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Estimating rice production in the Mekong Delta, Vietnam, utilizing time series of Sentinel-1 SAR data

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ABSTRACT

Rice is the most important food crop in Asia and rice exports can significantly contribute to a country's GDP. Vietnam is the third largest exporter and fifth largest producer of rice, the majority of which is grown in the Mekong Delta. The cultivation of rice plants is important, not only in the context of food security, but also contributes to greenhouse gas emissions, provides man-made wetlands as an ecosystem, sustains smallholders in Asia and influences water resource planning and run-off water management. Rice growth can be monitored with Synthetic Aperture Radar (SAR) time series due to the agronomic flooding followed by rapid biomass increase affecting the backscatter signal. With the advent of Sentinel-1 a wealth of free and open SAR data is available to monitor rice on regional or larger scales and limited data availability should not be an issue from 2015 onwards. We used Sentinel-1 SAR time series to estimate rice production in the Mekong Delta, Vietnam, for three rice seasons centered on the year 2015. Rice production for each growing season was estimated by first classifying paddy rice area using superpixel segmentation and a phenology based decision tree, followed by yield estimation using random forest regression models trained on in situ yield data collected by surveying 357 rice farms. The estimated rice production for the three rice growing seasons 2015 correlates well with data at the district level collected from the province statistics offices with R^2s of 0.93 for the Winter–Spring, 0.86 for the Summer–Autumn and 0.87 for the Autumn–Winter season.

1. Introduction

The Mekong Delta, often referred to as “Vietnam's Rice Bowl”, is the biggest rice producing region in Vietnam with the majority of its land area used for cultivating paddy rice. In 2015 Vietnam was the world's third biggest exporter and fifth largest producer of rice (FAOSTAT, 2015). Accurate and timely information about the rice production is vital in the context of food security, trade policy, land and water management and budgetary planning. Rice production and trade affect people on a global scale, as rice feeds half of the constantly growing population, especially in developing regions in Asia, Latin America and Africa (Kuenzer and Knauer, 2013; Fairhurst and Dobermann, 2002; Alexandratos and Bruinsma, 2012; Khush, 2005; United Nations, 2015). The world market price of rice is highly linked to the export from the 12 biggest rice exporters, which are responsible for 90% of the global rice trade (Muthayya et al., 2014). To alleviate the effects on food security in rice importing countries caused by the volatile rice market, initiatives like the FAO Rice Market Monitor, the GEOGLAM Crop Monitor and Asia-RiCE provide information on crop status, early warning on crop damage and factors influencing expected rice production. In spite the importance of this topic decision and policy makers still heavily rely on data published by national statistics offices, collected through samples, aggregated to administrative units and published six months to a year after the relevant harvest has been performed. The Mekong Delta is a coastal floodplain and subject to natural hazards such as floods, droughts and saltwater intrusion, which destroy rice crops and impact farmers livelihoods and food security. Remote sensing based rice production estimations can aid in the timely delivery of relevant information to decision and policy makers regarding rice production, trade and food security.

Rice is one of the few crops that can be grown under the condition of agronomic flooding. This management practice refers to a constant or periodic water layer covering the soil in which the plants grow, for the purpose of weed and pest control. In the Mekong Delta rice fields are usually flooded prior to transplanting rice seedlings from a nursery into the fields. The growth of rice plants can be divided into the vegetative, reproductive and ripening phase (De Datta, 1981) and each phase coincides with a change in plant morphology. These changes affect the

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wave-plant-water interaction of electromagnetic waves in the visible light as well as the microwave spectrum, resulting in a unique temporal signal of rice areas when observed with multispectral or SAR sensors. Detecting this temporal signal in remotely sensed time series has been the most frequently applied method to map rice areas with multispectral and microwave sensors (Kuenzer and Knauer, 2013; Mosleh et al., 2015; Dong and Xiao, 2016).

More than 90% of the global rice production is grown in Asia, where rice is often cultivated in areas with high precipitation and frequent cloud cover. Frequent cloud cover has been listed as a challenge for remote sensing of rice with multispectral sensors, which therefore require acquisitions with a high temporal frequency to accurately measure the flooding events of rice fields (Xiao et al., 2006). Active microwave sensors are much less affected by cloud cover and due to their all-weather, day and night imaging capabilities and have been used since the 1990s to map rice areas. Studies using time series data from C- and X-band sensors have shown their potential for rice mapping, the European Remote Sensing satellites (ERS) 1 and 2 (Aschbacher et al., 1995; Kurosu et al., 1995; Patel et al., 1995; Chakraborty et al., 1997; Le Toan et al., 1997; Panigrahy et al., 1997; Liew et al., 1998b; McNairn and Brisco, 2004; Diuk-Wasser et al., 2006), Radarsat (Liew et al., 1998a; Panigrahy et al., 1999; Ribbes, 1999; Shao et al., 2001; Li et al., 2003; Choudhury and Chakraborty, 2006; Yonezawa et al., 2012; Yang et al., 2016; Zhang et al., 2016), Envisat ASAR (Advanced Synthetic Aperture Radar) (Bouvet et al., 2009; Bouvet and Le Toan, 2011; Karila et al., 2014; Nguyen et al., 2015), TerraSAR-X (Lopez-Sanchez et al., 2011; Pei et al., 2011; Asilo et al., 2014; Nelson et al., 2014), COSMO-SkyMed (Asilo et al., 2014; Nelson et al., 2014; Corcione et al., 2016; Busetto et al., 2017; Boschetti et al., 2017; Phan et al., 2018) and more recently Sentinel-1 (Clauss et al., 2017; Torbick et al., 2017; Onojeghuo et al., 2018; Nguyen et al., 2016; Son et al., 2017). These studies focussed on mapping rice areas, which are flooded prior to transplanting or seeding and achieved accuracies between 78% and 98%.

The backscatter signal over rice crops is sensitive to changes in above-ground plant biomass at the C- and L-band wavelengths, due to the penetration of the leaf canopy by the microwaves (Aschbacher et al., 1995; Le Toan et al., 1997; Inoue et al., 2002). This behavior can be exploited to monitor rice growth and estimate rice yield, which is correlated to the above-ground biomass (De Datta, 1981). The complex interaction of electromagnetic waves with the rice plant in its various growing stages leads to a backscatter signal consisting of multiple backscatter mechanisms, such as volume scattering from the canopy, double and multiple bounces between plants, soil and water (Le Toan et al., 1997). A number of modelling approaches have been studied to use the resulting backscatter signal to calculate biophysical parameters of the rice plant and estimate rice yield. Multivariate regression (Li et al., 2003) and neural networks (Chen and Mcnairn, 2006; Jia et al., 2013) have been used to predict rice yield and biomass, plant height and age has been correlated to C-band σ^0 with polynomial regression (Chakraborty et al., 2005), rice ear weight derived from a rice canopy scattering model has been used to predict rice yield with a linear regression model (Zhang et al., 2017) and SAR backscatter has been used as input parameter to estimate rice yield with the DNDC (Salas et al., 2007) and ORYZA2000 (Shen et al., 2009) models. While it has been noted that SAR backscatter is influenced by biophysical plant variables besides the weight of the grains (i.e. yield) and linear models might be unsuitable to fully explain the backscatter-yield relation, multiple empirical models have been successfully applied to estimate rice yields (Zhang et al., 2017; Li et al., 2003; Chen et al., 2011).

Estimating rice production, the product of yield and harvested area, from remote sensing data requires the mapping of rice area and estimation of rice yield for the mapped area. In this study we propose to combine a previously published, Sentinel-1 time series based, rice mapping procedure (Clauss et al., 2017) with rice yield predictions based on seasonal random forest regression models to estimate the rice production in the Mekong Delta, Vietnam, for three rice growing seasons centered on the year 2015. The objectives of this study are to:

- estimate rice production in the Mekong Delta in 2015 using empirical models
- study the potential of Sentinel-1 time series for rice production estimation at the regional scale
- estimate the transferability of seasonal regression models by predicting rice production for years differing from their training data

2. Materials and methods

2.1. Study area

The Mekong Delta (MKD) covers an area of circa 40,000 km^2 and is located between 8.5°–11.5° N and 104.5°–106.8°E where the Mekong River empties into the South China Sea. It is Vietnam's second most populous administrative region, with a population of 17,600,000, and the source for half of Vietnams yearly rice production (General Statistics Office of Vietnam, 2017b). The Mekong Delta consists of 13 provinces, including the independent municipal city of Can Tho, further sub-divided into 133 urban and rural districts, provincial cities and towns (see Fig. 1). The Delta is a flat plain with fertile soils originating from alluvial sediments transported by the Mekong River. Large parts of the plain where subject to regular flooding by the single-peak pulse of the Mekong River. The current flooding regime, especially of agricultural areas, is controlled by multiple dams, dykes, sluices and regulatory measures being implemented upstream (Kuenzer et al., 2013b,a). Fields under controlled flooding schemes are flooded every three to four years in-between rice cycles to cover the soil with a new layer of sediment (Nguyen et al., 2012). The Delta as a whole is in an anthropocene state and subject to challenges of urbanization, agricultural intensification, anthropogenic water management, land subsidence salinization, sea-level rise, climate change and natural hazards, such as typhoons, flooding and drought (Renaud et al., 2013; Erban et al., 2014; Van Khanh Triet et al., 2017). In 2016 disasters caused by natural hazards lead to 264 deaths, 5,400 destroyed houses and 527,700 kilohectare (kha) of damaged rice crops (General Statistics Office of Vietnam, 2017b).

The Delta is located in the monsoon climate zone, *Am* according to the Köppen-Geiger classification (Peel et al., 2007), with monthly mean minimum temperatures exceeding 20°C throughout the year. Precipitation is on average 1800mm per year and characterized by a rainy season from June–December, caused by the SW monsoon, and a dry season from December–May, caused by the NW monsoon (see Fig. 1 – inset climate chart). This climate in combination with the water available from the Mekong River for agronomic flooding enables the year-round cultivation of rice plants with up to three harvests per field and year.

The cultivation of rice in the Delta is grouped into three growing seasons, according to sowing and harvesting dates:

- Hè-Thu (Summer–Autumn season)
- Thu-Đông (Autumn–Winter season)
- Đông-Xuân (Winter–Spring season)

The specific transplanting and harvest dates are governed by local water management practices and irrigation plans as well as the farmers selection of rice variety and fertilizer input. Availability of irrigation water is dependant on dykes that are usually controlled at the commune level. This results in heterogenous crop calendars with spatial variations. The sowing and harvest dates for rice are not defined in the statistical yearbooks where seasons are grouped by their harvesting dates. Due to inconsistency in existing definitions used for the rice seasons and lack of a definitive source we defined the temporal boundaries for each season. We define rice grown between 1st of November of the previous year and 31st of March to belong to the