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Publication Date

2016-09-01

DOI

10.1016/j.scitotenv.2016.05.146

Science of the Total Environment 565 (2016) 1020–1027

Contents lists available at ScienceDirect

Science of the Total Environment

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

Food, water, and fault lines: Remote sensing opportunities for earthquake-response management of agricultural water

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HIGHLIGHTS

- Remote sensing to improve agricultural disaster management
- Introduce post-earthquake agrohydrologic remote sensing (PEARS) framework
- Apply PEARS framework to 2010 Maule Earthquake in Central Chile

ARTICLE INFO

Article history:
Received 31 December 2015
Received in revised form 19 May 2016
Accepted 19 May 2016
Available online 28 May 2016

Editor: D. Barcelo

Keywords:
Agro-hydrology
Disaster management
Monitoring
Plant-water relations
Post-earthquake agrohydrologic remote sensing (PEARS)
Remote sensing

ABSTRACT

Earthquakes often cause destructive and unpredictable changes that can affect local hydrology (e.g. groundwater elevation or reduction) and thus disrupt land uses and human activities. Prolific agricultural regions overlie seismically active areas, emphasizing the importance to improve our understanding and monitoring of hydrologic and agricultural systems following a seismic event. A thorough data collection is necessary for adequate post-earthquake crop management response; however, the large spatial extent of earthquake's impact makes challenging the collection of robust data sets for identifying locations and magnitude of these impacts. Observing hydrologic responses to earthquakes is not a novel concept, yet there is a lack of methods and tools for assessing earthquake's impacts upon the regional hydrology and agricultural systems. The objective of this paper is to describe how remote sensing imagery, methods and tools allow detecting crop responses and damage incurred after earthquakes because a change in the regional hydrology. Many remote sensing datasets are long archived with extensive coverage and with well-documented methods to assess plant-water relations. We thus connect remote sensing of plant water relations to its utility in agriculture using a post-earthquake agrohydrologic remote sensing (PEARS) framework; specifically in agro-hydrologic relationships associated with recent earthquake events that will lead to improved water management.

1. Background, scope & need

Earthquake events threaten food security, resource management and human life, and are observed to be steadily increasing (Ellsworth, 2013). As observed earthquake events continue to increase, it is important to explore and improve response and recovery strategies. Infrastructural damages, especially in urban environments, are at the forefront of research in remote sensing of earthquake-associated damage. Agricultural environments also face catastrophic impacts, often due to adverse hydrologic behavior following the event. The earthquake-water linkage poses particular threats to agricultural productivity, yet difficulty lies in predicting the location, destructiveness, and extent of damage. While effects of earthquake-induced hydrologic changes on crops remain largely unexplored, remote sensing of crop water relations provide a suite of tools to monitor responses and to mitigate crop loss. Remote sensing can address these challenges with archived imagery that has extensive spatial coverage. There are conceptual models that explicitly walk through remote sensing in disaster management (Joyce et al., 2009b) and remote sensing of post-earthquake urban damage (Eguchi et al., 2003) – leaving a gap at the interface of post-earthquake remote sensing of agricultural impacts. We therefore draw attention to current research in understanding earthquake impacts on agricultural systems, particularly agricultural and hydrologic (agro-hydrologic) relations, and the growing science to remotely detect damage and monitor recovery. The scope of this paper focuses on earthquake-induced hydrologic changes, specifically regarding elevated groundwater effects on the canopy zone, its impact in plant physiology and viability of the crop, and how farm management can adapt to these conditions. We focus on describing how remote sensing imagery, methods and tools allow detecting, changes in local hydrology, crop responses and damages incurred after earthquakes, and what

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http://dx.doi.org/10.1016/j.scitotenv.2016.05.146
0048-9697/

management actions can be done to ultimately avoid adverse crop and socioeconomic impacts.

2. Earthquakes at the food-water nexus

Some of the most prolific and valuable agricultural regions of the world are located over fault lines (Fig. 1). Considering earthquake linkages to water supplies (Montgomery and Manga, 2003; Wang et al., 2004), the vulnerability of agricultural lands to an earthquake event can disrupt food production and threaten food security. Additionally, human resource extraction and land uses can exacerbate seismic activities, including groundwater overdraft (Amos et al., 2014), changes in groundwater pumping (Bawden et al., 2001), and hydraulic fracturing (Ellsworth, 2013). Earthquake-water dynamics can affect agriculture through damage of infrastructures, access to and operation in the field, and crop productivity. There is much to be studied in this field, and often very little, if any, pre-earthquake data will have been collected. Remote sensing data mitigates these challenges with longstanding legacies of archived data, such as the Landsat archive, with extensive global coverage. We therefore connect available data inventories and current remote sensing achievements in plant-water relations to earthquake-water dynamics; this allows detection of crop responses to changes in the hydrology and improving post-earthquake farm management.

3. Earthquake water dynamics

Earthquakes are known to influence changes in hydrology related to quantity and quality (Jang et al., 2008). There are a variety of earthquake mechanisms that can influence changes in hydrologic flows that include liquefaction and surface and subsurface flows (Montgomery and Manga, 2003, Wang and Manga, 2009). While any abrupt change in water delivery can threaten vegetative health, extent of crop damage depends on the type, magnitude, and duration of the temporary change. Additionally, management practices preceding and responding to the event can mitigate or exacerbate damage. The variety and complexity of natural and anthropogenic factors emphasize the need for extensive research and broad case studies. Remote sensing can be used to monitor water supply changes either by direct monitoring of stream and subsurface water, or of secondary effects upon photosynthetic processes, plant tissues, leaf area, and background soil properties. We discuss appropriate remote sensing methodologies and satellite imagery analysis applicable for agricultural water monitoring of post-earthquake changes in water quality and composition.

4. A conceptual model: post-earthquake agrohydrologic remote sensing (PEARS)

Early and effective monitoring techniques help avoid irreversible tree, vine and crop damage that may be undetected on foot, thus promoting socio-economic improvement for local growers who may face post-earthquake water management issues for the first time. An organized monitoring protocol optimizes mitigation action for crop impacts following an earthquake, and streamlines the monitoring process of crop recovery. We introduce a conceptual model that integrates remote sensing of plant-water relations for cropping systems, earthquake-water dynamics, and farm adaptation responses (Fig. 2). The post-earthquake agrohydrologic remote sensing (PEARS) framework in Fig. 2 visualizes remote sensing as an active, iterative process that is best applied to pre- and post-earthquake conditions to assess affected crop health and uniformity. Adverse conditions can be identified through reflectance, thermal, visual or physically modeled conditions, dependent on earthquake-water dynamics and farm adaptation responses. Crop water supplies can suffer water quantity (too much or too little) and/or quality (aquatic geochemistry) problems – yet these problems are not always clearly defined and can be combined. Farm water management can therefore mitigate crop and tree death ultimately promoting food security by expediting and advancing post-disaster decision-making. In this paper, we elaborate the most common post-earthquake challenges in agricultural water management, connect and discuss appropriate remote sensing techniques for the context and provide examples of farm management responses to mitigate these problems.

5. Too much, too little: a disrupted crop water budget

The primary goal in agricultural water management is to provide optimal resources that maximize plant yields, tailored to specific moisture regimes and climatic factors unique to a crop's region. Earthquake events oftentimes cripple food-water systems by introducing radically unnatural and unexpected moisture regimes, calling for emergency management actions. An uncontrollable influx of water may cause waterlogging. On the contrary, earthquakes may cause preferential downward flow through cracks, decreasing the groundwater table which effectively may enforce drought conditions – both of which threaten global food productivity (Akhtar and Nazir, 2012). Plant tolerances to flooding may be more or less urgent dependent upon plant type, time of year and duration of flooding (Kozlowski, 1984; Kozlowski 1997). While management strategies may be less urgent

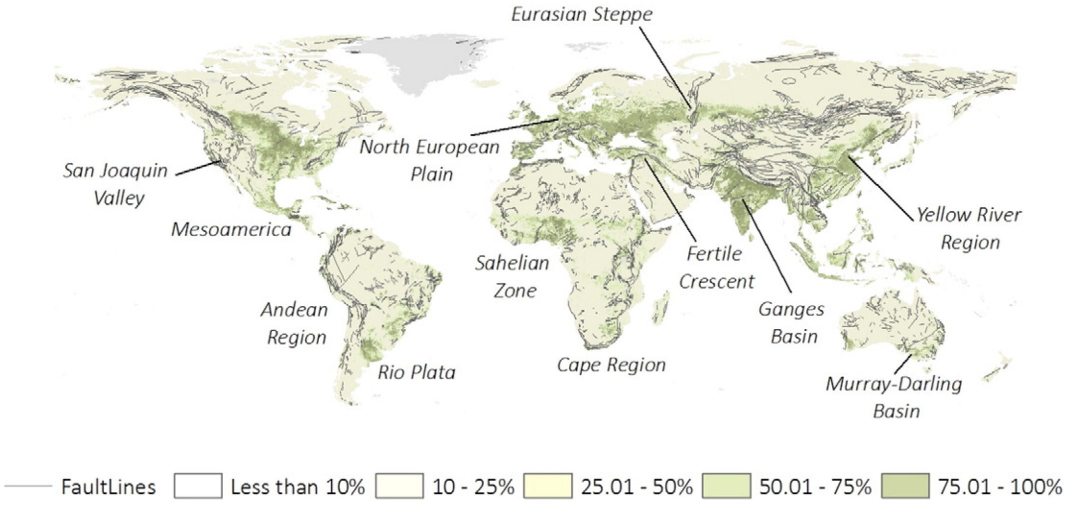

Fig. 1. Major agricultural regions overlie active global fault lines, revealing the vulnerability of food security to abrupt earthquake events. Land use data shows spatial distribution of percent cropland derived from FAOSTAT's Global Agricultural Lands dataset (Ramankutty et al., 2000). Global fault line dataset provided by ESRI.

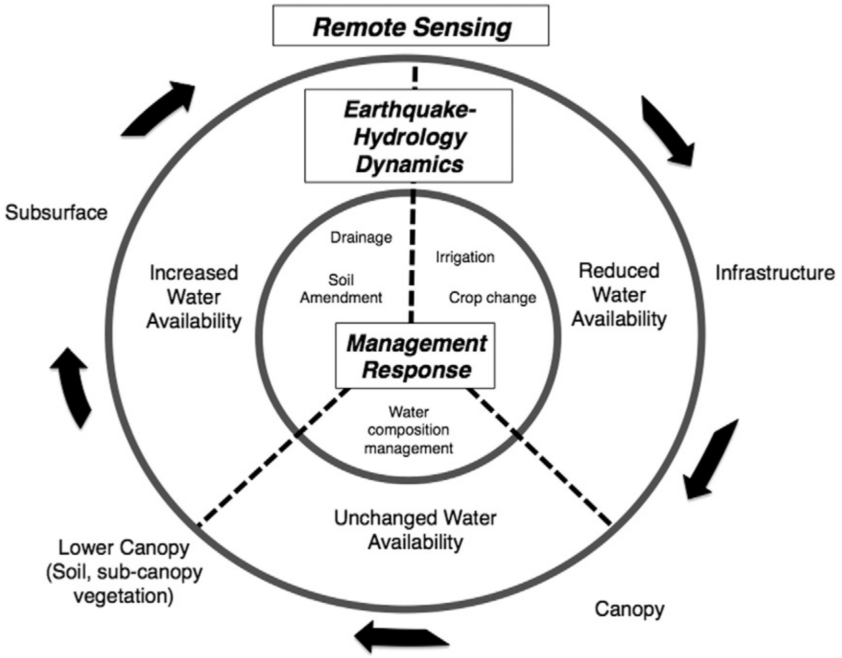

Fig. 2. The PEARS framework for farm water management following earthquake events is shown above. Remote sensing is a dynamic process that can be executed at all stages to provide a pre-earthquake baseline, post-earthquake impact and post-farm management response (i.e. recovery, if applicable). This is a generalized conceptual model, as these dynamics are highly complex and unique to the earthquake and location. Additionally, the water quantity-quality responses are not clearly defined, represented by dashed lines, as earthquake effects can be and are often combined.

for perennial rootstocks during the dormant season (e.g. Northern Hemisphere grapes in December), water sensitive row crops in the middle of the growing season (e.g. Northern Hemisphere tomatoes in July) or non-dormant evergreen citrus crops can experience serious injury from saturated soil conditions that include leaf wilt, chlorosis and growth reduction (Ford, 1968, Kozlowski, 1997, Yelenosky et al., 1995). How does one choose the best-suited technology for a potentially urgent situation? This paper elaborates on various remote sensing approaches useful in identifying plant responses to infrastructural damages, changes in water transport across the landscape, canopy stress itself, changed soil moisture and subsurface water processes (Fig. 3).

5.1. At the surface: remote sensing of superficial damages

Impacts of seismic shaking and crustal movements can be detected across the earth's surface, affecting water delivery through irrigation

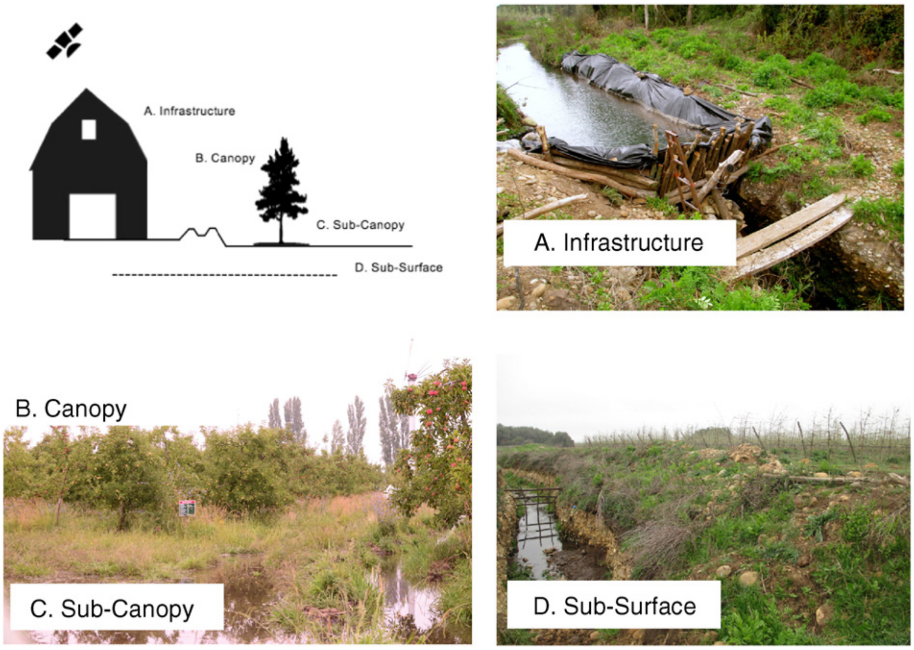

Fig. 3. A diagram shows a stepwise remote sensing process for post-earthquake monitoring of agro-hydrologic impacts that include A) infrastructural, B) canopy, C) sub-canopy, and D) subsurface impacts. These tactics were practiced to assess infrastructural damages across the farm water system for a Central Chilean orchard affected by the 2010 Maule earthquake to assess changes in infrastructure, canopy health, and drainage below the canopy and elevated subsurface water levels. Capturing a complete picture of the farm water system using remote sensing can improve steering of post-earthquake management and thus mitigate socioeconomic damage.

infrastructures, water uptake through loss of trees and changing hydrologic flowpaths through changed surfaces and hydraulic gradients. Commercial providers such as Worldview, GeoEye, or QuickBird provide useful datasets for infrastructural monitoring and public communication following catastrophic earthquakes due to their high spatial resolution (several meters to sub-meter) and commitment to collect data – typically with on-demand delivery – for monitoring after disasters, which often only requires natural color imagery that utilize the visible wavelength region (VIS, 400–700 nm). High spatial resolution imagery can be supplemented with crowdsourcing on social media and other technologies that can generate comprehensive imagery-based building and constructed infrastructure damage assessments (Bevington et al., 2015). For farm-water management, agricultural assessments of infrastructural damages can be expedited if the analyst has specific knowledge of the site; however, this can be cumbersome and slow for large and complex properties or if the analyst has limited knowledge of on-ground activities. Natural color, high spatial resolution can be supplemented with additional imagery from other spectral regions to better explore otherwise undetected surface damage, tree loss and elevation and slope changes.

Active sensors are often used to create digital elevation models and can thus infer changes in water flow across the landscape that includes changes in slope, aspect and elevation. Detecting changes across the earth's surface structure is key to supporting digital elevation models (DEMs), digital terrain models (DTMs) and digital surface models (DSMs). Pre- and post-earthquake synthetic aperture radar (SAR) backscattering can be applied to identify areas affected by uplift, subsidence, and coastline modification (Chini et al., 2008), yet is time and weather dependent (Chini, 2009). LiDAR is used extensively for high spatial resolution of topographic changes and is often used in fusion with optical data (Blackburn, 2007). However, because there is no current operational LiDAR satellite, this option has limited application today. Challenges in detecting damage across terrain surfaces can be expedited by the development of automated classification of features to detect damage (Chini, 2009). Integrated GIS and image analysis procedures, such as the Rapid Damage Assessment Telematic Tool (RADATT), also provide reliable post-disaster damage assessment in near real-time (Gamba and Casciati, 1998) and can play a useful role in detection of agricultural infrastructure damages and terrain uplift or subsidence.

5.2. Monitoring crop canopies and water stress

Plant functional types – or optical types – link remote sensing observations to plant and ecological information, linking observations from plant to canopy level (Ustin and Gamon, 2010). Upon the onset of plant-stress, stomatal closure changes canopy reflectance and elevates leaf temperature. These plant responses to water content changes are detected as reflectance, transmittance and absorption changes across the electromagnetic spectrum (Fig. 4, Jacquemoud and Ustin, 2001). These wavelength regions serve as the foundation of radiative transfer (RT) models that simulate predicted changes in spectral reflectance due to the changing environmental conditions (Jacquemoud et al., 2009) as well as contribute to advanced spectral indices that are more precisely targeted to specific changes. Plant reflectance properties in the red and near infrared regions are especially recruited for differentiating soil, water and vegetation with vegetation indices (Glenn et al., 2008). Vegetation indices can be used to estimate vegetation water content (Cheng et al., 2006, Cheng et al., 2008), based on gravimetric or leaf water content (Cheng et al., 2011, Cheng et al., 2013), equivalent water thickness (EWT; water depth/per pixel; knowledge of pixel area provides the volume estimate), changes which are detectable in the short wave infrared region (1.1–2.5 μm), and evapotranspiration processes by including temperature from thermal infrared measurements (Glenn et al., 2010, Nagler et al., 2005a, Nagler et al., 2005b), thus together, identifying agricultural regions receiving excess or insufficient water supplies. Plant physiology and thus reflectance properties respond differently depending upon the time of year, crop type, and management strategies. For example, wine grapes undergoing deficit irrigation (DI) prior to harvest may exhibit dramatically decreased reflectance following increased water deliveries through surface water or groundwater surges, as experienced following the 2014 South Napa Earthquake (Sumner, 2014; Wang and Manga, 2014). Measurement of these optical properties are however limited by available remote sensing platforms and their sensor constraints, and on the ground knowledge of crop types, all which guide selection of the appropriate data to use. Remote sensing across the optical wavelength regions is further enhanced with utilization of measurements in the thermal region.

Thermal remote sensing (8–14μm) can be applied to detect water stress across the crop canopy based on temperature differences (Anderson and Kustas, 2008, Labbé et al., 2012). Under drought-induced conditions, stomata will close and leaf temperatures will increase, thus allowing construction of spatial maps of temperature differences across the canopy. Conversely, increases in water supplies, especially in deficit irrigated crops, can reduce temperatures as the plant canopy is cooled by increased latent heat exchange processes. Spectral indices, such as NDVI, have been used conjunctively with surface temperature maps (Chuvieco et al., 2004), to enable detection of water content changes in response to changing hydrology. Coupling thermal estimates with ancillary data has advanced applications of plant-water relations and physical models to detect crop water stress, and thus providing a way

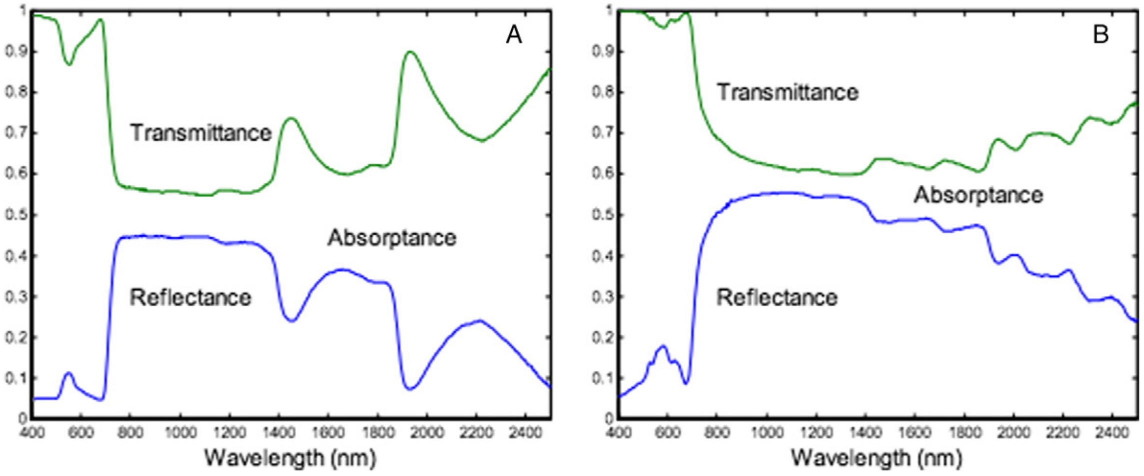

Fig. 4. Reflectance, transmittance and absorption spectra compared between (A) fresh poplar leaves and (B) dry leaves illustrating the increase in reflectance with decreasing leaf water content enabling the detection of water stress with changing water supplies (Figure adopted from Jacquemoud and Ustin, 2001).

to improve post-earthquake farm water management (Allen et al., 2011).

Physical models incorporate visual identification of terrain features, reflectance properties, spectral indices, and thermal estimates to quantify biological, chemical, ecological and physical properties. Evapotranspiration (ET) modeling, for example, is advancing with sensors having narrow spectral band capabilities (Rodriguez, et al. 2011), as agribusinesses frequently employ remote imagery to monitor crop water dynamics (Morse et al., 2004; Allen et al., 2007a). These models utilize physical weather station measurements combined with remote sensing images of the visible, near infrared and thermal wavelength regions. A few examples of ET models exercised in agricultural water mapping include METRIC (Mapping EvapoTranspiration at high Resolution using Internal Calibration; Allen et al., 2007b) and SEBAL (Surface Energy Balance Algorithm for Land; Bastiaanssen et al., 2005). These models are however limited by weather station data, spatial resolution of the spectral bands – often limited by the resolution in the thermal regions – and the normalization procedure used by the models.

5.3. Below the canopy: detecting changes in soil moisture

Detecting sub-canopy properties can provide early detection of changes in local hydrology by improved monitoring of soil moisture, sub-canopy crop water uptake and water ponding. Soil indices have improved, specifically with utilization of the Moderate-Resolution Imaging Spectrometer (MODIS; Huete et al., 1994). Characterization of soil moisture also uses remote imagery in the microwave region (1–5 Hz), which relies on sensitivity of thermal microwave radiation to the dielectric constant of water (Njoku and Entekhabi, 1996). While remote sensing of the lower canopy is challenged by soil surface roughness, vegetation cover density and canopy architecture, there are still opportunities for gathering spectral information and monitoring responses to changing hydrology.

5.4. Subsurface: groundwater monitoring

Exploration of remote sensing technologies for groundwater monitoring is advancing rapidly, presumably responding to the need for improved management of our global freshwater reserves. Harnessing remote sensing technologies for interpreting groundwater dynamics is a cost-efficient approach to capture phenomena at a greater extent more quickly than possible on the ground (Waters et al., 1990, Fernandez, 2013). There are, however, many constraints in remote sensing and GIS applications due to limited understanding of how to interpret groundwater hydrology (Jha et al., 2007). New technologies utilizing data provided by the Groundwater Recovery and Climate Experiment (GRACE) can directly monitor changes in groundwater elevation, yet are useful for supplementary monitoring of crops at best, due to its coarse spatial resolution (300-500 km).

5.5. Decision support in agricultural water management

Remote sensing tools can detect more subtle changes in crop health across an entire orchard, or if a larger site is affected, at selected ‘hotspots.’ It is, of course, left to the grower to make executive decisions, or whether the specific crop can withstand intermittent or prolonged flooding. Saturated soils may be less problematic in a moving water table, versus stagnant saturated soils that can create anoxic conditions, promoting crop disease and death. Farm management responses to remove water can include drainage ditches, land smoothing, vertical drainage, bedding systems and mounds, and in extremes, tile drainage (Troeh et al., 2004). Remote sensing following the stepwise process from infrastructural, canopy, sub-canopy and subsurface responses offers a decision support tool for farm management to pinpoint problems and closely monitor recovery.

5.6. Case study: Coihueco, Chile

Remote sensing assessments of post-earthquake orchard management using the PEARS framework is demonstrated in the case of the 2010 Maule Earthquake. On February 27, 2010, an 8.8 magnitude earthquake occurred off the coast of Concepción, Chile, and incurred catastrophic damages. An apple orchard in Coihueco, Chile – approximately 200 km inland from the epicenter – observed compacted soils and elevated groundwater levels immediately after the earthquake; these conditions directly threatened apple orchard resiliency. Prolonged flooding or waterlogging of soils underlying apple trees during the growing season creates anoxic conditions, inhibits root growth, and predisposes the orchard to reduced yields, disease, and death (Kozlowski, 1984). The grower mitigated waterlogging by trenching along the orchard perimeter to facilitate rapid drainage and needed emergence direction in monitoring and assessing resiliency of the orchard. Remote sensing monitoring was dedicated to orchard canopy resiliency, as waterlogging occurred mid-season and tree health was paramount to the post-earthquake management. Consequently, increased groundwater under an orchard canopy connected the following components of the PEARS framework as follows: I.) increased groundwater causing waterlogging, II.) management action to drain excess water supplies via trenching, assessed by III.) remote sensing of orchard canopy.

The apple orchard was planted in 2007, with Fuji, Gala, and Cripp's Pink Cultivars grafted to M106 and M9 rootstocks. Both rootstocks have demonstrated similar plant-water relations (Olien and Lakso, 1986) and similarly moderate sensitivity to flooding (Kozlowski, 1984). Landsat 5 Thematic Mapper (TM+) and Landsat 8 Operational Land Imager (OLI) imagery was used for pre- and post-earthquake monitoring from 2009 to 2014. The normalized difference vegetation index (NDVI) was calculated to measure orchard vigor (Tucker, 1979; Aguilar et al., 2012):

$$\frac{\rho_{NIR}-\rho_{RED}}{\rho_{NIR}+\rho_{RED}}$$

A time series analysis of NDVI in the orchard revealed spatial heterogeneity and average NDVI values decreasing to adverse values (Panel B) and returning to acceptable and uniform NDVI values (Panel C). Fig. 5 displays the trenched orchard's NDVI, which revealed initial reduction in orchard canopy health as identified by low NDVI, followed by improved orchard response over time (increased NDVI). The imagery enabled the grower to locate and mitigate the most adversely affected orchard areas (hotspots) and attain orchard uniformity the following growing season, despite sustained water flow throughout the orchard.

The application of the PEARS framework suggests that temporary flooding by increased groundwater levels of the cultivar-rootstock combinations mid-growing season did initially impose orchard stress with mean 2010 pre-earthquake NDVI at 0.69 (Fig. 5A) reduced to a mean NDVI of 0.43 after the earthquake (Fig. 5B). This time series analysis enabled growers to monitor and identify vulnerable regions (low NDVI values) in response to concurrent management decisions, ultimately achieving full orchard recovery. Over time and proactive management, the orchard returned to acceptable mean NDVI of 0.67 (Fig. 5C). Focus on the orchard canopy level proved sufficient to meet management in needs in the orchard space; the PEARS framework, however, poses ample opportunity for additional applications.

5.7. Additional framework applications

The customizability of the framework to a grower's specific needs enables triage of worst affected areas. Application of the PEARS framework in the Maule Earthquake case study thus focused on canopy assessment to support orchard health management, but can be expanded to other less-urgent agronomic levels if necessary that include infrastructure, sub-canopy, and sub-surface monitoring.

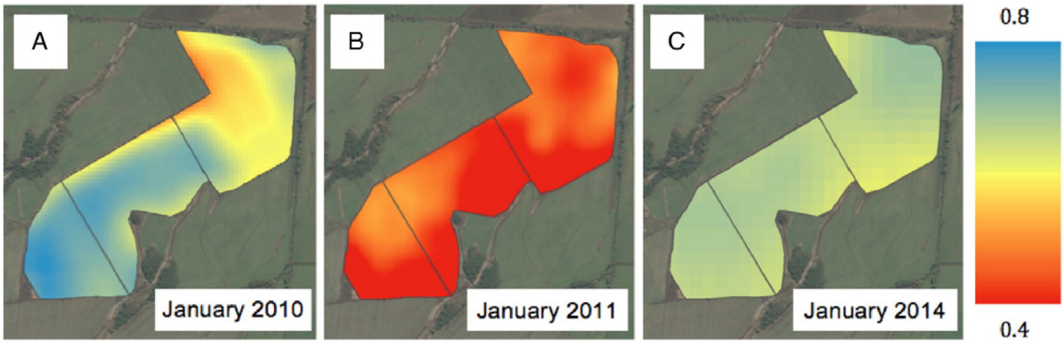

Fig. 5. A case study in Coihueco, Chile demonstrates the utility of remote sensing of orchards in response to earthquake-driven water supplies. We conduct a time series analysis of Landsat-derived NDVI following the 2010 Maule Earthquake, with low vigor (NDVI = 0.4) and high vigor (NDVI = 0.8). We detected initially acceptable orchard vigor (mean NDVI = 0.69) prior to the earthquake (A), followed by severely reduced canopy health with mean NDVI values of 0.43 after earthquake (B), and ultimately see recovery and canopy uniformity of mean orchard NDVI = 0.67 after management decisions to facilitate drainage through trenching (C).

The role of irrigation infrastructure in agriculture is vital, particularly in regions solely dependent upon irrigation for water delivery. The 2010 earthquake in Baja California, Mexico, for example, resulted in extensive irrigation canal damage (Stenner et al., 2010; Wilson et al., 2011). Additionally, the vulnerability of California's Sacramento San Joaquin Delta is largely attributed to local seismic activity coupled with an aging levee system, putting Delta agricultural at risk (Suddeth et al., 2010). Remote sensing has been utilized to monitor farm infrastructure – specifically irrigation canals – after earthquake events (Guo et al., 2011; Irwansyah, 2010), providing a useful tool for agricultural decision making. The PEARS framework can support local-management through such previously demonstrated post-earthquake infrastructural assessments using remote sensing.

Application of PEARS at the sub-canopy canopy could be applied in the Coihueco case study had the earthquake occurred during orchard dormancy, providing a bare canopy, or across bare soils or shorter vegetation. Other temporal and spatial combinations would allow exploration of the sub-canopy level to identify unique soil moisture or vegetation patterns connected to other potential earthquake-water dynamics. Methodologies explored in the literature that identified post-earthquake sub-canopy soil and vegetation responses enable various pathways of agricultural support using the PEARS framework. Bastiaanssen et al., 2000 thoroughly discusses the applications and deliverables that remote sensing can provide to monitor plant-water relationships. In general, agricultural crops have demonstrated detectable trends to insufficient water supplies – both in flooded and drought conditions – using remote sensing and GIS technologies (Jeyaseelan, 2003). Soil moisture changes, specifically attributed to seismic liquefaction, have been mapped using a three-tier remote sensing approach (Ramakrishnan et al., 2006). Liquefaction patterns, or blistering and rupturing, have also been visually identified underlying cultivated lands using remote imagery (Almond et al., 2010). Additionally, short sub-canopy vegetation such as forage, annual crops, or natural cover crops have revealed trends that serve as hydrologic indicators (Nagler). Dual monitoring of both tree vigor and soil water patterns in the Coihueco, Chile case study could allow interpretation of stress-waterlogging connections unique to the case study.

Remote sensing of groundwater resources has been successful applied through various imagery techniques (Meijerink, 1996; Becker, 2006) that can be similarly applied in the PEARS framework depending upon the temporal and spatial extent of the agricultural context. Changes in groundwater availability can be directly assessed and monitored through remotely sensed subsurface indicators that include: elevation (Gabriel et al., 1989), surface temperature (Huntley, 1978), groundwater-dependent ecosystems (Barron et al., 2014), and at a larger regional scale, groundwater elevation change (Rodell and Famiglietti, 2002). A useful compliment to NDVI monitoring of the apple orchard in the Coihueco, Chile case study could also utilize thermal imagery to monitor soil moisture patterns – likely resulting from elevated groundwater tables.

6. Discussion

6.1. Broader impacts: social, political, and economic implications

Earthquake effects on agricultural food production have been linked to the food-water-energy nexus that can predispose civilizations to collapse (Leroy et al., 2010). Agricultural vulnerability to earthquake events threatens food security and thus the sociopolitical and economic well-being of agricultural regions (Kishida et al., 2009). The PEARS framework integrates an articulated need for an advanced disaster support paradigm that promotes social and political well-being. Improved disaster planning in the Sacramento-San Joaquin Delta, for example, is the best defense against social and economic instability should this vital water source be disabled upon a catastrophic earthquake (Burton and Cutter, 2008). Additionally, the ability to map spatially identify damage to optimize management can minimize yield losses at the local scale, and socioeconomic distress regionally (Wilson et al., 2011). Remote sensing services the emergency management cycle at all phases with powerful opportunities to mitigate socioeconomic vulnerability (Joyce et al., 2009a; Joyce et al., 2010). Improved disaster recovery with the PEARS framework approach can thus provide the agricultural sector guidelines for post-disaster socioeconomic planning.

6.2. Call for research

While there has been considerable research conducted to improve understanding of earthquakes and their impacts on a variety of ecosystems, less has been explored in connection to agricultural systems. The many types of remote sensing (visible, reflected infrared, thermal infrared and LiDAR and RaDAR) provide highly useful tools to explore the extent and types of changes within the field, orchard or vineyard following an earthquake, while also providing archived data to allow assessment of conditions before and after the earthquake. Research findings discussed in this paper demonstrate successful applications of remote sensing of crops in response to abrupt changes in surface and subsurface hydrology. Current research connects spectral properties of crop canopies to crop responses following such changes after earthquake events. Strategies discussed can be translated to other events that may cause abrupt hydrologic changes, such as anthropogenic activities causing flooding.

6.3. Advancements

Improvement of crop-water responses to earthquakes can be dramatically improved through the incorporating imaging spectroscopy (measurements from hyperspectral imagers), particularly in concert with thermal imagery. The proposed NASA Hyperspectral InfraRed Imager (HyspIRI) mission for example will provide global wall-to-wall coverage of thermal and hyperspectral imagery, meeting shortcomings of precursor spaceborne imagers such as Landsat and ASTER (Abrams and Hook, 2013). HyspIRI will provide an imaging spectrometer (380 nm–2500 nm) with a 16-day revisit and an eight band multispectral thermal imager with a 5-day revisit, both at 30-m spatial resolution (Lee et al., 2015). The HyspIRI capabilities provide information that is specifically useful for natural disaster studies and vegetation monitoring. Capabilities of the HyspIRI mission include photosynthetic mapping for natural vegetation and agricultural crops that will significantly contribute to the advancement of agricultural monitoring following abrupt changes in the local farm-water system (Hochberg et al., 2015). Remote sensing capabilities across the thermal wavelength region is advancing in both spatial and spectral capabilities. Thermal was once limited to relatively coarse spatial resolutions, often imagery 10 times the resolution of optical counterparts, and is now improving. These capabilities will allow optical and physical models that have been limited to airborne campaigns up to the present to be conducted with repeatable delivery across the globe.

6.4. Additional opportunities: flooding agricultural lands

Remote sensing applications discussed in this paper can be applied to other types of abrupt hydrologic changes in agricultural lands, specifically to opportunities in agricultural flooding to optimize groundwater recharge. Currently, groundwater recharge is of paramount importance in regions experiencing drought and overdraft. Aquifers with overdrafted groundwater supplies also underlie expansive agricultural land use, allowing the possibility to temporarily flood these regions. While recharge over agricultural lands can facilitate groundwater banking, it is important to identify crops best suited for saturated conditions (O'Geen et al., 2015). Remote sensing of agricultural responses to groundwater banking activities can play an important role in sustaining crop health and productivity while also restoring water supplies.

Acknowledgements

We acknowledge National Science Foundation grant #1148897 for the conduction of our investigations and communication of this research. We are also grateful to the University of Concepción – Chillàn for academic support, specifically Dr. Diego Rivera Salazar, Jose Luis Arumi, and Carlos Sea for their efforts, assistance and provision of resources for data collection and analysis. We are also grateful to Luis Acuña and Nicolas Simian of Viva Tierra Organic for their cooperation and contribution of ground data, and their enthusiasm for our research.

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