A Methodological Proposal to Support Estimation of Damages from Hailstorms Based on Copernicus Sentinel 2 Data Times Series

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Abstract. Hail is one of the risks that most frightens farmers and one of the few currently insured climatic-related phenomena. In the last years, a significant increase occurred of adverse events affecting crops, highlighting that ordinary strategies of insurance companies should migrate to a more dynamic management. In this work a prototype of service based on remotely sensed data is presented aimed at supporting evaluation of hail impacts on crops by mapping and qualifying areas damaged by hail. Further, a comparison was done testing effectiveness of approaches based on short term (i.e. with reference to images acquired immediately after the event) and long term (i.e. with reference to images acquired close to crop harvest) analysis. Investigation was solicited by the Reale Mutua insurance company and focused on a strong hailstorm occurred on 6th July 2019 in the Vercelli province (Piemonte - NW Italy). The analysis was based on Copernicus Sentinel-2 level 2A imagery. A times series made of 29 NDVI maps was generated for the growing season 2019 (from March to October) and analyzed at pixel level looking for NDVI trend anomalies possibly related to crop damages. Phenological behavior of damaged crops (NDVI local temporal profile) was compared with those of unharmed fields to verify and assess the impact of the phenomenon. Results showed evident anomalies along the local NDVI temporal profile of damaged cropped pixels, permitting a fine mapping of the affected areas. Surprisingly, short and long term approaches led to different conclusions: some areas, appearing significantly damaged immediately after the event, showed a vegetative recover with the proceeding of the growing season (temporary damages). Differently, some others showed that damages detected after the events never turned into a better situation (permanent damages). This new information could drive to considered a revision of the ordinary insurance procedures that are currently used by companies to certify and quantify damages of crops after adverse events. It can therefore said that, the high temporal resolution of the Copernicus Sentinel 2 mission can significantly contribute to improve evaluating procedures in the insurance sector by introducing temporal variables.

Keywords: Crop insurance · NDVI · Hail in agriculture · Risk management in agriculture · Remote sensing-based services

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1 Introduction

All economic activities are exposed to risk factors, and agriculture is probably the most vulnerable one being sensitive to several exogenous events, not controllable by farmers. Hail is one of the risks that most frightens farmers and, consequently, one of the few insured climatic-related phenomena. In the last years, a significant increase occurred of adverse events affecting crops, highlighting that ordinary strategies of insurance companies should mi-grate to a more dynamic management. According to FAO, between 2003 and 2013 agriculture absorbed 25% of the total impact of climate disasters in developing countries. These numbers are significantly higher than the previously reported ones and suggest to strengthen planning actions and increase investments in disaster risk reduction. The likelihood of worsening conditions will increase if no improvement of the resilience of the agricultural sector is achieved and specific investments to strengthen food security and productivity are done [1]. Agriculture is an essential practice for growth and development of societies, but it is exposed to multiple risk factors [2]. The production risk is related to the possibility that the quantity or quality of products may be lower than expected as a result of adverse weather conditions or phytopathogens. The financial risk is related to the possibility of bankruptcy due to lack of financial reserves to repay debts or to advance expenses. The market risk is related to the possibility of not finding outlets at expected prices or of not being able to find production factors at favourable prices. The institutional risk is related to the possibility that rules and regulations may change unexpectedly as a result of certain production decisions. The personal risk is related to the ability of the farmer and other permanent employees to continue to carry out their activities effectively. Risk management tools are therefore mandatory and should be addressed to take care about crop diversification, utilization of resistant varieties, irrigation practices, adoption of anti-hail coverings, utilization of physical barriers against insects, use of chemical products (e.g. pesticides or herbicides), finalization of supply chain contracts and underwriting of insurance policies. When insurances transfer part of the income risk out of the farmers' portfolio they can afford to invest in high-risk/high-yield technologies such as improved seeds and inputs [3, 4]. The role of insurance tools for risk management in agriculture is increasing [5, 6]. The insurance is based on a contract between the insurer and the economic agent (e.g. the farmer). The latter pays a premium (i.e. a cash sum) to receive, in case of adverse events, compensation for losses due to specific risks covered by the insurance contract. Agricultural insurance is fairly well developed in US and Canada, where no shortage of issues is present related to stimulation of demand for insurance [7–9]; in Europe, although it has been growing in recent years, it still presents some limitations. The European agricultural insurance system is very diversified: different types of instruments and public intervention measures characterize the European scenario. In Italy, insurance market is still underdeveloped, despite strong political attention and large subsidies (up to 80% of the insurance premium) paid to farmers. The participation (i.e. the percentage of farmers taking out agricultural insurance contracts) is around 15%. There are different types of contracts: single risk, multiple risk and multi-risk contracts. Since 2004, single risk policies are no longer supported by state subsidies to favour multi and multi-risk

policies. Multi-risk policies are also known as yield policies: farmers are compensated for yield losses with reference to historical yields calculated over previous years. These policies, despite being subsidized and more attractive, are not very widespread, even though the trend of contracts is increasing. Among the new policies there are the so called indexed ones, that operates with reference to: a) proper indices (e.g. weather related, like temperature and humidity regimes; or, possibly in future, remote sensing based); b) attribute thresholds (e.g. maximum or minimum average temperatures). Positive or negative deviations from a reference threshold will result in the payment of the premium by the insurance to the farmer. In many countries, governments are showing great interest in these new types of insurance policies, and many pilot projects are promoted worldwide [10–12]. Technologically innovative insurance programs are currently privileging "index insurances" that link payments to environmentally based proxy variables instead of losses. These are announced as promising strategies for reducing poverty and improve climate risk management and system resilience especially in countries that are heavily dependent on smallholder agriculture [13, 14]. In future, insurance policies are expected to focus on optimization of the efficiency of the company's resources for both economic performance and climate/environmental impacts mitigation [15]. In this context, some insurance companies are currently testing new strategies to increase business profitability, to attract a greater number of customers and to be competitive and innovative in the market. Satellite remote sensing is one of the new tools that can be proficiently used in agriculture. Free of charge or low price satellite data can be an excellent starting point for the analysis of large areas, especially if completed with ground data [16, 17]. Satellite images can be useful to support the estimation of damage caused by extreme weather events such as floods, hail or drought [18], to estimate the loss of agricultural production due to climate change [19, 20] and to manage risk in forested and urban green areas [21, 22]. The future potential of index-based insurance policies is very high; expectation is that insurance expert ground surveys could be activated with reference to preventive controls operated by remotely sensed data. For all of the false claims (detected by comparison between farmer's claim and satellite based information), insurance company could save the cost of the expert's report. Savings could consequently, reduce the cost of insurance fees by offering farmers better conditions than at present [23]. In this work a prototype service based on remotely sensed data is presented aimed at supporting evaluation of hail impacts on crops by mapping and qualifying areas damaged by hail. Further, a comparison was done testing effectiveness of approaches based on short term (i.e. with reference to images acquired immediately after the event) and long term (i.e. with reference to images acquired close to crop harvest) analysis. This study was suggested by the Reale Mutua insurance company and was addressed to analyze effects of a strong hailstorm occurred on 6th July 2019 in the Vercelli province (Piemonte - NW Italy), where rice is the dominating crop. Copernicus Sentinel-2 level 2A imagery was used for this purposes. It is worth to highlight that, even if the proposed methodology concerns the Vercelli province area, results can be thought globally valuable, i.e. applicable in any part of the world (cloudiness permitting).

2 Materials and Methods

2.1 Study Area

Reale Mutua insurance company reported a strong hailstorm occurred on 6th July 2019 in the Vercelli province (Piemonte - NW Italy, Fig. 1). Rice cultivation plays a leading role in the agricultural local context. The area has a typically temperate continental climate, where NW Alps gradually determines a temperature reduction while altitude rises. The entire surface affected by the hail was not known by Reale Mutua.

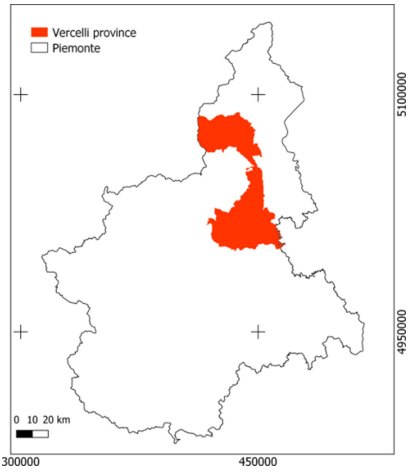

Fig. 1. The study area is located in Vercelli, NW Italy (Reference frame: WGS 84 UTM 32N).

2.2 Available Data

For this work, 29 Sentinel 2 Level-2A images were obtained from the Copernicus Open Access Hub geoportal (scihub.copernicus.eu). They are supplied as 100 × 100 km^2 tiles orthoprojected in the WGS84 UTM reference frame [24]. Level-2A products are supplied already calibrated in "at-the-bottom of the atmosphere" reflectance (BOA), guaranteeing immediate usability for land applications. Table 1 shows main technical specifications of S2 MSI (Multi Spectral Instrument).

Table 1. Sentinel-2 characteristics

Launch date	23/06/2015
Orbit height	786 km
Geometric resolution	b2–b4, b8: 10 m
	b5–b7, b8a, b11, b12: 20 m
	b1, b9, b10: 60 m
Radiometric resolution	12 bit
Spectral resolution	13 bands
Temporal resolution	5 days

Reale Mutua provided a vector map representing some reference fields: some damaged by hail during the event of 6th July 2019; some others unharmed (Fig. 2). Additionally some ground information were supplied too (Table 2).

Table 2. Characteristics of the unharmed and damaged fields (D = damaged; ND = not damaged)

State	Municipality	Crops	Area (ha)	ID
ND	Vercelli	Rice	6.76	–
	Prarolo	Soybean	5.08	–
	Prarolo	Soybean	7.14	–
	Prarolo	Wheat	8.21	–
	Borgo Vercelli	Corn	17.49	–
D	Vercelli	Soybean	17.46	1
	Vercelli	Soybean	13.66	2
	Vercelli	Wheat	19.99	3
	Vercelli	Rice	14.18	4
	Vercelli	Rice	7.16	5
	Vercelli	Corn	10.97	6

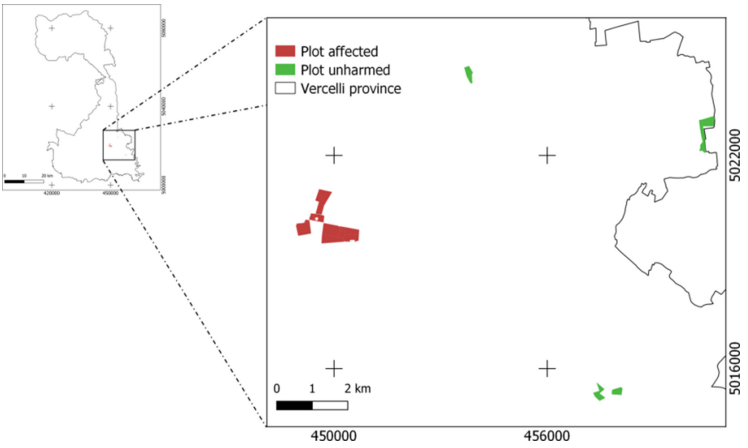

Fig. 2. Fields provided by Reale Mutua. In blue unharmed fields (ND), in red fil damaged (Reference frame: WGS 84 UTM 32N). (Color figure online)

2.3 Procedure

Many studies have already explained the importance of remote sensing in agriculture [25–29] introducing specific spectral indexes like EVI (Enhanced Vegetation Index), SAVI (Soil-Adjusted Vegetation Index), NDVI (Normalized Difference Vegetation Index) and many others [30–34]. In this work the authors choose NDVI because it is

well suited to the study area proposed by the insurance company and it works better than other indices featured in literature. Reliability, convenience and ease of use of data are extremely important for external users like insurance company can be.

Leprieur affirms that NDVI (Eq. 1) is a vegetation index that can be used for retrieval of vegetation canopy biophysical properties [35]; consequently, it can be reasonably thought to be used for the new index-based crop insurance design [36, 37] being a good predictor of crop yield [38–40].

$$\mathrm{NDVI} = \frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + \rho_{RED}} \tag{1}$$

where ρ_{NIR} and ρ_{RED} are respectively the NIR (band 8 of S2) and RED (band 4 of S2) at-the-ground reflectances. NDVI negative values are related to water/snow surfaces, NDVI values close between 0.1 and 0.25 refer to bare and dry soils, highly positive values (>0.4) refer to vegetated surfaces characterized by photosynthetic activity (earthobservatory.nasa.gov). With respect to vegetated surfaces (e.g. crops), comparison of NDVI values before and after an occurred catastrophic event can generate good prediction and mapping of damaged areas [41]. Nevertheless, this approach neglects the reaction of crops to the event. Some crops, in fact, that appear as damaged immediately after the event, at the end of the season can, however, provide an excellent production. Obviously, plants must have the necessary time to fully resume all their functions. In other words, the time of the damage along the growing season of crop is more important than the instantaneous intensity of the event. For example, during flowering and before harvesting crop are more sensitive event occurs damages could be highly relevant for the final production. For this reason, authors retain that remote sensing based deductions should be done with reference to different investigations: one close to the event (short term analysis) and one for the remaining time separating the date of the event from the harvest (long term analysis). According to these premises, in this work, an NDVI time series, covering the entire growing season of the investigated crops, was generated and assessed.

Damaged Fields Mapping

Hailstorm area was detected by producing NDVI difference (DM1 = after-before) calculated by grid differencing using the available "good" NDVI maps closer (before and after) to the event. NDVI maps of 16/07/2019 and 06/07/2019 were selected showing the post- and pre-event situation, respectively. Destructive action of hail on crops is expected to lower local NDVI values in damaged fields. Consequently, DM1 should show positive and negative values for unharmed and damaged fields, respectively. It is worth to remind that, only significant NDVI differences can be related to an actual occurred change. According to literature [42], only DM1 values (absolute value) > 0.02 were assumed as significant, and, consequently, reliable. To automatically map damaged and not-damaged fields, with reference to DM1 a threshold value of −0.05 was applied, admitting that values < −0.05 correspond to damaged pixels.

Level of Damage

Phenological behavior of damaged crops (averaged for each individual plot) was assumed to be well represented by the correspondent NDVI temporal profile; to verify

and assess the degree of damage, it was therefore compared with the NDVI profile of close not-damaged fields looking for long-term effects on crop production. In fact, damaged crops can possibly recover, totally or partially, their health after a while moving towards a good production anyway. Degree of damage and recover can also vary in space within the same field, making damage effects not similar in spatial distribution. This is a very common situation when exploring hail damages, that are known to be very local and fast changing in space.

To answer the first question, a long-term analysis was achieved comparing by differencing the pre-event scene (6/7/2019) with one acquired one month after the event (5/8/2019). A new NDVI difference map was generated (hereinafter called DM2). Nevertheless, sometimes, long-term analysis is not enough to determine the remaining/recovered vitality of crops; it is possible that positive DM2 values are false positives; in fact, died plants can be substituted by a different vegetation type, like weeds, that can determine positive DM2 values. For this reason a "single shot" difference (even though on long-term basis) can be not enough to describe the actual occurring phenomena. Conversely, it is essential to monitor crop during along its entire phenological development, i.e. with reference to its complete NDVI local profile. An accurate analysis of NDVI profile can be greatly helpful to correctly interpret positive DM2 values.

As far as spatial distribution of damage within the field is concerned, the local anomaly of NDVI, $PA_i(t)$, was computed at field level by Eq. 2, for both the post-event dates (16/7/2019, 5/8/2019). Only damaged fields were taken into account.

$$PA_i(t) = \frac{a_i(t)}{\mu_j(t)} \tag{2}$$

where $a_i(t)$ is the NDVI value of a single pixel within the damaged field at the t day and $\mu_j(t)$ the NDVI mean value of that field at the same t day. For some of the investigated fields, a map of $PA(t)$ was therefore generated to make possible to locally tune the average damage caused by hail. Pixels showing a PA value > 1 indicates that suffered from a weak damage in respect of the others; PA value < 1 refer to those areas within the field that were heavily damaged. PA map can be therefore useful to farmer to understand how calibrate agronomic operations; to insurance company to define the compensation for the damage in case the impact of hail is only on a portion of the field. The driving value to decide if the damage is significant or not within the field is, obviously, its mean NDVI value.

3 Results and Discussion

Damaged Field Mapping

The area potentially damaged by hail during the explored event, was mapped (Fig. 5) according to DM1 (Fig. 4). Compared NDVI maps are shown in Fig. 3 (16/07/2019 and 06/07/2019). All those areas showing a DM1 value lower than −0.05 were labeled as "damaged" and resulted in 1568 ha. Results were compared with the reference fields (damaged and not-damaged) supplied by Reale Mutua showing a total consistency (Fig. 6).

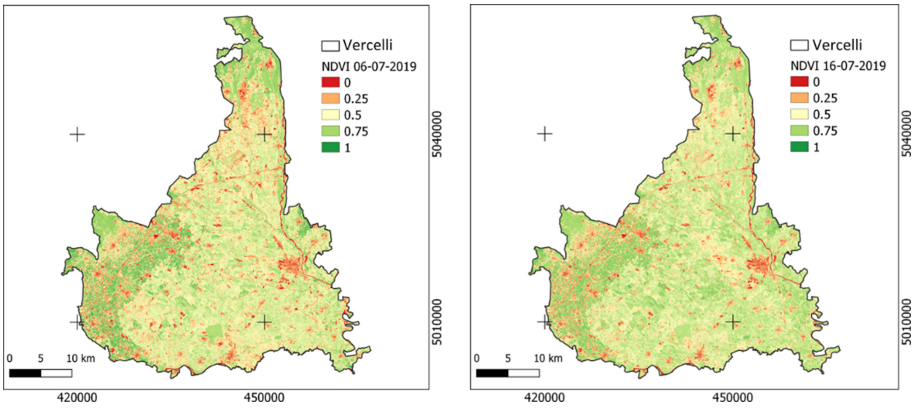

Fig. 3. NDVI map of 16th July (left) and map of 6th July (right). Reference frame: WGS 84 UTM 32N.

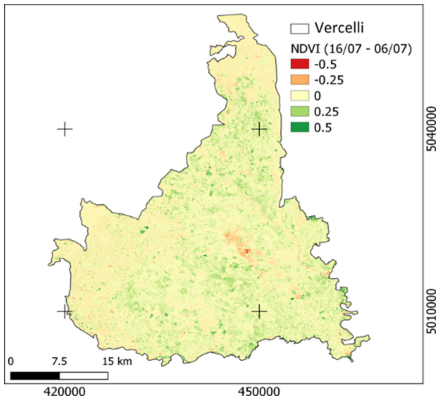

Fig. 4. NDVI difference map (DM1) obtained by differencing between the NDVI map of 16th July and that of 6th July. Reference frame: WGS 84 UTM 32N.

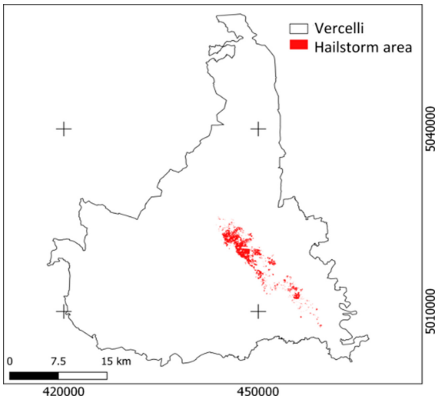

Fig. 5. Map of the areas damaged by the hailstorm of July 6th 2019. Reference frame: WGS 84 UTM 32N.

Level of Damage

To quantify the level of damage caused by hail the ordinary change detection approaches was adopted based on the comparison a single couple of images (after – before). DM1 and DM2 were therefore computed. With reference to DM1 all fields that, according to Reale Mutua data, were declared as damaged confirmed to fall in the "damaged" area as mapped by satellite. An exception came for the soybean field in the North side and fro the rice field in the East side (Fig. 7-left). In fact, these fields were the only ones presenting positive DM1 values (Table 3). Differently, while looking at

DM2, some differences can be observed (Fig. 7-right). On August 5th (about one month after the hailstorm) a recovery of local vegetation seemed to be occurred, corn and wheat fields excluded. With specific focus on wheat, a negative DM2 value was expects since, in the area, harvest is normally scheduled around 10th July. Consequently, the only crop that after one month from the event showed weak negative DM2 values was corn (Table 3).

Table 3. Average NDVI difference in the short (DM1) and long term (DM2) for each damaged field

Fields	Area (ha)	Average NDVI difference in the short term	Average NDVI difference in the long term
Soybean Nord	17.46	0.08	0.22
Soybean West	13.66	−0.05	0.19
Rice East	14.18	0.01	0.22
Rice in the middle	7.16	−0.06	0.09
Corn	10.97	−0.17	−0.20
Wheat	19.99	−0.07	0.03

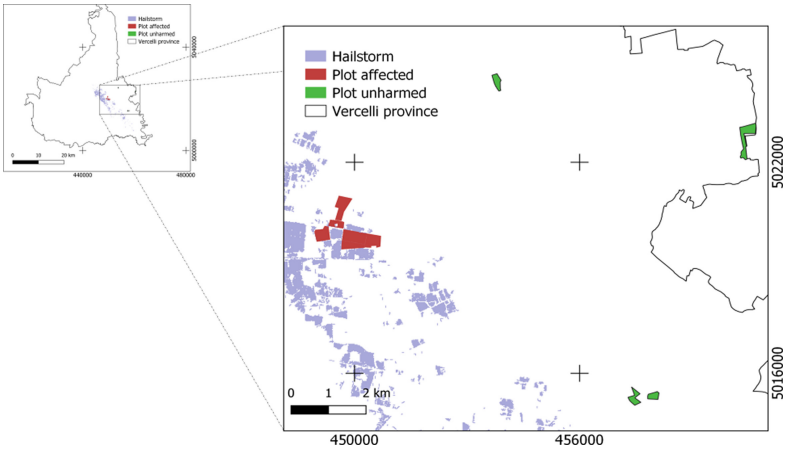

Fig. 6. Map of the fields unharmed and damaged in relation to the hailstorm area (Reference frame: WGS 84 UTM 32N).

These results could be misleading, if one assumed that all fields showing DM2 positive values recovered from damages. As previously mentioned, DM2 positive values could be related to weeds within damaged fields. To solve this doubt the mean temporal profile of NDVI was observed looking for evidences of removal of profile

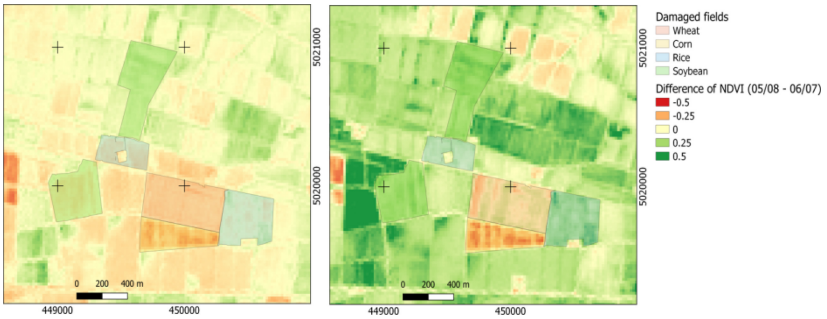

Fig. 7. DM1 (left) and DM2 (right) maps. Reference frame: WGS 84 UTM 32N.

from its expected trend (crop type dependent). This was achieved by comparing the phenological behavior of damaged crop (NDVI local temporal profile) with the one expressed by a not-damaged field having the same crop (Figs. 8, 9 and 10).

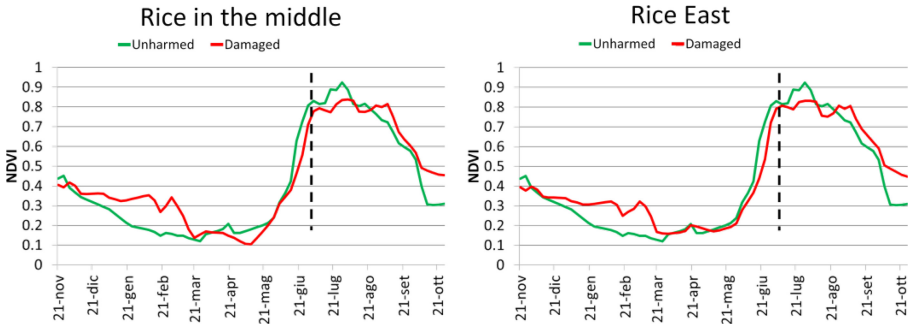

Fig. 8. Comparison of NDVI profiles of rice fields (damaged and unharmed). Left - Rice field in the middle. Right – Rice field in the East. Dotted line corresponds to the day of the hailstorm.

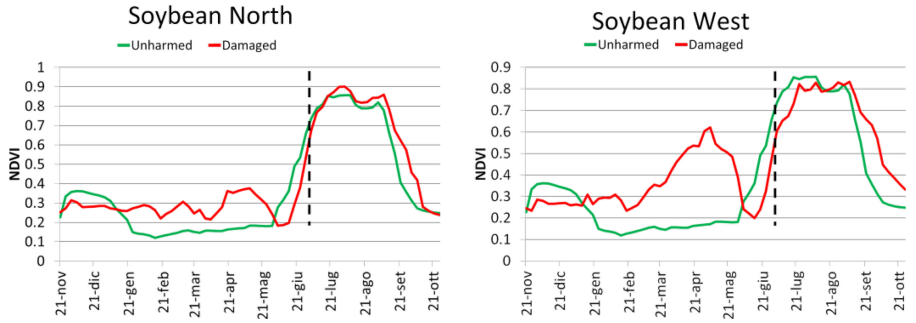

Fig. 9. Comparison NDVI profiles of soybean fields (damaged and unharmed). Left - soybean field in the North. Right-soybean field in the West. Dotted line corresponds to the day of the hailstorm.

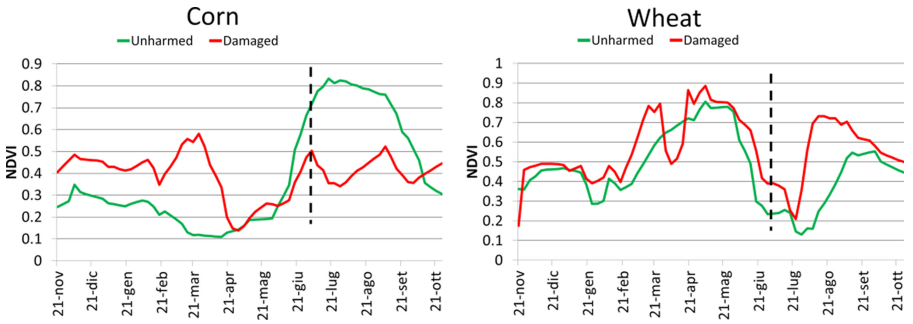

Fig. 10. Comparison of NDVI profiles for corn (left) and wheat (right) fields. Dotted line corresponds to the day of the hailstorm.

NDVI profiles of soybean and rice fields show little differences between damaged and unharmed fields: only in the very proximity of hailstorm, NDVI significantly reduced suggesting that, despite the hail, crops properly reached the harvest time. Wheat fields, differently showed a different behaviour, since harvest occurred few days after the event. In these cases NDVI values reduction was possibly related to harvest and not to hail. Corn fields instead show an evident permanent damage, never recovered. NDVI profile of corn in Fig. 10 shows, in fact, a drastic decrease of NDVI values after hail; NDVI tends to increase slowly after the event with such a trend that can be reasonably interpreted as related to weeds. In fact, the NDVI profile of corn in a not damaged field appears as completely different. Maximum NDVI value for damaged corn was around 0.5, while for not damaged corn was above 0.8.

Results showed that just one out of the reference fields was actually damaged by hail: the corn one. Consequently, a focus was done on this field aimed at mapping the spatial variation of damage within the fields. An anomaly map was therefore computed for both July 16th and August 5th (Fig. 11) with the following meaning:

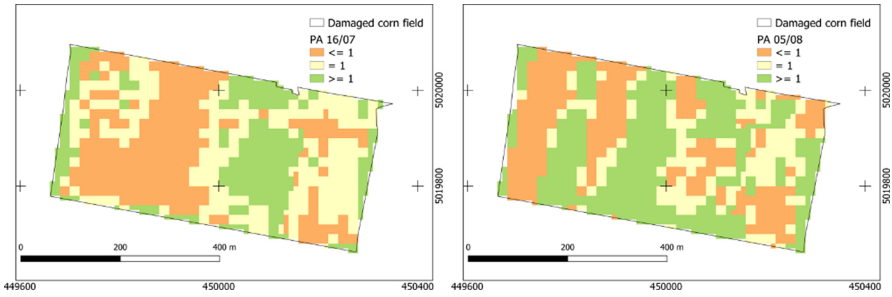

Fig. 11. Map of corn field anomalies in the short (left) and long (right) term. Reference frame: WGS 84 UTM 32N.

- PA > 1: local NDVI value greater than 1 means that in that position the damage was lower than the average one of the investigated field;
- PA < 1: local NDVI value lower than 1 means that in that position the damage was higher than the average one of the investigated field;
- PA = 1: local NDVI value correspond to the average one of the investigated field.

For the explored field it was found that in the 41.02%, 23.39% and 35.58% of the field area showed a PA value <1, >1, = 1 respectively immediately after the event. In the long-term negative anomalies (PA < 1) decreased, suggesting that weeds spread over the field or corn partially developed. Nevertheless these preliminary tests showed that, only one out of the 6 reference fields declared as damaged for insurance claims was found to be actually damaged by hail. Since it is authors' conviction that remote sensing-based information are not conclusive, ground surveys area always required, the final verdict can only come after a field survey.

4 Conclusions

In crop insurance sector remote sensing could support experts in the evaluation of crop damages after hail events. It proved to be an excellent tool that can provide proper information to insurance companies. Presently, insurance companies must operate a ground survey to evaluate each compensation request; in a not-too-far future, remote sensing systems could circumstantially explore the entire context locating those anomalies useful to better target losses appraisals. Economical and management strategies, supported by this new type of information, are expected to increase competitiveness and business income of insurance companies. Optical images from Copernicus, obtainable for free, proved to effectively support hail damage analysis in agriculture. NDVI time series showed that they can reasonably describe impacts of hail on crops. This study suggests that the use of ordinary analysis systems, integrated with the NDVI time series could drive to interesting results for insurance companies, providing more reliable information about hail damaged fields. Copernicus data are the natural tool for this type of investigation, given their temporal frequency (5 days, nominally) and geometric resolution (GSD = 10 m) and will certainly improve effectiveness, reliability and competitiveness of insurance company. It is also expected that this technology will allow companies to provide more precise and detailed information to farmers moving to a more transparent quantification of damage compensations. It is worth to remind that remote sensing-based approaches do not exclude ground survey, that are still needed to precisely interpret indications from satellite data but moving towards an easier, faster and more effective way of generating reports.

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