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The relation between land use and subsidence in the Vietnamese Mekong delta

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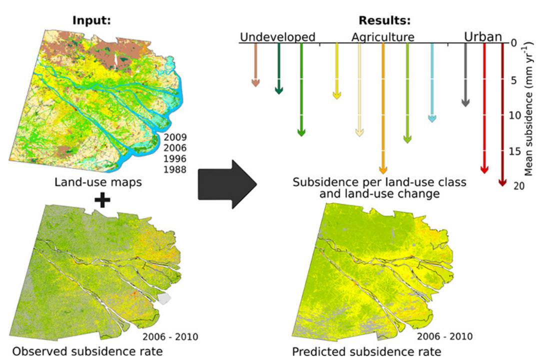
HIGHLIGHTS

- Land-use practices can influence subsidence processes, amplifying natural subsidence or inducing anthropogenic subsidence.
- We assess the relation between land use and subsidence using land-use time series and InSAR-derived subsidence rates.
- Different land-use classes are experiencing different rates of subsidence.
- Highest subsidence rates were found for land-use classes in which natural conditions were most altered by human activities.
- Land use and land-use history have an indirect, causal relationship with subsidence rates in the Mekong delta.

GRAPHICAL ABSTRACT



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ABSTRACT

The Vietnamese Mekong delta is subsiding due to a combination of natural and human-induced causes. Over the past several decades, large-scale anthropogenic land-use changes have taken place as a result of increased agricultural production, population growth and urbanization in the delta. Land-use changes can alter the hydrological system or increase loading of the delta surface, amplifying natural subsidence processes or creating new anthropogenic subsidence. The relationships between land use histories and current rates of land subsidence have so far not been studied in the Mekong delta.

We quantified InSAR-derived subsidence rates for the various land-use classes and past land-use changes using a new, optical remote sensing-based, 20-year time series of land use. Lowest mean subsidence rates were found for undeveloped land-use classes, like marshland and wetland forest (~6–7 mm yr^{-1}), and highest rates for areas with mixed-crop agriculture and cities (~18–20 mm yr^{-1}). We assessed the relationship strength between current land use, land-use history and subsidence by predicting subsidence rates during the measurement period solely based on land-use history. After initial training of all land-use sequences with InSAR-derived subsidence rates, the land-use-based approach predicted 65–92% of the spatially varying subsidence rates within the measurement error range of the InSAR observations (RMSE = 5.8 mm). As a result, the spatial patterns visible in the observed subsidence can largely be explained by land use. We discuss in detail the dominant land-use change pathways and their indirect, causal relationships with subsidence. Our spatially explicit evaluation of these

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pathways provides valuable insights for policymakers concerned with land-use planning in both subsiding and currently stable areas of the Mekong delta and similar systems.

1. Introduction

Many of the world's major deltas have experienced significant anthropogenic change during the past decades. Within Southeast Asia, the Vietnamese Mekong delta stands out as hotspot of anthropogenic land-use change (Giri et al., 2003). Following Vietnam's transition towards an open-market economy in 1986, the vast majority of natural wetlands and forested areas in the delta have been converted to agricultural lands dominated by rice paddies (Funkenberg et al., 2014; Tran et al., 2015). Along the Mekong river branches, orchards and fish farms have been created, and in the coastal zone vegetables farms sprouted on the higher elevated beach ridges. Furthermore, mangroves have been cut to make place for shrimp farms and other aquaculture (a. o. Binh et al., 2005; Sakamoto et al., 2009; Tong et al., 2004). Over the years, rice production in the delta has increased as intensified irrigation allowed for more crops per year (Sakamoto et al., 2006). Moreover, the delta has become progressively urbanized, with an ever-densifying and expanding network of roads connecting the fast-growing settlements, cities and industrial areas (Karila et al., 2014; Tran et al., 2015). Other large-scale alterations of the delta system include increased flood control through extensive dike systems (Triet et al., 2017), sand mining activities in the river branches (Brunier et al., 2014), and wide-spread exploitation of groundwater resources (Wagner et al., 2012). The Vietnamese Mekong delta is further impacted by reduced sediment supply due to upstream dams (Kummu and Varis, 2007; Kondolf et al., 2014), decreased hurricane activity (Darby et al., 2016), salinization (Renaud et al., 2015), coastal erosion (Anthony et al., 2015) and global sea-level rise in response to climate change (Wassmann et al., 2004). On top of that, the delta is subsiding at rates up to several centimeters a year, exceeding current absolute sea-level rise by up to a magnitude (Erban et al., 2014; Minderhoud et al., 2017).

Land subsidence is a natural phenomenon in delta systems. Deltaic sediments are highly compressible and susceptible to significant natural compaction during deposition and subsequent soil formation. Enhanced land subsidence in deltas due to human activities is widely recognized (e.g. Syvitski et al., 2009; Giosan et al., 2014). Human use of land and groundwater resources can amplify natural subsidence processes or initiate new anthropogenic subsidence in different ways (Galloway et al., 2016). Firstly, subsidence can be enhanced by direct loading of the delta surface, both by natural material, such as water and sediment, and by anthropogenic artifacts, such as buildings and infrastructure. Secondly, drainage of wetlands to prepare for agricultural use leads to a lowering of the phreatic water table, causing compaction and aeration of the subsoil. Consequent decomposition of organic material (oxidation) causes additional volume reduction (e.g. Van Asselen et al., 2009). Additionally, the extraction of groundwater from deeper aquifers (water-bearing sediment layers), to meet the increasing freshwater demands of rapidly urbanizing areas, agriculture and aquaculture, can trigger aquifer-system compaction (e.g. Galloway and Burbey, 2011; Gambolati and Teatini, 2015). In the Vietnamese Mekong delta evidence of widespread absolute subsidence was recently revealed by InSAR (Interferometric Synthetic Aperture Radar) (Erban et al., 2013, 2014). Minderhoud et al. (2017) demonstrated that a steady increase of groundwater use and excessive pumping over the past decades has dramatically accelerated subsidence in this area. Together, these land-use developments of the past decades in the Vietnamese Mekong delta have affected the natural environment, and introduced anthropogenic drivers, enhancing subsidence rates.

Subsidence is a sluggish process that may show a remarkably slow but pertinent response to a change in land use, due to time-dependent effects of both subsidence *drivers* and *processes*. For example, the amount of groundwater extraction (*driver*) might grow gradually over the years following a change in land use. The consequent aquifer-system compaction (*process*) increases even more slowly, as it takes time for overpressure to dissipate from clay-rich sediments which than start to compact and due to time-dependent secondary consolidation. This process can continue up to decades after initiation. This implies that groundwater extractions under past land use still can affect present-day subsidence rates; hence land use and land use history might be important indicators of present-day subsidence rates in a delta.

In this study, we aim to quantify the relationship between land use and land subsidence rates and to determine the effect of past land-use changes in the Vietnamese Mekong delta. We hypothesize that land use and land-use history correlate to subsidence in two ways: 1) by affecting subsidence drivers and processes as described above, and, 2) through location preference of certain land-use types for a geomorphological setting with specific subsidence characteristics, e.g. orchards prefer higher elevated, sandy natural levees, which are less prone to shallow compaction. Thus, land use could potentially explain part of the spatial patterns of observed subsidence rate and may serve as an indirect proxy for subsidence rate. We used optical remote sensing-based products to map land use and land-use change, together with InSAR-derived subsidence rates for a representative part of the Mekong delta. We created a time series of land use from Landsat TM5 images and determined subsidence rates for specific land-use sequences both for areas with unchanged land use in the period 1988–2006, and for areas in which land-use changes occurred during this period. Subsequently, we assessed the impact of land use and land-use changes on subsidence rates and derive time-dependent effects of subsidence. Moreover, we evaluate the strength of the relationship between land use and subsidence rate by predicting and mapping subsidence rate solely based on land use and land-use history. The ability to predict subsidence rates based on land use and land-use history, after the initial training of individual land-use change sequences with observed subsidence rates, reveals the relation between land use and subsidence in the Mekong delta.

2. Data and methods

2.1. Consistent land-use time series

A consistent land-use time series of the Mekong delta over the past decades is required to study the relation between land use, land-use change and subsidence rates. The Vietnamese government produces land-use maps every five years (Dijk et al., 2013; Phuong and Catacutan, 2014), but they are not publicly accessible and, if available, lack metadata on data sources and used methods. Besides these national maps, many land-use maps exist for the Mekong delta, however they all vary in terms of *subject* (e.g. rice cropping system: Bouvet and Le Toan, 2011; Karila et al., 2014; Kono, 2001; shrimp farm expansion: Giang and Hoa, 2013; Tong et al., 2004; Vo et al., 2013), *spatial extent* (regional: e.g. Chen et al., 2012; delta-wide: e.g. Sakamoto et al., 2006, 2009; Son et al., 2013 and Xiao et al., 2006), *defined land-use classes* (Kuenzer et al., 2011), *used satellite imagery* (MODIS (e.g. Kuenzer and Knauer, 2013), SPOT (e.g. Nguyen et al., 2012), Landsat (e.g. Funkenberg et al., 2014) or Rapid Eye (e.g. Huth et al., 2012)) and *classification method and accuracy* (Kuenzer et al., 2011; Kuenzer and Knauer, 2013). Consequently, no single study or combination of studies provided a consistent land-use time series of the Mekong delta appropriate for our study.