CHAPTER 7

A Framework for Agricultural Water Management Support Following the 2010 Maule Earthquake

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Introduction

Abrupt changes in the hydrologic system can severely alter environmental functionality, requiring immediate emergency responses to facilitate appropriate disaster management techniques. Disaster management has therefore become increasingly important for mitigation actions. However, emergency management of post-earthquake disasters largely focuses on infrastructural and humanitarian threats, which has left a significant gap in understanding of agricultural responses and potential for recovery. We address this problem to aid improved farm recovery from earthquakes at the food-water nexus, and ultimately, food security. Remote sensing—that is, imagery datasets through satellite or aerial platforms—can provide information about conditions that precede an abrupt disaster event and improve a grower's understanding of the impact, and consequently make better management decisions (Joyce et al., 2009a).

Significant gaps in knowledge of hydrologic vulnerability and resilience following earthquakes are best attributed to the unpredictability of the time and location of an extreme event which need data collection prior to

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its occurrence (Geller, 1997; Hough, 2009). While comprehensive ground measurements cannot be established in advance for an unspecified time and place of an earthquake, remote sensing can supplement these gaps using current and archived data. Remote sensing enables us to gather information prior to agricultural damage, providing a technical opportunity to monitor disaster response and recovery across a variety of temporal, spatial and spectral resolutions (Joyce et al., 2009b). As a case study, we investigate agricultural recovery from hydrologic damage at the field scale following the 8.8 Maule earthquake by coupling ground and remote measurements. We specifically investigate orchard recovery management from seismically influenced waterlogging following the 2010 Maule, Chile earthquake.

Earthquake Hydrology

Earthquake-water dynamics are well studied, with observed connections to a variety of behaviors that can include changes to groundwater supply, surface water supply and water quality. These effects vary in timing and magnitude, dependent on earthquake magnitude, distance to epicenter and aquifer structure (Montgomery and Manga, 2003). Unexpected changes in local hydrology can be especially problematic for crop management, and hence threaten local food security. To improve our understanding of agricultural management following abrupt environmental changes, this study focuses on the effects of seismically related groundwater changes on agricultural land use. Table 7.1 displays observed groundwater level responses to a variety of earthquake magnitudes and locations. Varying behaviors of earthquakes observed show groundwater connections, positioning crop water distribution uniformity as vulnerable to such abrupt hydrologic shifts. As the need to explore crop recovery from natural disasters

Table 7.13 Recorded seismic effects on groundwater levels following earthquake events illustrate the frequency of earthquake impacts on groundwater behavior as well as the unpredictability of hydrologic responses.

Year	Location	Magnitude	Δ Depth (m)	Author
1989	Loma Prieta, California, USA	7.1	–21.0	Rojstaczer and Wolf, 1992
1993	Taiwan, China	7.3	1.0–11.1	Chia et al., 2001
1994	Parkfield, California, USA	4.7	–0.16 – + 0.34	Quilty and Roeloffs, 1997
1997	Tono, Japan	5.8	–0.29–1.8	King et al., 1999
2004	Japan	9.0	+/–5.0	Kitagawa et al., 2006
2010	Canterbury, New Zealand	7.1	5.0–20.0	Cox et al., 2012

is clear, we narrow our focus on local decision-making to facilitate crop recovery in the wake of earthquake-induced waterlogging.

Waterlogging of Agricultural Soils

Waterlogged agricultural soils can adversely affect crop health, dependent on factors such as time of flood, duration and crop affected. While waterlogging during cold, dormant months is known to cause minimal damage on dormant trees and crops, the same conditions during the growing season can eliminate entire crops or orchards (Kozlowski, 1984). Specifically, orchards and crops with poor drainage can suffer from hypoxic soils (Crawford, 1982), vegetative diseases (e.g., phytophthora) and salinity (Oster, 1994). It is thus important to better understand waterlogging effects upon orchards, specifically how orchard crops recovery from temporary waterlogging during the growing season. Capturing the spatial variation and progression of crop health over time to such stress can be especially useful for irrigation uniformity and responsible farm water management. Such time and space analysis can be optimally understood through remotely sensed imagery.

Remote Sensing in Agricultural Water Management

The usefulness and importance of satellite and airborne platforms for emergency management based on sensor capacities is widely acknowledged in the remote sensing community (Joyce et al., 2009a; 2009b). Joyce et al. (2010) reviews the use of remote sensing imagery in emergency management, identifying a large gap in understanding recovery to natural disasters and emphasizing the need for collaboration among various stakeholders to better understand disaster management in smaller niches such as agriculture. It is therefore clear that the substantial need to improve disaster response strategies in agricultural settings can be addressed in the utilization of remote sensing technologies. Remotely sensed imagery has been used to understand aspects of cropland recovery from disasters for land-use planning (Burby et al., 2000). In this chapter, we investigated the use of satellite imagery in a more narrow focus, specific to agricultural needs. We direct remote sensing to capture spatial heterogeneity of agricultural impacts following the earthquake event to pinpoint areas of orchard vulnerability (canopy stress) and resiliency (canopy vigor).

Remote Sensing of Orchard Stress

In this study, it is important to note that apple orchards can tolerate waterlogging during dormancy, but submergence during active growth—suggested for any length of time—has been known to cause root death

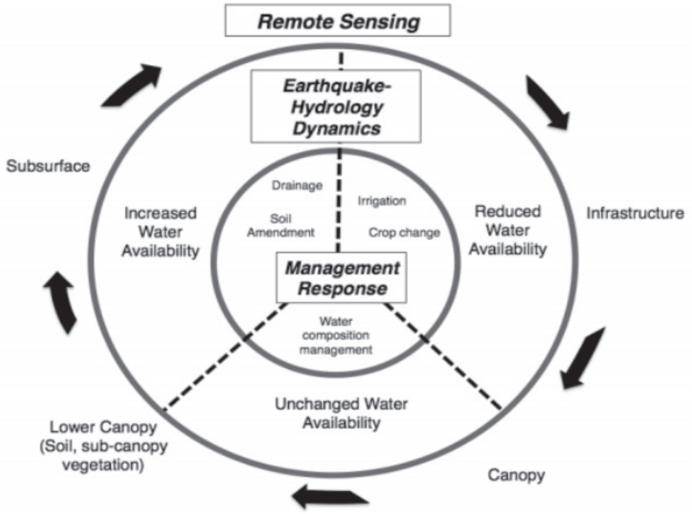

Fig. 7.36 A framework to support agricultural decision-making after earthquake events, specific to remote sensing of earthquake-water dynamics Rodriguez et al. (2016).

(Faust, 1978). Waterlogging observations associated with the Maule earthquake began in February 2010—Central Chile's growing season. To strategize remote sensing applications of this orchard following an abrupt hydrologic change, we follow the newly introduced framework by Rodriguez et al. (2016) for post-earthquake agrohydrologic remote sensing (PEARS, Fig. 7.36). This approach navigates through remote sensing of crop stress at the canopy, sub-canopy or subsurface level dependent upon the hydrologic behavior associated with the earthquake and what can be sensed from an aerial or orbital perspective—from which we will draw upon remote sensing exploration of the orchard canopy. While waterlogged soils are a sub surface impedance on tree health, summer orchard canopies are fully open and thus intercept sub-canopy and soil reflectance. Waterlogged soils can be visually identified with sufficient multispectral sensor data (Dwivedi et al., 2009), using specific wavelengths (Zarco-Tejada et al., 2012), or by calculating spectral ratios in vegetation indices (Glenn et al., 2008). It is important to note that ground data collection is crucial to eliminate unlikely stressors (water quality, over- or under-irrigation, abnormal weather, etc.) to narrow down the best-suited remote sensing approach for the context.

Applying a Framework

We apply a newly introduced conceptual model that dovetails current research of earthquake-water dynamics with applicable remote sensing of soil-plant-water relations. Figure 7.36 illustrates the PEARS framework to support post-earthquake agricultural management using remote sensing techniques specific to earthquake-water dynamics (Rodriguez et al., 2016). The framework of focus categorizes earthquake-water dynamics into three components: (1) changed surface water supplies, (2) changed groundwater supplies, and (3) water quality change. For this study, observed groundwater elevation coupled with mid-growing season occurrence prioritized management of increased groundwater levels. We thus apply the framework to assess vulnerability of an apple orchard site to abruptly elevated water tables, monitoring canopy vigor. This approach allows us to assess the effectiveness of the grower's decision to facilitate drainage through trenching, as well as the resiliency of the orchard amidst mid-season waterlogging. We additionally set the stage for remote sensing guidelines to monitor and improve farm operations amidst agro-hydrologic disruptions that can be employed in similarly affected sites.

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Objectives

This study characterizes field-scale responses of apple orchard operation to extreme waterlogging, in a case study of Coihueco, Chile (–37 latitude, –71.82 longitude). Specifically, we will improve understanding of agricultural land management at the field scale by monitoring local farm decisions implemented to sustain apple orchard production amidst abrupt waterlogging. Here, we investigate variables driving orchard stress (groundwater elevation) and characteristics that indicate stress (decline in vigor as indicated by decreasing canopy greenness). Assessment of rootstock and cultivar vigor responses to poor drainage conditions is critical for organic apple growers—the leading organic commodity in Chile. Varying rootstocks across the study site must be considered as apple trees have demonstrated varying abilities among rootstocks to conduct water to the scion (Olien, 1986). Furthermore, we employ remote sensing technologies in alignment with a consistent post-earthquake framework to support agricultural management.

Materials and Methods

Background & study site

An 8.8 magnitude earthquake event occurred February 27, 2010 off the coast of Concepcion, Chile that devastated the Maule and Bíobío Regions. Local observations recorded structural damages (Tang et al., 2010), liquefaction compaction (Verdugo, 2012) and increased streamflow (Mohr et al., 2012) following the earthquake. Groundwater supplies serve as an important source of irrigation water, especially during the growing season (December–February) when seasonal mountain snowmelt is no longer available, thus changes in availability has secondary impacts. Abrupt hydrologic changes in this region can threaten local agricultural productivity, driving the motivation of our study.

The study site observed is located in Coihueco, Chile of the Cato River Watershed, approximately 500 kilometers south of the capital city of Santiago (Fig. 7.37a). Coihueco is in the Biobío Region (Region VIII, –37 latitude, –71 longitude) whose economy relies largely on agriculture, supporting 16% of the employment sector, behind personal services (28%) and commerce (18%, Dresdner et al., 2009). The Biobío Region traditionally experiences a Mediterranean climate of hot dry summers and cool wet winters, systematically bringing spring snowmelt to irrigate throughout the Cato River Watershed dominated by andisols, sands and fluvial deposits (OECD, 2009). Here, appropriate crop water deliveries are vulnerable to winter snowpack, irrigation infrastructure and good drainage. It is thus important to assess if there were changes in hydrologic conditions following the February 27, 2010 earthquake, how local crop management can adapt, and whether strategies were successful.

The specific site of study is a 20-hectare apple orchard (approx. 50 acres) located at –37 latitude, –71.82 longitude managed by Viva Tierra Organic

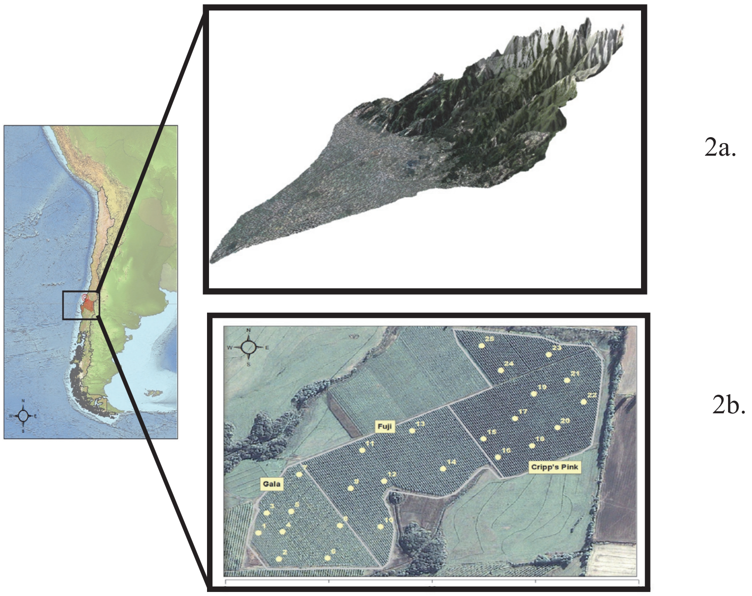

Fig. 7.37 (2a) The Cato River Watershed in the Biobío Region (VIII) of Central Chile, and (2b) The study site: a 20-hectare organic apple orchard (approx. 50 acres) of Gala, Fuji, and Cripp's Pink apples located at –37 latitude, –71.82 longitude, managed by Viva Tierra Organic within the Cato River Watershed.

Table 7.14 Apple cultivars planted with associated rootstocks and installed boreholes.

Cultivar	Rootstock	Boreholes
Gala	M106 + M9	1–8
Fuji	M106	9–14
Cripp's Pink	M106 + M9	15–26

(Fig. 7.37b). In 2007, three different varieties of apple cultivars—Gala, Fuji, and Cripp's Pink—were planted with various rootstocks (Table 7.14). The growing season for this crop runs approximately from green-up in November through harvest in early-mid March. Following the February 27, 2010 earthquake, elevated water tables were observed by local growers, provoking suspicion of waterlogging. To salvage the newly planted trees, emergency management decisions were made to trench along the entire southern border of the orchard to accelerate drainage, thus preventing hypoxia and onset of disease. The methodology conducted characterized field-scale apple orchard responses to earthquake-induced waterlogging, assessed the apple orchard resiliency to temporary waterlogging, and assessed effectiveness of local decision-making following a remote sensing framework. Results support framework development to identify actions and decision-making that promotes agricultural recovery following abrupt hydrologic disruption.

Borehole Observations

Twenty-six monitoring wells were distributed across the orchard in December 2009 using polyvinyl chloride (PVC) tubes 150 cm deep, providing records of pre-earthquake subsurface hydrology. While 26 wells were installed, only a fraction of the wells were selected to use for data purposes. Boreholes that did not experience any change in groundwater were not selected for data collection. Specifically, wells 5, 7, 8, 12, 15, 17, 18, 20, 21, 22 and 25 were the only wells showing elevation change after the earthquake event. These boreholes were selected to utilize data representative of the phenomena observed by the farm manager and owner. The borehole locations were geo-located using a Garmin Oregon Global Positioning System (GPS) to interpret spatial variation of water table fluctuations before and after the earthquake event. The depth to water table was measured consistently by the same irrigation manager using steel measuring tape from the top of the PVC tube as the reference point (Harter, 2008). The date, well depth and comments were logged and saved in an electronic spreadsheet file. Borehole observations were recorded from December 2009 until May 2014 when consistent records indicated 'good drainage', at 120 cm from observation surface or deeper. After good drainage was declared by the grower, data collection activities were reduced to bi-annual occurrences. A trench was excavated three days after the earthquake to mitigate waterlogging (March 2, 2010) along the south and southwest borders of the orchard to counteract elevated ground water levels. This data was also used for spatial interpolation to remotely monitor tree health variability throughout the orchard before and after the earthquake event. Water quality measurements were also sampled and provided by a contracted vendor following the earthquake event to ensure that salinity levels were not adversely elevated, thus narrowing our focus to monitor effects of groundwater elevation on orchard canopies using PEARS.

Precipitation Records

Agro-meteorological stations recorded the precipitation data used for this study, collected and managed by the Department of Hydrologic Resources at the University of Concepción–Chillán. The station is located on the university campus at –36.5667 latitude, –72.1 longitude, and 129.92 meters above mean sea level. Data was collected beginning January 1965 and is still recording weather data. Data was analyzed according to total sum precipitation recorded each month. This dataset provides data prior to the earthquake event to better interpret environmental conditions preceding the earthquake and associated groundwater changes, as well as precipitation following the event to confirm that abnormal groundwater levels were not influenced by an abnormally wet rainy season (Fig. 7.38).

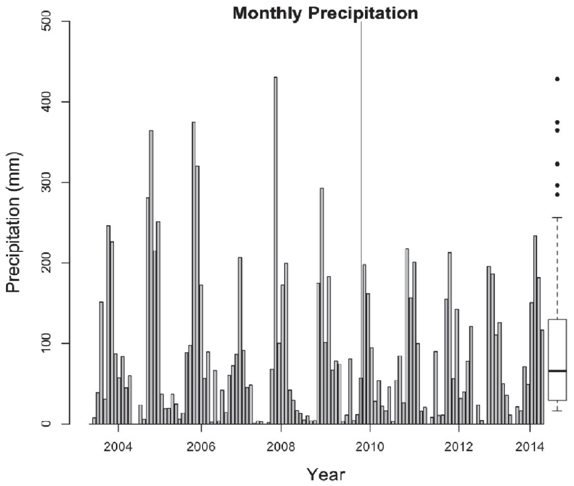

Fig. 7.38 Precipitation records from 2008 to 2014. Earthquake event is indicated by red vertical line to delineate precipitation events prior to and following the hydrologic disturbance. Mean distribution of precipitation measurements from 2004–2014 is displayed by boxplot at right.

Imagery

Imagery was collected from the Landsat Data Continuity Mission (LDCM), utilizing Landsat Thematic Mapper 5 and Landsat Enhanced Thematic Mapper (ETM+) 7. This sensor sufficiently covers the 20 hectare (20,000 m^2) orchard study site, as Landsat 5 TM and Landsat 7 ETM+ provide coverage at 30 × 30 meter pixels, allowing spectral measurements across approximately 222 unique pixels. Atmospherically corrected imagery from LEDAPS was selected for Landsat 5 TM and Landsat 7 ETM+. Dates were selected prior to and following the earthquake with consideration of cloud cover, the apple growing season and irrigation scheduling. Satellite overpasses within 3 days of irrigation scheduling were not used. Irrigation events can cause artificially high spectral measurements, as sprinkler-irrigated water can cause abnormal blue band measurements from water, dampened reflectance from soil darkening and green or infrared measurements due to immediate leaf and cover crop green up the following day.

Vegetation Indices

While we know that the visible and near infrared are important in monitoring vegetative trends, there are many spectral ratios that have been demonstrated as useful throughout the literature. This study utilizes the Normalized Difference Vegetation Index (NDVI), calculated by the ratio:

$$\frac{p_{NIR} - p_{RED}}{p_{NIR} + p_{RED}} \tag{10}$$

NDVI has successfully monitored and identified vegetative trends with responses to groundwater elevation changes (Aguilar et al., 2012; Sun et al., 2008). NDVI is sufficient for this study, as the orchard study site provides near complete vegetative cover, removing the need for soil correction indexes (e.g., Soil Adjusted Vegetation Index) or overly dense tree canopies due to consistent pruning and younger trees (Enhanced Vegetation Index).

Results and Discussion

Groundwater responses

Knowledge of groundwater depths is important for farm management to facilitate proper drainage, maintain root zone aeration for crops and monitor subsurface irrigation supplies. Figure 7.39 displays groundwater stages before the earthquake, after the earthquake and longer-term water level tracking following emergency water management decision-making (i.e., trenching). Measurements prior to the earthquake from December 2009–February 2010 were categorized as ‘Pre-Earthquake’ observations,

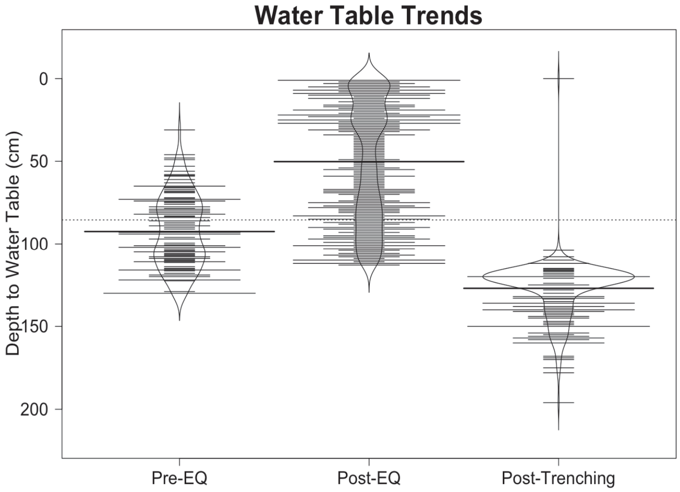

Fig. 7.39 Water table observation records suggesting elevated water table after the earthquake event (February 2010–2011) and longer term (October 2011–January 2014).

while records taken following the earthquake event were conducted from October 2010–December 2011 were labeled as 'Post-EQ' records. Records were later categorized as 'Post-Trenching' from 2012–2014, as these records revealed groundwater table levels returning to depths once again acceptable for apple production. Observation well records show an initial increase in average groundwater elevation after the earthquake, followed by a return to optimal depths (120–150 cm) likely due to management decisions (i.e., trenching) that facilitated groundwater drainage. Figure 7.39 shows initial groundwater table elevation at acceptable depths, with some borehole measurements indicating groundwater closer to the root zone than desired by the farmer—that is, above 120 cm impeding root aeration. These records also followed trenching decisions, yet were still influenced by waterlogging conditions. The lag time observed from the date of trenching to subsided groundwater levels is likely a combined product of soil properties and subterranean water sources. This can often be attributed to a sustained high groundwater table or underground spring released during the earthquake event, as can occur during earth movement (Montgomery and Manga, 2003).

Precipitation Trends

Precipitation records show that seasonal rainfall before and after the February 2010 earthquake, denoted by the red vertical line, did not exceed normal moisture regimes (Fig. 7.38). Figure 7.38 describes average historical precipitation to determine significantly higher or lower precipitation trends that could affect groundwater overdraft or recharge. Historical precipitation records for Chillán, Chile fall within 68.5–236.5 mm during the rainy season (May–October) and 14.9–26.2 mm during the dry season (November–April; Fontannaz, 2001). Average monthly precipitation records across the 2004–2014 period revealed that only 6 of 126 observations were significant outliers. Furthermore, the rise in subterranean water levels occurred during the growing season, at the trough of precipitation inputs and traditional peak of irrigation drawdown by local farmers. The station observations thus suggest that sustained groundwater level elevation was not influenced by above average rain events. We can therefore deduce that the shallow groundwater phenomena noticed abruptly after the earthquake event was likely driven by subterranean sources.

Orchard Spatial Responses to Groundwater Trends

Remote imagery used to calculate the Normalized Difference Vegetation Index (NDVI) across the orchard study site allowed identification of pre-earthquake orchard health and post disaster responses. It is clear that prior to the earthquake, canopy health was not unhealthy nor of concern to the grower, while moderate stress was detectable along the northeastern border of the Cripp's Pink block. Although orchard canopy health is still adversely affected one year after the earthquake event, yet shows improvement after the earthquake (2012–2014). Canopy health improvements are likely attributed to improved drainage facilitated by trenching, lowering a relatively high water table. Additionally, management decisions that preserved the life of the trees allowed younger trees planted prior to the earthquake to grow larger with age, consequently producing larger tree canopies. While struggling orchard health was evident immediately following the earthquake throughout the 2011 growing season, orchard health recovered fully and became more uniform with less hotspots of poor orchard health. Spatial mapping of orchard health before and after the earthquake indicated reduced orchard health in response to an abruptly elevated water table (0 to 120 cm) that gradually decline ds to optimal depths below 120 cm. Figure 7.40a–c displays NDVI maps that, over time, become more uniform, with less 'hotspots'—areas suffering from exceptionally low canopy health—after the earthquake event. This lag time to recovery is likely a function of the soil properties and groundwater table sources that sustained groundwater levels even after trenching. A time series analysis of canopy health using NDVI not only allows a time series analysis and identification of areas most adversely affected, but also allows correlation of remotely estimated canopy health to ground measurements (i.e., groundwater depths).

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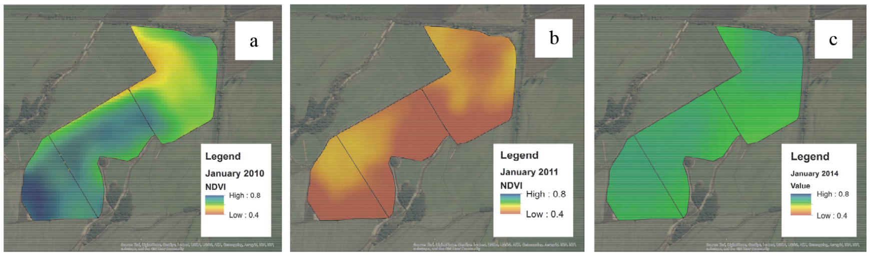

Fig. 7.40a–c Spatial visualization of orchard NDVI suggests variability of orchard health, reduced greenness after earthquake, and recovery after trenching.

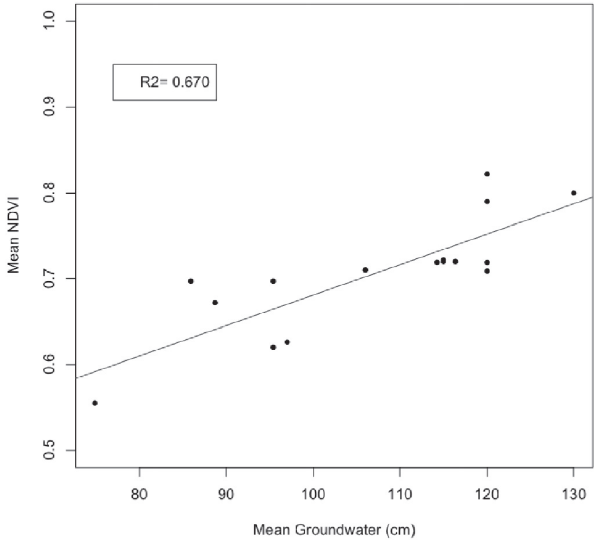

Fig. 7.41 Correlation of mean NDVI measurements to mean groundwater levels across 16 different observation dates, suggesting improved orchard health with a deeper groundwater table.

Groundwater Relationship to Orchard Behavior

In addition to spatial mapping and time series analysis, remotely estimated NDVI values were also utilized to identify a significant relationship to adverse waterlogging conditions. To do so, mean calculated groundwater levels recorded *in situ* across the orchard were correlated to corresponding mean NDVI estimations from atmospherically corrected Landsat imagery. The correlation revealed that mean groundwater table levels approaching the surface inhibited orchard greenness (NDVI), while groundwater levels that remained closer to target depth of 120–150 cm were tied to improved orchard canopy health. The correlation fit value of 0.67 suggests that groundwater depths influenced orchard health as represented by NDVI; this suggests that the rootstocks and apple cultivars selected were tolerant to short-term waterlogging during the growing season and likely recovered due to the receding groundwater table. The correlation detected also indicates that decisions to facilitate drainage by trenching did improve orchard canopy health, hence, prevent tree damage and death. These findings will be especially valuable if waterlogged (e.g., flooding) conditions persist in the Cato River watershed, or if extreme events forcing similar conditions recur in this region.

Conclusions

This study was largely limited by the data collection surrounding the earthquake. While it proved fortuitous to have pre-earthquake baseline information. Data collection stalled following the earthquake as efforts largely went to infrastructural, farm and personal recovery needs. Additionally, data collection followed varying protocols as water table levels were recorded largely at the convenience of farm operations, and by multiple people. These limitations are typical of data collection in a working farm site and largely contributes to the utility of remote sensing in agricultural practices.

As climate projections suggest a high likelihood of increasing extreme events, we must better prepare our vulnerable food supplies through coping strategies such as emergency management and disaster recovery. These efforts, though essential and urgently needed, are still immaturely explored. Further research is therefore needed, especially if we expect to create a more comprehensive and robust framework for efficient and rapid agricultural management following abrupt disruptions to agricultural water deliveries. Ample opportunities are present and contributing to this emerging field, with a more thorough understanding enabled by remote sensing applications. This research can support land-use management for recovery of irrigation supplies as well as aid in anthropogenic changes to local hydrology.

In the broad scope of food production and water resource management, groundwater supplies become increasingly depleted in arid and semi-arid climates. To better harness seasonal snowmelt that fuels seasonal irrigation, groundwater recharge projects are now a priority if not mandatory for sustainable population support. Target recharge locations must allow temporary inundation during snowmelt periods without damage to overlying land use. In many Mediterranean climates, valley farming practices are supported by spring snowmelt, requiring recharge locations to typically be rangeland or crops that can survive temporary waterlogging. Crops overlying unconfined aquifers are in prime target areas for groundwater recharge projects. While it is ideal to channel recharge areas while perennial are dormant, spring snowmelt can often times fall within the period of green up. Recharge during dormancy may become even less likely if changes in climatic trends begin to shorten. This study therefore provides a better understanding of crop responses to temporary water inundation during the growing season.

While natural causes of flooding are inevitable, it is also important to identify crops more tolerant to anthropogenic flooding. Our results suggest that temporary (3 days) flooding of the observed cultivar-rootstock combinations during the growing season did initially impose orchard stress, but permitted fruit production without tree death. The orchard of study was also found to reach full recovery after prolonged drainage. These results enable a better understanding for local crop management that can aid pre-hazard planning for local growers, as well as empower informed decision making for crop extension educators and agencies navigating projects to temporarily flood agricultural lands.

Acknowledgements

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