Field Crops Research 196 (2016) 426–437

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Hail defoliation assessment in corn (*Zea mays* L.) using airborne LiDAR

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ARTICLE INFO

Article history:
Received 1 April 2016
Received in revised form 28 July 2016
Accepted 28 July 2016
Available online 3 August 2016

Keywords:
Corn
Hailstorm
Canopy defoliation
Airborne laser scanning (ALS)
LiDAR sampling point density

ABSTRACT

The insurance industry reports a pronounced intensification, at the global level, of weather-related events such as droughts, windstorms and hailstorms. As an efficient quantification tool, improved capacities can be built adopting innovative remote sensing methods to map vegetation damage spatial distribution, to quantify its intensity and impact. New airborne LiDAR (Light Detection and Ranging) sensors provide high vertical resolution data, which are potentially suitable not only for forest canopies but also for monitoring shorter crop canopies (e.g. corn – *Zea mays* L.) for crop injury and lodging assessment.

To evaluate the potential of LiDAR metrics to map corn canopy height and hail defoliation, a flight campaign was organized in 2014 in Wampersdorf (Austria) in a cropland area affected by a hailstorm. Ground-truth observations were carried out in 16 plots, where defoliation was assessed both visually (observed range from 0% to 70%) and using a biophysical parameter-based method. The performance of both traditional and newly-introduced metrics (i.e. Canopy Metric, Ground Metric) was assessed at different sampling point densities. The results showed the ability of LiDAR data to map both corn canopy height and defoliation (predicted vs. observed regression: $R^2 = 0.69$ for both canopy height and defoliation; point density 5 and 42 points/m^2, respectively). The presented approach has distinct advantages compared to previous remote sensing methods and has a clear application potential for farmers and insurance industries. Larger-scale studies are needed to verify its best implementation strategies and to investigate its economic and logistic benefits.

1. Introduction

In the last decades, the frequency of extreme weather events such as storms, heat waves and droughts has significantly increased. In Europe and many areas of Russia, unprecedented heat waves were recorded during the summers of 2003 and 2010. During summer 2007, the United Kingdom experienced a series of destructive floods across the country such that defenses were overwhelmed (EASAC, 2013). In 2013, record-breaking floods affected Germany, Hungary and other countries. In late July and early August of 2013, unusually high temperatures dominated Europe, from the Mediterranean Sea northward to Scandinavia and the British Islands. Particularly high temperatures (exceeding 40 °C, 104 °F) were reached in Austria: the July averaged temperature was 2.2 °C (4.0 °F) above the 1981–2010 average (NOAA, 2013).

Severe thunderstorms and associated extreme events such as hail represent a substantial hazard potential for crops, and the frequency of occurrence of atmospheric conditions which can potentially determine such events in Europe is increasing (Mohr and Kunz, 2013). According to the report on extreme weather events in Europe, produced by the Norwegian Meteorological Institute in collaboration with the EASAC (European Academies Science Advisory Council) the insurance industry reports a pronounced increase – observed at the global level- of the number of weather-related events, which caused significant losses in Europe (Hov et al., 2013). In the agricultural sector, in 2013 the Austrian Hail Insurance estimated damage of 240 million EU due to extreme weather events (Österreichische Hagelversicherung, 2013).

As the number of claims to agriculture insurance companies has significantly increased in many areas of the planet, there is a bottom-up urgent interest towards innovative tools to face this urgent situation. Adaptation can strongly reduce vulnerability, especially when it is embedded within broader sectorial/sector-based initiatives. Improved monitoring tools can provide strategic

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http://dx.doi.org/10.1016/j.fcr.2016.07.024
0378-4290/

information for planning adaptation measures in the agricultural and forestry fields. Such measures are required to reduce the adverse impacts of projected climate change and variability. As highlighted by the last Intergovernmental Panel on Climate Change report (IPCC, 2014), some planned adaptation measures to climate change are already occurring on a limited basis, but improved and integrated management capacities are needed in order to monitor vegetation damage spatial distribution, to quantify its intensity and its impact (Clements et al., 2011).

In this context, new opportunities can be provided by technological development and by the application of existing state of the art remote sensing methods in new fields of application. Innovative precision agriculture monitoring tools would be beneficial not only for the insurance industry, but also for large scale farming as damage mapping can provide important information for improved farm management.

Remote sensing has been widely used in agricultural and forestry management to assess biophysical characteristics. Optical data from ground, aerial and satellite platforms (Peters et al., 2000; Erickson et al., 2004; Zhao et al., 2012) were shown to be able to estimate hail defoliation in corn canopies and these remote sensing monitoring platforms were presented as possible solutions to limit the expenses of in-situ inspections to map losses. Hail defoliation assessment can be carried out using remote sensing imagery collected right after the event, or comparing before-damage imagery to after damage imagery. While the second scenario can be considered quite difficult and unpractical, the acquisition of imagery and ground-truth information as quickly as possible right after the event (according to the weather conditions, which represent a major limitation for near real-time spectral data acquisitions) appears to be a more suitable scenario to map the defoliation levels of corn canopies (Erickson et al., 2004). The use of radar in combination with spectral observations was also proposed to monitor large-scale hail events from the satellite platform (Gallo et al., 2012; Molthan et al., 2013), although the low spatial resolution of the presented products may represent a major problem when fragmented agricultural landscapes are observed. Experiences about exploitation of airborne Light Detection And Ranging (LiDAR) to support forestry are especially focused on qualitative and quantitative characterization of forest stands and description of their morphological and structural attributes (Hudak et al., 2009; Wulder et al., 2012; Torresan et al., 2014), and on quantitative estimation of forest standing volume and above-ground biomass (Maltamo et al., 2014; Corona et al., 2012; Dalponte et al., 2011; Tonolli et al., 2011). Considering that canopy vegetation height is a function of species composition, climate, and site quality, the results can be used for land cover classification, habitat mapping, and forest management.

LiDAR data in agriculture are widely used for drainage application, to develop flood maps, tile and surface drainage (Cazorzi et al., 2012), to produce topographic layer for precision agriculture, to map linear features of agrarian landscapes (Bailly et al., 2008). Terrestrial laser scanner (TLS) is used in precision agriculture to obtain 3D data for then digitally reconstruct and characterize the geometric trees in orchards (Rosell Polo et al., 2009a, 2009b). Such high quality data are acquired with state of the art TLS methods, which are not applicable for operational use in remote sensing due to the high cost of equipment, data acquisition and analysis (Hämmerle and Höfle, 2014). These data allow quantifying changes in canopy structure at various times providing detailed assessments of canopy growth and allocation responses to field experiments including fertilization, irrigation, soil warming and fumigation. LiDAR in grapevine crops (Rinaldi et al., 2013) and citrus (Lee and Ehsani, 2009) has been used to characterize the canopy and its variation at all growth stages which, together with the spatial distribution of plants in the field, is used to determine the volume rate in fruit crops. For a number of crops and forest types, these tools provide a high potential which has not been fully and specifically exploited to monitor vegetation canopy structure changes due to mechanical and physiological effects of extreme weather events.

The use of LiDAR to assess biophysical parameters of annual crops (such as e.g. corn, wheat, barley, soybean) is still in its infancy, partly because the architecture of such short, dense structure canopies is quite challenging. To this regard, Li et al. (2015) highlighted that crops, compared with forests, are more affected by signal saturation problems because of the high canopy density which limits the penetration depth of the detecting beam. Consequently, a high-density LiDAR point cloud is required to increase the penetration probability. However, new emerging technologies – delivering denser discrete return point clouds (Ussyshkin and Theriault, 2011; Oshio et al., 2015) – seem to provide sufficient information for detailed modeling, analysis and quantitative characterization of three-dimensional vegetation structure for a variety of applications, based on canopy height assessment and canopy density. In this respect, canopy height information obtained by LiDAR observations can be used for crop yield modeling and mapping (Yin et al., 2011; Grenzdörffer, 2014) but such methods may also provide a good potential for detecting canopy architecture anomalies related to extreme events such as crop injury and lodging due to windstorms.

Another possible important application related to canopy density assessment is the estimation of hail defoliation and damage in corn canopies. Defoliation can have a significant impact on the yield of corn harvested for both grain and forage production (Lauer et al., 2004) and the damage is a function of both the timing and extent of defoliation as highlighted by damage assessment policies and charts (Die Österreichische Hagelversicherung, 2015a, 2015b). For forage production, 100% defoliation results in decreased forage yield by 43, 70, and 40% at V10 (late vegetative stage with 10 leaves), R1 (early reproductive stage), and R4 (late reproductive stage), respectively (Ritchie et al., 1996). The impacts of defoliation on grain yield can significantly differ from those on forage: the standard industry hail damage chart (National Crop Insurance Services, 1998) predicts a 97% grain yield reduction with 100% defoliation at R1. As highlighted by Roth and Lauer (2008) regarding corn production, defoliation affects both quantity and quality.

In this context, the use of LiDAR-based models for detecting defoliation caused by hailstorms is of high interest both for large-scale farmers and insurance companies who, due to the increased frequency of extreme events, are in need of innovative and cost-effective tools for extensive monitoring. In-situ observations carried out by insurance inspectors could be integrated with remotely-sensed information to optimize resources. Similarly, defoliation and damage maps would help farmers to efficiently manage the harvesting operations, e.g. excluding the highly-damaged areas from harvest. For this reason, new research is needed to explore the potential of LiDAR in this field.

The objectives of this study were the following:

- to investigate the possibility to use *in-situ* biophysical measurements (based on canopy height and canopy denseness) as a quantitative proxy for corn canopy defoliation (which is generally assessed by visual estimation);
- to test the ability of LiDAR data to retrieve canopy height of corn crops;
- to analyze the canopy density profile and the LiDAR return patterns in corn canopies with different hail defoliation rates;
- to investigate the ability of LiDAR models, based on both traditional and new metrics introduced in this study, to retrieve canopy denseness and canopy defoliation;
- to highlight the effect of adopting different LiDAR sampling point densities on the ability of ALS metrics to retrieve canopy height and canopy defoliation.