79. Funk, C.; Budde, M.E. Phenologically-Tuned MODIS NDVI-based production anomaly estimates for Zimbabwe. *Remote Sens. Environ.* **2009**, *113*, 115–125.
80. Genovese, G.; Vignolles, C.; Negre, T.; Passera, G. A methodology for a combined use of normalised difference vegetation index and Corine land cover data for crop yield monitoring and forecasting. A case study on Spain. *Agronomie* **2001**, *21*, 91–111.
81. ESA. *Industry Workshop on Satellite EO for the Insurance Sector: New Technologies and Opportunities*; European Space Agency ESA/ESRIN: Frascati, Italy, 2012; p. 19.
82. Ebel, U. Requirements for EO Service in the Insurance Industry. Available online: http://earth.eo.esa.int/workshops/Insurance/files/EO_services_report.pdf (accessed on 6 November 2014).

© 2014 by the authors; licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution license (<http://creativecommons.org/licenses/by/4.0/>).