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ORIGINAL ARTICLE

Effects of soil subsidence on plantation agriculture in Indonesian peatlands

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Abstract

Several million hectares of Indonesian peatlands have been converted to plantations, with oil palm being the most important plantation crop. This has contributed to the economic development of Indonesia. At the same time, it poses environmental challenges. An as yet insufficiently understood concern is that the drainage required for cultivation of peatlands causes soil subsidence. Subsidence progressively increases flood risks in plantations and will, over time, render peatlands unsuitable for cultivation since oil palm and other plantation crops are sensitive to waterlogged conditions. This paper assesses subsidence and flood risk in the main peatlands of Sumatra, and examines when peatlands will become unfit for crop production. We show that, under current management, 21% of oil palm production will be lost due to flooding, and 17% of oil palm plantations in East Sumatran peatlands will become unfit for agriculture in the coming 30 years. Over time, all peatlands will be lost for agriculture. With reduced drainage, these effects can be postponed, but not avoided. In the medium and long term, the only sustainable and economically profitable option for Indonesia is to use peatlands for no-drainage land use including crops that do not require drainage (paludiculture). This also strongly reduces the carbon footprint of cultivating in peatlands. Profitable no-drainage land use options have been tested, but their scaling up urgently needs further support from the government, industry, and international donors to materialize.

Keywords Indonesia · Peat · Oil palm · Soil subsidence · Impacts · Environment

Introduction

Indonesian peatlands cover between 15 and 20 million ha (Wahyunto and Suparto 2004; Page and Banks 2007; Koh et al. 2011). Over half of this has been drained for the production of, in order of importance, oil palm, acacia wood (for pulp and paper), coconut, and paddy (World Bank and BPS 2019). The conversion of Indonesian peatlands has brought important economic opportunities for plantation companies and smallholder oil palm farmers—as well as a range of environmental and social problems (e.g., Yule 2010; Hooijer et al 2012; Schrier-Uijl et al. 2013; Varkkey 2013; Naylor et al. 2019). A critical element of cultivating the abovementioned plantation crops on peat is that they all require drainage, with typical drainage depths between 60 and 90 cm (e.g., Dohong et al. 2018; Evans et al. 2019).

Drainage of peatlands leads to irreversible subsidence. Subsidence occurs due to a combination of compaction (compression of aerated peat), consolidation (compression of peat below the water table due to loss of buoyancy of overlaying peat), and oxidation (aerobic decomposition of organic matter to CO_2) (Evans et al. 2019). Given that peat contains around 90% water, draining the water out of the peat leads to compaction, lowering the surface level by up to 1.5 m in the first 2 years (Wösten et al. 2008; Hooijer et al. 2012; Couwenberg and Hooijer 2013). Pressure resulting from using heavy equipment on peat may further exacerbate compaction. Once drained, subsidence continues due to oxidation of the peat. Oxidation is the decomposition of peat in the aerated zone above the water table due to breakdown of organic matter, resulting in carbon loss through release of CO_2 to the atmosphere (Hooijer et al. 2012; Miettinen et al.

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2016). Oxidation is a continuous process and is directly correlated with drainage: the lower the water table, the higher the oxidation of peat and the faster the soil subsidence. It is also influenced by other factors, such as pH and fertilizer application, that influence microbial activity. Drained peat soils are susceptible to fire, and burning peat soils are particularly hard to extinguish because some of the burning is underground. When both peat oxidation and peat fires are considered, drained Indonesian peat soils emit some 2 to 4% of global CO_2 emissions, with considerable variations between years as a consequence of major differences in fire occurrence, for instance, between El Niño and La Niña years (World Bank and BPS 2019).

In Indonesia, soil subsidence due to oxidation proceeds with up to 5 cm per year in drained peat (Hooijer et al. 2010; Evans et al. 2021). For instance, in 24 sites in a previously deforested and drained tropical peat in West Kalimantan, Ansharia et al. (2022) found that the average peat subsides at a rate of 3.8 ± 1.2 cm per year. In an elaborate study, Evans et al. (2019) found subsidence rates of 4.3 ± 2.0 cm per year in Sumatran Acacia plantations ($n=220$). They also found that subsidence extended at least 300 m into adjacent native forest where subsidence rates averaged − 3.4 ± 1.8 cm per year ($n=92$). Peat fire can further lead to a loss of peat: in one peat fire, a layer of peat of up to 50 cm can burn (Page and Hooijer 2016). After several decades of subsidence and fire, the geomorphology ("shape") of the peat landscape changes: peatlands will increasingly become relatively low-lying parts of the landscape. When this happens, rainwater will accumulate in the peatland areas, causing seasonal flooding. Furthermore, the surface level of peat layers may become lower than the high water level in nearby rivers or the sea, also leading to flooding of peatlands.

Consequently, over time, the surface of the peatland will become lower than the river and/or sea water level, something that has happened on a large scale in, for example, the western provinces of the Netherlands (Schultz van Haegen and Wieriks 2015). In the Netherlands, extensive investments have been made to control water levels in peat, and water is pumped out of polders so as to ensure that housing and farming are not impeded by regular floods. The investment costs of the Dutch water management system in the peatlands cannot be realistically assessed: these investments have been made over a period of over 500 years. The operation and maintenance costs for water management in Dutch polders in peat typically amount to 300 to 500 euro/ha/year (PBL 2016). In Indonesia, where rainfall is double that of the Netherlands, where rainfall intensity is higher, and where the peat areas used for farming are vast and sparsely populated, it is highly questionable if similar investments can be made to control water levels.

It is therefore relevant to understand when cultivation on peat is no longer viable due to flood risks brought by ongoing subsidence. At present, companies and local governments are not always keen to promote other forms of land use on peat due to the short-term economic benefits that oil palm and other plantation crops bring. Understanding the long-term consequences of subsidence and the time left to reap these benefits can assist stakeholders including plantation companies and smallholder farmers in transitioning to more sustainable land use—which will also bring economic benefits in the longer term.

The objective of this paper is to assess the remaining lifetime of East Sumatran plantations on peat. We consider peat elevation, drainage levels, subsidence rates, and cropping patterns, and assess impacts of subsidence on future oil palm production in East Sumatra, where most oil palm plantations on peat in Sumatra are located. We study the remaining lifetime of oil palm plantations existing in this area in 2018 (based on World Bank and BPS 2019).

The scientific novelty of our paper is in bringing together a range of datasets related to elevation of the terrain (based on Lidar data) and current flooding patterns (from remote sensing observations) and combining this with a basic subsidence model. The flooding data that we use has been analyzed specifically for this paper and has not been published before, so we describe the methods used to analyze these data in some detail. The other datasets we use have been described in various other publications that we refer to, and we only provide a synthesis of methods and data quality. We build upon earlier work (Sumarga et al. 2016), but have scaled up our earlier work to a much larger area, and enhanced our methodology, among others by including in the model the current flood pattern based on remote sensing.

Methods

Case study area

We focus our work on the oil palm plantations in the peatlands of East Sumatra, because (i) this is one of the first, and one of the main areas of Indonesia where peatlands have been converted to oil palm; and (ii) detailed elevation data have been made available for this part of the country (Vernimmen et al. 2019). The peatlands that we study are located in the four provinces of Riau, Jambi, South Sumatera, and Lampung. These four provinces comprise a total of 5.8 million ha of peatland (around 38% of the total peatland area in Indonesia), of which in total 1.5 million ha (26%) is covered with oil palm in 2018 (based on spatial data from Ritung et al. 2011 and World Bank and BPS 2019). Figure 1 shows the location of the peatlands in East Sumatra, and the peatlands covered with oil palm. Supplementary materials show the overall land use in the peatlands of East Sumatra.

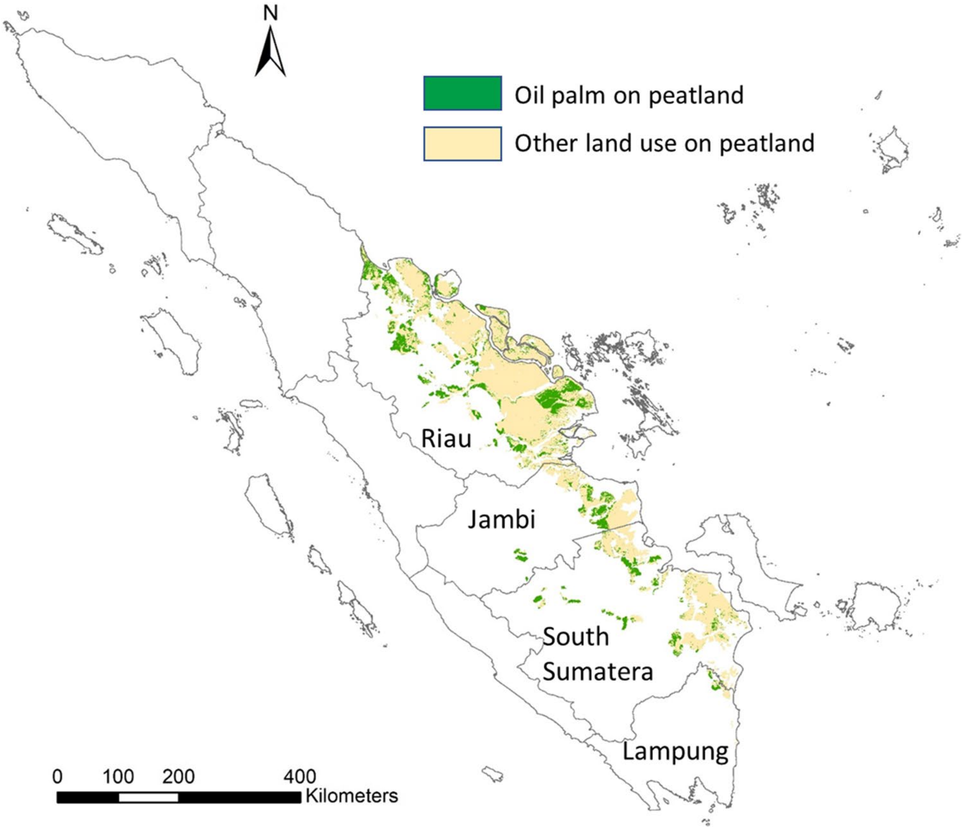


Fig. 1 Peatlands included in this study

The regression model

We model the effect of subsidence on flood risk in order to assess the remaining lifetime of oil palm plantations. The remaining asset lifetime of plantations in peat is influenced by a number of factors: (i) the geomorphology of the landscape determining the elevation of the peat vis-a-vis the surrounding landscape, river- and the seawater level; (ii) the subsidence rate; and (iii) the occurrence of peat fires further causing loss of peat. Flood risks in peat are influenced by the subsidence that has already taken place in the past: where peat areas are higher than the surrounding landscape, water may be drained laterally and flood risks are smaller compared to subsided peat areas where water accumulates in the peatland itself. To model subsidence and flood risks, we deploy a statistical model. Our approach is as follows.

First, we assess flood risk as a function of elevation, per 500 by 500 m grid cell. The flood risk is expressed as the number of weeks per year the area is inundated, as an annual average over 3 years (2017–2019) (elaborated below). We regress flood risk against elevation; the lower the elevation, the higher the flood risk. Second, we assess the level of annual subsidence in each grid cell as a function of landcover. We assess the mean drainage depth in oil palm plantations based on water level data of the Government of Indonesia (i.e., the peat monitoring stations of the Peatland Restoration Agency). Using the equations of Hooijer et al. (2012), we model annual subsidence as a function of water depth. In line with Hooijer et al. (2012), we assume that subsidence as a consequence of oxidation and compaction is linear in drainage, except during the first 2 to 3 years after drainage when subsidence, due to compaction, is much quicker because of the extraction of water from peatlands. We assess the asset lifetime of plantations that exist in our baseline year (2018) and do not consider the lifetime of plantations that are established after 2018. Of course, further land conversion is possible, and indeed has taken place since 2019, but we do not assess the asset lifetime of these newly drained plantations. We assume that there is no fire in well-managed oil palm plantations; the amount of fires in oil palm or other plantations is generally low (e.g., Cattau et al. 2016; Carlson et al. 2017), contrary to the amount of fire in degraded (unused) peatlands including abandoned plantations. Hence, our study is conservative: where fires occur in the plantations in the peatlands, asset lifetime will be markedly shorter depending upon the intensity of the fire (up to ~ 10 years shorter for every fire).

Third, we model the elevation of the peatlands covered with oil palm in 2018 for the period 2018–2050. For our scenario analysis, we analyze subsidence rates based on actual drainage in oil palm plantations and a best practice drainage level of 60 cm, from the Roundtable on Sustainable

Palm Oil (see Lim et al. 2012). The expected subsidence rate (S)—assuming that all plantations in these three provinces were first drained over 5 years ago, as is generally the case in Sumatra (see for example Miettinen et al. 2016)—can be estimated at $S = 1.5 - 4.98 \times$ Water Depth (Hooijer et al. 2012). We classify the peatlands in elevation classes, in steps of 10 cm, from 0.8 m above mean sea level (AMSL) to 10 m AMSL. In each annual timestep, land subsides depending upon drainage depth, and we assess the hectares in each elevation class as a function of subsidence. Clearly, the relation between drainage depth and subsidence rate is prone to uncertainty; we acknowledge these uncertainties and elaborate on them in the "Discussion" section.

Fourth, we assess the impacts of floods on oil palm production, based on a regression model of oil palm versus duration of flooding. These data are from the Malaysian Oil Palm growers association that recorded impacts of flooding during the 2010/2011 El Nino episode (Ayat and Ramli 2012). The study included floods in 402 oil palm estates with an area of 428,912 ha. The floods disrupted oil palm yields, as well as harvesting and collecting activities. Based on the Malaysian survey data, we specify the crop losses as a function of the duration of the flood. The line is fitted through the point (0.0) so as to reflect that if there is no flooding, the impact of flooding on production is zero. We note that oil palm is sensitive to flooding; even a flood duration of several weeks drastically reduces oil palm productivity (Abram et al. 2014; Sabari et al. 2014).

Finally, we combine the equations developed in the previous steps and develop a model that covers the oil palm plantations in the peatlands of the four provinces of Riau, Jambi, South Sumatera, and Lampung. The model operates with time steps of 1 year, and is applied from 2018 to 2050. We model the peatland area covered by oil palm in each elevation class, by year, based on the 2018 elevation and the annual subsidence rates in two scenarios corresponding respectively to actual drainage practices and best practice drainage. Subsequently, we assess the impacts of flooding on oil palm production in each year, and the amount of land that will be taken out of production each year because flooding prohibits palm oil production, for both scenarios. In modelling the impact on production, we assume that per hectare oil palm yields do not change over time as a function of better management or increased disease occurrence, for instance.

Remote sensing analysis and data

We combined different sensors to map flooding underneath and outside the canopy. We use C-band radar data to detect open water areas not under the canopy (see Hess et al. 1990; Martinis et al. 2015; Clement et al. 2018). C-band radar data are from the ESA European Space Agency Sentinel-1 satellites. To map flooded areas under the vegetation canopy, we use L-band radar, as documented in Hoekman (2007) and Hidayat et al. (2012). L-band radar data are from the ALOS PALSAR L-band system from the Japanese Space Agency JAXA, in particular ALOS PALSAR Wide Beam (WB)-dual-polarization (HH/HV) SCANSAR mosaics at 50-m resolution with tiles of 1×1 degree. In addition, we used yearly mosaics of the PALSAR Fine Beam (FB) dual-polarization (HH/HV) system (see Shimada et al. (2009) and Jaxa (2021) for details of these datasets). In order to use the highest possible number of images for the analysis, both the PALSAR FB and WB HH polarization are used to detect flooding under the canopy, using the occurrence of a scattering mechanism called double bounce. The radar wave penetrates the canopy of the forest and interacts with both the flooded terrain under the canopy and the trunk of the trees, creating a return wave with a high intensity that appears bright in the radar images. Since double bounce effects also occur in built-up areas and in strongly sloping areas, we do not consider double bounces in these areas (slopes above a few degrees do not occur in peatlands and built-up area is rare; built-up areas have been masked and excluded). The C band Sentinel-1 system operates with a shorter wavelength (3 cm) than the L-band, which means that it can only be used to detect flooding outside of the canopy, but is has more extensive archives with freely available data, with a higher temporal resolution compared to ALOS PALSAR. With Sentinel-1, flooding on open terrain is detected, based on the very low backscatter of flooded areas since the wave energy is reflected away from the radar.

We detect flood occurrences underneath and outside of the canopy using all available images from ALOS PALSAR and Sentinel-1 that cover (part of) the case study site, over a period of 2 years (18 February 2017 to 24 January 2019). Data compilation was done extensively from data repositories of the JAXA (JAXA 2022) and ESA (ESA 2022) space agencies. Some data was made available as part of the K&C initiative of JAXA. Supplementary materials include a list of processed radar images. Observations every 12 days were possible with the time series of the Sentinel 1 A/B, and every 42 days within ALOS PALSAR system. Radar data was corrected and processed using processing software documented in Hoekman (2007) and Quiñones et al. (2016). Radiometric corrections of the images were done with standard Gamma radar processing software (Gamma 2022).

Subsequently, the processed and classified ALOS PALSAR and Sentinel-1 images were combined based on vegetation cover—for forests and plantations, we used ALOS PALSAR and for all other land uses Sentinel 1. All remote sensing data were registered to a pixel resolution and resampled to 25-m spatial resolution. All thematic classifications from both systems were compiled and normalized by the total number of observations or flood frequency. The observed flood frequency is translated into flood duration by assuming that flooding continued in between two periods in which a flood was observed (observations every 12 days) and that a flooding occurred or ceased halfway two points in time representing a flooded and a non-flooded situation. Flooding was expressed as flood duration in weeks per year, noting that the accuracy of the flooding outside the canopy is somewhat higher (since based on 30 observations per year, during 2 years) compared to the accuracy under the canopy (based on 9 observations per year, during 2 years).

Other data

DTM This study uses the Digital Terrain Model (DTM) that has been made available for East Sumatra and part of central Kalimantan by Vernimmen et al. (2019). This DTM was developed based on airborne LiDAR, which is currently the most accurate data type for elevation mapping. Given the costs of airborne LiDAR, a DTM based on parallel flight lines ("strips") covering between 10 and 35% of the land depending on terrain characteristics, and manual interpolation, was developed. Their method shows DTM differences within 0.5 m, relative to full coverage LiDAR data, for 87.7–96.4% of the land surface in a range of conditions in 15 validation areas, and within 1.0 m for 99.3% of the area overall. The DTM of Vernimmen et al. (2019) has a 100-m spatial resolution covering 7.1 Mha of lowland area from 1.45 Mha of effective LiDAR coverage. A full 36.3%, or 2.6 Mha, of this area is below 2 m + MSL and, therefore, at risk of flooding in the near future as sea level rise continues.

Location of peatlands The location of peatlands in our model is based upon the so-called Puslitanak map of the Indonesian Ministry of Agriculture (MoA) (Ritung et al. 2011). The MoA map indicates that there are 14.9 million ha of peat in Indonesia. The MoA map is mostly based on an earlier map produced by Wetlands International, which however indicated that there are around 20.9 million ha of peatlands in the country (Wahyunto and Suparto 2004). Hooijer and Vernimmen (2013) find that the MoA peat maps underestimate peat extent in Kalimantan and Sumatra by around 25%. However, the largest differences between the map of Ritung et al. (2011) and other maps are found in Papua province (Warren et al. 2017). We acknowledge that there may be an underestimation of the peat areas of Sumatra in the map that we use; hence, our study is limited to studying plantation asset lifetime for peatlands that are included in the map of Ritung et al. (2011). We come back to this in the "Discussion" section.

Land use The location of the oil palm plantations was derived from World Bank and BPS (2019). The report specifies the location of the main types of plantations in the peatlands of Sumatra and Kalimantan, including oil palm, acacia, coconut, hevea rubber, and paddy fields. Land use was classified using LandSat 8, Sentinel-1, and ALOS Palsar images that were processed at a pixel size of 25 by 25 m. The classification accuracies were very high, for all classes on peat above 90%, and for oil palm 98.5% (World Bank and BPS 2019). Further details of the classification procedure and data used can be found in World Bank and BPS (2019).

Drainage in oil palm plantations We downloaded from the website of the Peat Restoration Agency, Government of Indonesia (Badan Restorasi Gambut, or "BRG") (https://sipalaga.brg.go.id), the daily water levels of 167 water monitoring stations, over the complete year 2019. We selected the 25 stations in oil palm plantations in East Sumatra, out of these 167, and we averaged the drainage depth over these stations. Note that, whereas interannual fluctuations in soil water are influenced by rainfall (Wösten et al. 2008), when averaged over the year, the water depth in oil palm plantations depends primarily on water management (canal spacing, management of water levels in canals) (Adhi, et al. 2020).

Results

Current flood patterns

Figure 2 shows the flood risk map, expressing the average duration of the inundation in the period 2017–2019, with a spatial resolution of 25 by 25 m. Open water areas (52 weeks per year flooded) have been removed from the map. The map was produced by combining the results of the ALOS PALSAR and Sentinel classifications as described above.

Flooding by elevation class

Figure 3 shows the percentage of time an area is flooded, by elevation. We transform the average time that an area was flooded in weeks (Fig. 2) to an expected value of the part of the year that an area is flooded, where 10% corresponds with 5 weeks a year flooded. Subsequently, we plot this percentage and regress it with elevation class. Each dot in the graph represents the average flood risk of a specific elevation. We fitted a curve through the data, with an R^2 of 0.89. We underestimate the flood risk for low elevations (< 1 m) but this does not influence our model results, since oil palm no longer is productive once flood duration exceeds 12 to 13% (see next section). The total number of observations over these 10 classes is 288. We note that the variability within elevation classes is considerable: the standard deviation ranges from 51 to 79% of the percentage of flooding. This reflects local variations in the landscape not strongly related to elevation: local depressions are prone to high flood

Fig. 2 Flooding in Sumatra, 2019

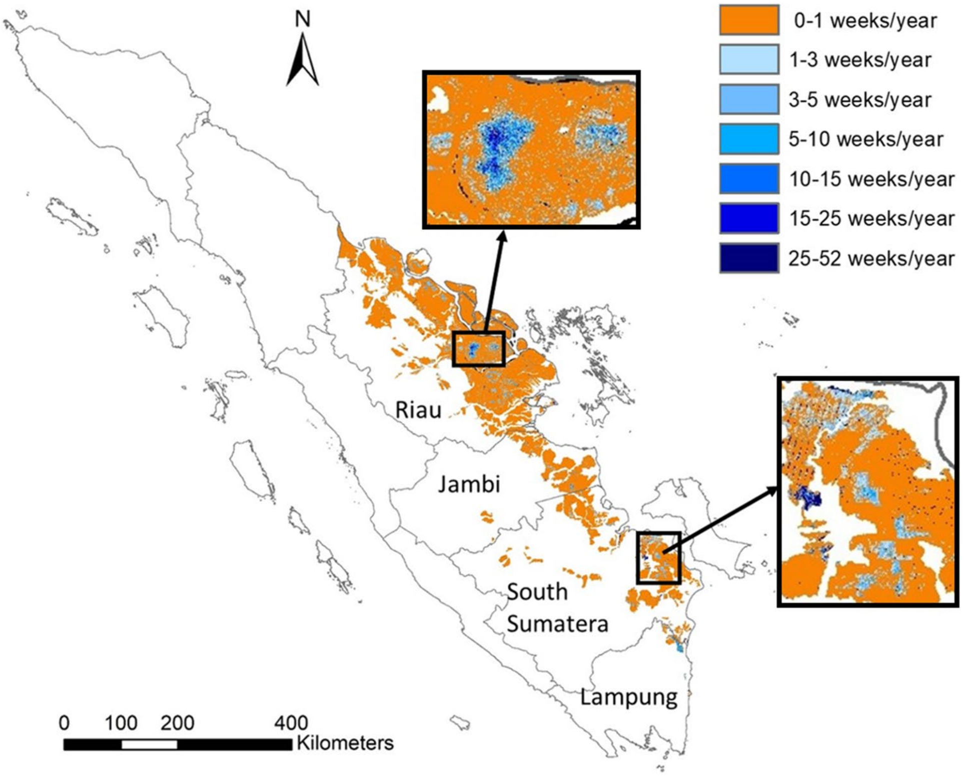
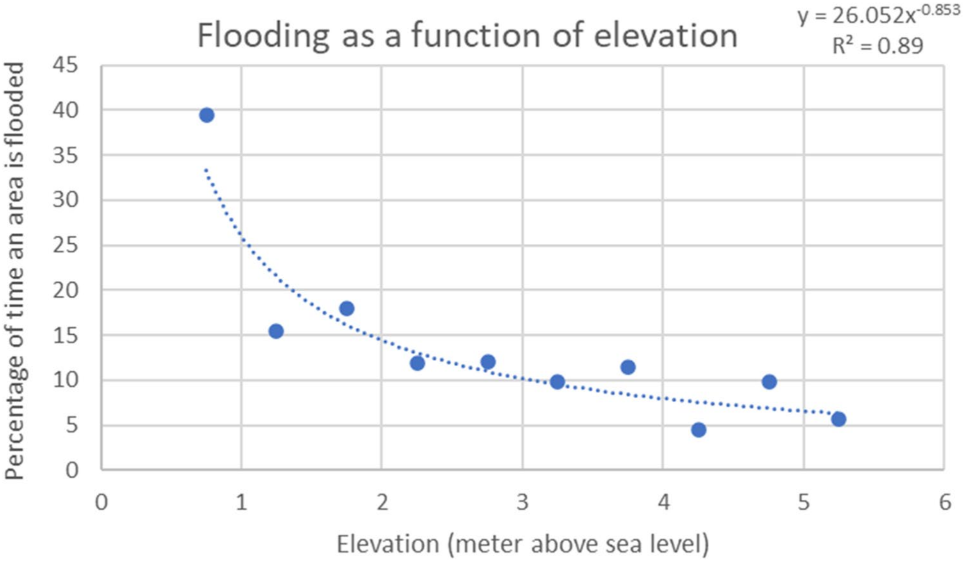


Fig. 3 Flood risk as a function of elevation (meters above mean sea level)



risks. We also tested if distance to a river is relevant, but this did not prove to be a significant explanatory variable.

Impacts of flooding on oil palm production

We regress oil palm productivity loss against duration of the flooding in percentage of the year flooded, based on Rahman et al. (2012), who record crop losses from flooding across oil palm plantations in Malaysia. The graph clearly shows the sensitivity of oil palm to flooding; when oil palm is flooded more than 10% of the time (i.e., 5 weeks or more), productivity declines to zero. The curve that can be best fit through the data is a 3rd order polynomial function (see Fig. 4). A range of biological processes determine the effect of flooding on crop losses, including water logging of roots and loss of stability of mature plants in wet peat (Lim et al. 2012). After testing linear, exponential, logarithmic, and 2nd order polynomial functions, we find that a 3rd order polynomial

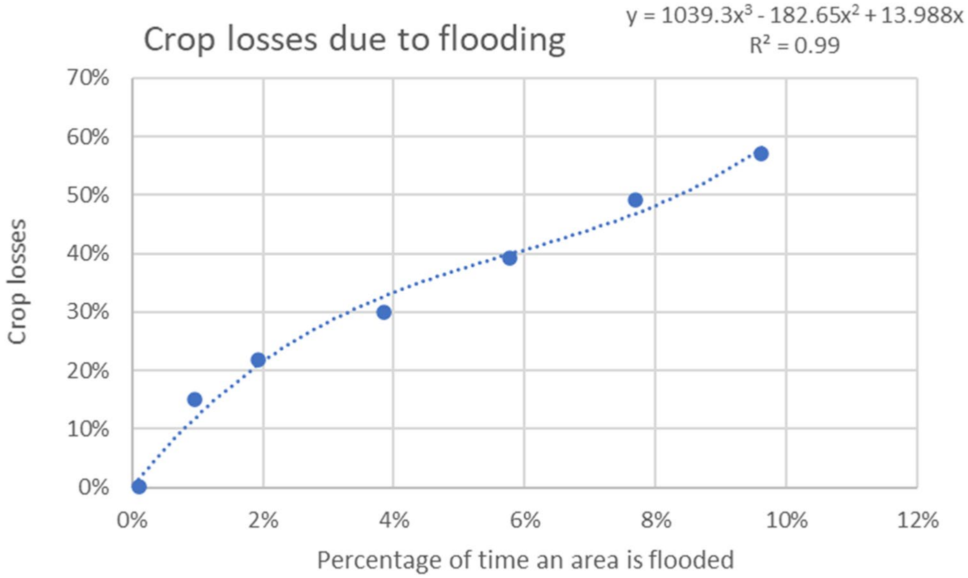


Fig. 4 Crop losses as a function of flooding

function describes the relation between flooding and crop losses with the highest R^2 (the R^2 of the fitted curve is 0.99). The main aim of our curve is to match the observed data as well as possible, and we therefore use the equation presented in Fig. 4 in our model.

Impacts of soil subsidence on oil palm production

Our model forecasts the impacts of subsidence on oil palm plantations up to 2050, as a function of drainage depth. BRG data indicate the annual average (over 2019) drainage depth in oil palm plantations to be 81 cm, with a standard deviation of 50 cm (which reflects both different drainage practices in oil palm plantations as well as measurement uncertainties in BRG measurement equipment). This is in line with, for instance, Hooijer et al. (2012) who found an average drainage depth of 73 cm in Sumatran oil palm plantations, Adhi et al. (2020) who found an average water table depth of 64 cm, and Ismail et al. (2021) who found an average of 1.2 m, both in Riau, Sumatra. In our scenario analysis, we therefore analyze subsidence rates based on 81-cm drainage in addition to a best practice drainage level of 60 cm (achieved by 10 out of 25 of the BRG-monitored stations). Hence, at 81-cm water depth, the subsidence will be 4 cm per year. At 60-cm water depth, the subsidence will be 3 cm per year.

Figure 5 shows the loss of oil palm production, in oil palm plantations operational in 2018, in the coming 30 years, due to subsidence. At 4-cm subsidence per year (current practices), the loss amounts to 21% in 2050, and at 3-cm subsidence per year (enhanced oil palm plantation management), this amounts to 13% in 2050. The amount of land lost for agricultural production due to subsidence in the period up to 2050 is shown in Fig. 6. The total amounts to 130,000 ha at 3-cm annual subsidence, and 250,000 ha at 4-cm annual subsidence, in 2050. In other words, East Sumatra will lose 17% of its oil palm plantations in the coming 30 years, under current management (i.e., 81-cm drainage). This can be reduced to a loss of 9% if plantations will, on average, drain at 60-cm water depth.

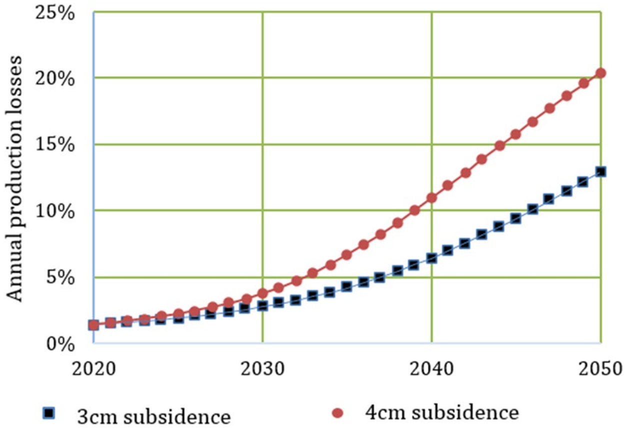


Fig. 5 Oil palm production losses in East Sumatra due to soil subsidence

Discussion

Implications, uncertainties, and limitations

The model shows that, with the conservative assumption that all fires will be controlled in the oil palm plantations, 17% of the 1.5 million ha of land currently under oil palm

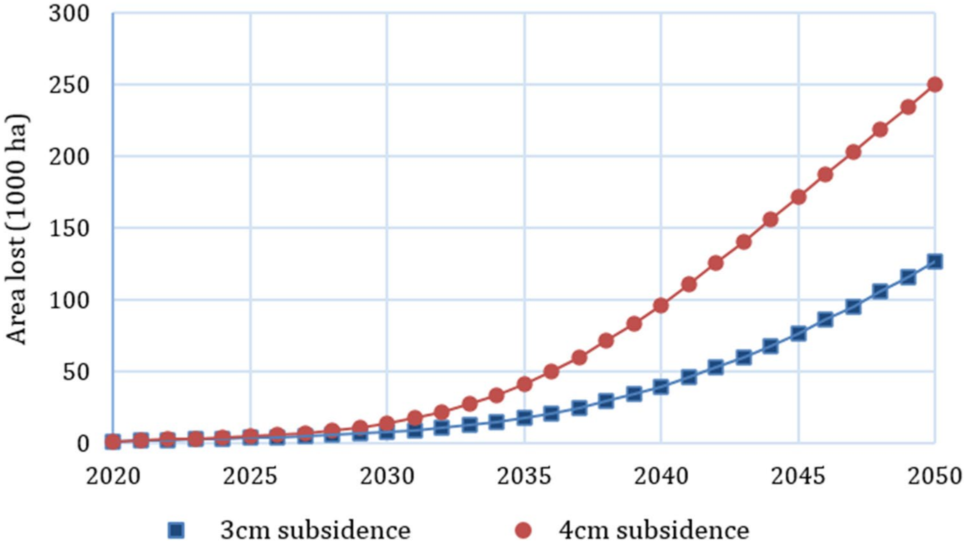


Fig. 6 Oil palm plantations that will no longer be suitable for oil palm production due to soil subsidence

in East Sumatra will become unsuitable for oil palm or other plantation crops such as acacia (that are equally if not more sensitive to flooding) due to soil subsidence in the coming 30 years. This can be reduced to a loss of 9% if plantations will, on average, drain at 60-cm water depth. This is likely to have major implications for the Indonesian oil palm sector, and it is important that the sector is aware of the medium-term risks posed by soil subsidence. Soil subsidence and flooding will also have major impacts on local people including people working in nearby oil palm plantations or growing oil palm in drained peat themselves: whereas large companies may shift production to other areas, moving may not be feasible for local people.

It is important to note that flooded lands can also no longer be used for other crops, since all currently grown tropical peatland crops are sensitive to flooding. Even most so-called paludiculture (zero-drainage) crops cannot be cultivated when land is seasonally flooded (e.g., Uda et al. 2020). Hence, flooded areas are at high risk of being abandoned when flooding exceeds several weeks per year. Once abandoned by oil palm plantation companies, the land may be subject to floods in the wet season, and fire in the dry season, further exacerbating health impacts of peat fires in Indonesia and neighboring countries (Hein et al. 2022).

In spite of using detailed spatial data, there are important uncertainties and limitations to our analysis—which may make our model outputs conservative. In addition to not considering fires, a key limitation is that we do not consider the effects of climate change in our paper. Climate change will lead to sea level rise, and will likely affect rainfall patterns. Sea level rise will increase the flood risk in the lowest lying areas that are affected by floods from the sea (Schuerch et al. 2018). Increased rainfall variability (for instance due to more frequent La Niña climate conditions) may increase flood risks from rivers (Lee 2015). We do not currently have the data to quantify these risks, yet higher rainfall intensity and sea level rise are likely to increase flood risks in plantations.

In terms of the modelling approach, there is uncertainty in terms of the relations between drainage and subsidence, between elevation and flood risk, and between flood risk and effects on production. There is some debate on the relation between drainage and subsidence, but recent papers converge on a linear relation in line with the parameters that we use (Hooijer et al. 2010, 2012; Couwenberg and Hooijer 2013; Evans et al. (2019),,,. We consider that the uncertainties are highest in the relation between elevation and flood risk. This is reflected in our regression analysis, and can be explained by the impacts of local variations in the landscape on flood risk. These local variations cannot be modelled with the data that we have, since they occur at scales of down to 10 s of meters. With ongoing subsidence, the occurrence of convex structures in the landscape will increase (Hooijer et al. 2012). This will probably increase the amount of flooding for a given elevation class. Hence, the limitations in our modelling approach mean that we are likely to underestimate the impacts of subsidence on future oil palm production.

As for the data that we use, uncertainties occur both in the flood risk mapping, the elevation data that we use, and in the spatial data on peat and the location of oil palm plantations. The uncertainty in the flood data is not known but arises from our use of a limited number of points to assess flood duration (once every 12 days with Sentinel 1 A/B and once every 42 days with ALOS PALSAR system). This means that floods under the canopy with a duration of less than 42 days, and floods with a duration of less than 12 days outside of the canopy, may not have been picked up (the shorter the duration the higher the chance of not being observed). Consequently, we underestimate the current flood risks, and therefore the future flood risks as a function of soil subsidence.

Vernimmen et al. (2019) indicate the uncertainties in the DTM. They map elevation in East Sumatra with airborne LiDAR data along parallel flight lines ("strips") covering between 10 and 35% of the land depending on terrain characteristics, in combination with manual interpolation. The method was shown to yield DTM differences within 0.5 m, relative to full coverage LiDAR data, for 87.7–96.4% of the land surface in a range of conditions in 15 validation areas, and within 1.0 m for 99.3% of the area overall. Elevations are both under and estimated with this approach. Vernimmen et al. (2019) do not report a structural bias in the comparison of estimated and observed elevations, and we therefore conclude that the inaccuracies in the LiDAR map do not materially affect our outcomes.

As for the location of the peat areas, there are some differences in the location of peatlands in Sumatra when different source are compared, e.g., Ritung et al. (2011) and Wahyunto and Suparto (2004). Uda et al. (2017) compare Sumatran peatland areas as mentioned in different sources and find a difference of up to 20% in peatland area (note that in some other parts of the country these differences in peatland area between sources are considerably larger). However, since we present our main result as percentage decline in oil palm production in Sumatran peatlands, the accuracy of the location and area of plantations on peat has no significant effect on our findings. We have also used accurate maps of the location of plantations in peat. The accuracy of oil palm classification in the map that we used is above 99%, noting that it is relatively easy to classify large oil palm plantations on remote sensing images, with the main risk being confusion with coconut plantations (which are also drained, when on peat).

Policy implications

The Indonesian government has put in place a wide and far-reaching set of policies to address the environmental externalities of draining peatlands for the cultivation of various crops including in particular oil palm. For example, the national government has frozen issuing new permits for large scale oil palm plantations on peat since 2018 (Presidential Instruction No. 8/2018 and No. 5/2019). The other, for this article, two most relevant policies are summarized in Table 1 below (based on Dohong et al. 2018).

Smallholder and large-scale commercial plantation companies face different opportunities and constraints. Whereas the large plantation companies are big commercial entities that are able to successfully compete in the world market, many of the smallholders are in the process of emerging from a poverty trap thanks to the high profitability of oil palm. A key question is if, in this complex context, the current policies are sufficiently effective to sustain the productive capacity of Indonesia's peatlands. The following observations can be made.

1. There is a severe lack of data on the specific boundaries of the peatlands, especially in Papua but also in Kalimantan and Sumatra. Often, the boundaries between deep and shallow peat are unclear (Rudiyanto et al. 2016; Uda et al. 2017; Warren et al. 2017). This lack of data, in combination with the general lack of control over smallholder land conversion, makes it difficult to plan and enforce detailed regulations on the conservation of peat over 3 m deep in many parts of the country—both related to smallholders and plantation companies.
2. Whereas conservation of at least 30% of peat domes is a worthy target, an issue is that drainage in part of the peat dome also affects water levels in other parts of the peat domes (which are hydrological units). Hence, drained fields also cause water levels to go down (and the land to subside) outside of the plantation perimeter. This effect can occur at distance of up to several kilometers from the plantation boundary, depending upon drainage depth (Hooijer et al. 2012). These drained zones are often susceptible to fire given that plantation managers may not feel responsible for controlling fires outside of the plantation boundary.
3. The government target of 40-cm drainage in oil palm plantations is in principle a very good idea, since it reduces CO_2 emissions, fire risks, and subsidence levels (to around 2 cm/year). However, in practice, it is very hard for plantation companies to reach this drainage level throughout the year (Evans et al. 2021), as also the BRG data on water levels show. Since oil palm roots cannot stand waterlogged conditions, oil palm growers

Table 1 Two key policies regulating peat drainage

Policy	Implication
Minister for Agriculture Regulation No. 14 of 2009 on "Guidelines on the utilization of peat for palm oil cultivation"	Only peat less than 3 m deep can be drained for agriculture
Government Regulation No. 57 of 2016 on "Peatland ecosystem management and protection"	Companies operating on peatland are required by law to set aside an area for conservation corresponding to 30% or more of the peat dome (Peat Hydrological Unit)
	Companies are required to ensure the water table in drained plantations does not exceed a depth of 0.4 m from the peat surface

> may prefer to err on the dry rather than the wet side of this boundary. Hence, it is questionable if this target can generally be reached in the plantations. Even if the target were to be met, of course, subsidence would still continue, albeit at a lower pace (~ 2 cm/year at 40-cm drainage). This would postpone, but not eliminate, the effects of drainage on productivity of peatlands.

Based on the above considerations, current Indonesian government policies—even though they are ambitious compared to what other countries (including the Netherlands) are doing to ensure sound management of peatlands—are still not optimal. The policies are difficult to enforce, especially in a country as big and diverse as Indonesia, and in the end they will only postpone the economic and environmental impacts of drainage and soil subsidence. Indeed, the subsiding of coastal peatland in combination with a rising sea level will substantially reduce the terrestrial area of the country in the century to come (Abidin et al., 2007). Given that Indonesian peatlands matter for the global greenhouse gas balance, it is critical that further thought is given to how sustainable and long-term productive use can be ensured.

Immediate abandonment of palm oil and other production in Indonesian peatlands does not make sense. Were this to happen, the abandoned areas would be prone to fires and there would be no environmental benefits, unless the area would be rehabilitated. Indonesia has ambitious targets for the restoration of drained and degraded (i.e., with no productive use) peatlands (Indonesian Peatland Restoration Agency 2016; Puspitaloka et al. 2021); however, it is proving very difficult and costly to restore degraded peatlands, especially when there is a lack of economic benefits that are generated from these peatlands, once they are rehabilitated (Yuwati et al. 2021; Budiman et al. 2020).

Hence, the most important steps that need to be taken in the short term are as follows: (i) to stop remaining conversion of undrained peatlands to drained plantation and smallholder cropping; and (ii) to develop economic strategies for using peatlands without drainage for both smallholders and plantation companies. Since rehabilitation of peatlands including blocking of canals is very expensive, it is paramount that further conversion and drainage of peatlands is arrested as a first priority (cf. Budiman et al. 2021). Furthermore, smallholders and plantation companies should be supported with the planting of paludiculture (no-drainage) crops (Budiman et al. 2020; Uda et al. 2020; Giesen 2021). Paludiculture uses crops that are adapted to undrained (and seasonally waterlogged) peat. Perhaps the most promising crop at the moment is sago, that can be cultivated in shallow peat (< 1.5 m deep) without drainage (Van der Meer et al. 2021), and that yields, once mature, profits in the order of 1000 to 1200 euro/ha/year, only marginally less than oil palm depending upon palm oil prices (Orentlicher 2019). Sago can be used to produce starch for which there is a large global market; it can also be used to produce bioplastics in Indonesia for the national market. The main bottleneck to large-scale adoption of sago is that it takes some 8 years before plantations are productive (which was initially also the case with oil palm). Therefore, financial support is needed to help smallholders and plantation companies to shift to sago (with intercropping in the first years), and the government should also consider support for sago breeding programs that will shorten the time to first harvest. Once the area is flooded over several weeks per year, sago can also no longer be planted, since seedlings tolerate waterlogged soil, but not flooding (Flach et al. 1977). Hence, the transition to such crops needs to be made before the land is regularly flooded. Rattan is another profitable crop suitable for peatlands (Sumarga et al. 2015), and it should be considered to revoke the export ban that has led to a collapse in the market for rattan (Uda et al. 2020). Finally, research should continue to identify, test, and scale-up other paludiculture crops (e.g., Uda et al. 2020).

On deep peat, carbon projects ("carbon farming")—i.e., rewetting, revegetating, and protecting peatlands from fire and land use change in order to develop and sell carbon credits—are an increasingly attractive business proposition. The market for REDD + credits is growing rapidly (e.g., Streck 2021), and a main bottleneck in Indonesia involves the efforts required to obtain the necessary permits to trade carbon. This is something that the government of Indonesia can address. Opportunities to engage with (associations of) villagers to pursue carbon farming in village forests is another potential option to combine profits, people, and sustainability. Further testing and scaling up of paludiculture crops, and enhancing the institutional environment for REDD + projects will facilitate transitioning to zero-drainage peatland use in the medium term (one to several decades). The alternative is continuing with oil palm and acacia in the short term, and irreversibly losing the productivity of the land in the medium term.

Conclusions

The effects of soil subsidence are going to be very large for Indonesia, rendering millions of hectares of land unproductive in the country in the coming decades. This paper shows that in 2050 between 9% (best practice oil palm production) and 17% (current practices) of Sumatran oil palm plantations on peat will need to be taken out of production due to recurrent flooding. Impacts on production are even larger (up to 21%) because also land not taken out of production will be less productive due to flooding. Eventually, all drained peatlands in the country will subside to the point that no crop production is possible. Abandoned peatlands are prone to fire in the dry season, and subsidence will, over time, also increase air pollution in the country and neighboring countries.

Current peatland policies in Indonesia, regardless of their good intentions and high ambition level, are unfortunately not likely to be sufficient to counter the trend. In addition to these policies, there is a need to (i) rigorously enforce policies that ban the further conversion of peatlands to drained agriculture; and (ii) develop profitable business models for paludiculture (c.f. Budiman et al. 2020). Paludiculture crops should be scaled up to areas that are undrained but where vegetation is lost, and be implemented in peat restoration areas so that peat restoration also leads to economic benefits for nearby residents. The most promising paludiculture crop at present is sago, which however can only be planted in peat shallower than 1.5 m. Since it requires waiting for 8 years prior to the first harvest, smallholders should be supported in this intermediate period—e.g., with supporting intercropping options or with schemes where they are paid for contributing to rolling out further peat restoration. Furthermore, the government should consider further promoting supplementary other options for peatland use such as revoking the ban on rattan export and facilitating carbon farming (e.g., REDD+) projects.

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