Assessment of differences in peat physico-chemical properties, surface subsidence and GHG emissions between the major land-uses of Selangor peatlands

Article

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Assessment of differences in peat physico-chemical properties, surface subsidence and GHG emissions between the major land-uses of Selangor peatlands

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ABSTRACT

Tropical peatlands are globally important ecosystems for carbon storage, biodiversity conservation, water storage and regulation, and several other valuable ecosystem services. Despite their importance, peatlands in Southeast Asia have been heavily degraded by anthropogenic disturbances such as drainage, agricultural conversion, and fire. In this spatially extensive study we characterised peat properties, nutrient concentrations, surface subsidence rates and greenhouse gas emissions from peatlands of Selangor, Peninsular Malaysia under different land-uses: Secondary Forest, Fire affected and replanted forest (Burnt), Pineapple Plantation, Mixed Agriculture, Smallholder Oil Palm Monoculture, and Industrial Oil Palm Monoculture. All the measured peat physico-chemical properties and nutrient concentrations were significantly different between land-uses. Principal component analyses indicated that peat under the Mixed Agriculture and Burnt land-uses showed the greatest degree of modification relative to peat under the Secondary Forest land-use. Burnt land-use also showed a significantly higher subsidence rate (4.4 ± 1.2 cm yr^{-1}) than all the other land-uses (ranging between 1.8 ± 0.47 and 3.2 ± 0.5 cm yr^{-1}). Water table was significantly higher at the Burnt land-use (-26 cm) than all other land-uses, likely reflecting fire-prevention drain blocking measures as well as lower land surface heights post fire. Smallholder oil palm land-use had the lowest water table (−68 cm), while water table level in all other land-uses did not significantly differ from that of Secondary Forest (−43 cm). Peat surface level changes were positively related to increase in drainage, showing the importance of maintaining a high water table level in reducing peat degradation and carbon loss from peatlands. Total CO_2 (mean range 492 to 1019 mg m^{-2} hr^{-1}) and CH_4 emissions (mean range 637 to 1422 μg m^{-2} hr^{-1}) did not significantly differ between land-uses or seasons. CH_4 emissions were negligible under all land-uses and higher emissions were correlated with a higher water table level. Taken together, the results show that anthropogenic land-use change impacts the physico-chemical properties and nutrient content of peat, and that increased drainage alongside changes in other peat properties leads to increased peat subsidence and carbon loss.

1. Introduction

Peatlands are unique carbon rich ecosystems that cover 3% of the world, extending from northern peatlands at high latitudes to the tropics (Loisel et al., 2017; Xu et al., 2018), spreading across 423 million hectares of land surface area and containing one third of the world soil carbon pool (Page et al., 2011; Xu et al., 2018). Peatlands are formed when primary production exceeds microbial decomposition due to

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waterlogged anaerobic conditions (Andersen et al., 2013; Frolking et al., 2011; Turetsky et al., 2015). This accumulation of organic matter has continued for millennia, making peatland ecosystems a reservoir for carbon storage (Frolking et al., 2011; Leifeld and Menichetti, 2018; Leifeld et al., 2019; Yu, 2012). Besides their role in carbon storage, peatlands also provide several other ecosystem services such as water regulation and conservation of biodiversity, including several endangered and endemic species (Wösten et al., 2008; Yule, 2010). Although the most extensive peatlands are found in the northern latitudes, there is a considerable cover in the tropics, including in Southeast Asia, Africa, and Central and South America (Page et al., 2011). Tropical peatlands are estimated to cover 0.25% of the world land surface area and store about 18% of global peat C (Page et al., 2011). However this is likely an underestimation (Xu et al., 2018) as peatlands have been recently identified in the Congo (Dargie et al., 2017), whilst the full extent of tropical peatlands in South America awaits confirmation by field surveys (Gumbricht et al., 2017). Even in relatively well mapped areas, small peat deposits, such as those in Terengganu, Malaysia (Dhandapani et al., 2019c) are still being described.

Southeast Asia is the global centre for tropical peatlands containing the majority of the world's cover, storing 69 Gt of carbon (Page et al., 2011). Unlike northern peatlands that are dominated by mosses, tropical peatlands support dense forests that are active throughout the year and are carbon rich ecosystems both above and below ground (Dargie et al., 2017; Dohong et al., 2017; Yule, 2010). Peat formation has been enabled due to the delicate balance and interactions amongst hydrology, topography, climate and microbial ecology, resulting in rates of primary production that exceed the rates of microbial decomposition (Miettinen et al., 2012; Page et al., 1999), despite high temperatures that are ideal for microbial activity (Nottingham et al., 2019). These delicate interactions are disturbed by anthropogenic drainage that effectively disrupts this fine balance and exposes the peat to aerobic decomposition (Hergoualc'h et al., 2017; Ishikura et al., 2018), which results in loss of C as CO_2 (Couwenberg et al., 2010; Hergoualc'h and Verchot, 2011; Hergoualc'h and Verchot, 2014) and associated peat subsidence (Evans et al., 2019). Understanding the consequences of land-use change is especially relevant to peatlands in Southeast Asia given their large carbon stocks, unique biodiversity and globally high rate of deforestation (Hansen et al., 2013; Miettinen et al., 2016).

For the last decade, oil palm has been the most consumed vegetable oil in the world (Lam et al., 2019; Pirker et al., 2016), with Southeast Asia producing 90% of the world's consumption (Danylo et al., 2021; Ng et al., 2012). Industrial plantations and smallholder plantations have a near equal share of land cover for oil palm land-use on peat in the region (Miettinen et al., 2016; Wijedasa et al., 2018). In Peninsular Malaysia, industrial agriculture and smallholder agriculture on peat cover 279,000 and 267,000 ha respectively, compared to just 41,000 ha of near-pristine and 152,000 ha of degraded peat swamp forests (Miettinen et al., 2016). Malaysia has witnessed the highest rate of deforestation of any country in the world in the 21st century (Hansen et al., 2013), while oil palm plantations on peat expanded rapidly during the same period (Shevade and Loboda, 2019). The strongest predictor for conversion of forest to oil palm plantations during the period of most rapid change (from 1988 to 2012) is found to be the proximity of the forest to already established oil palm plantations (Shevade and Loboda, 2019).

Fire is often used for land clearing after timber extraction from peat swamp forest as part of the conversion to croplands or plantations (Dennis et al., 2005; Dislich et al., 2017; Murdiyarso and Adiningsih, 2007). The use of fire becomes increasingly problematic in drained peatlands, as dried peat itself is highly flammable (Dhandapani and Evers, 2020; Smith et al., 2018; Turetsky et al., 2015). Fire is also widely used as an easy agricultural management practice to clear crop residues and to increase the fertility of naturally acidic and nutrient poor peat soils (Dhandapani and Evers, 2020; Giardina et al., 2000; Islam et al., 2016; Sjögersten et al., 2011; Turetsky et al., 2015). However, the increase in nutrient availability that occurs after fire will level off over time, because of the leaching of newly available nutrients, or nutrient levels are reduced by the uptake by newly planted crops (Dhandapani and Evers, 2020; Kutiel and Naveh, 1987).

These land-use changes driven by anthropogenic activity adversely impact peat physico-chemical properties and, most importantly, peat functions such as water and carbon storage (Cooper et al., 2019; Dhandapani et al., 2019a; Tonks et al., 2017). The major indicators to assess the impact of peat land-use change and loss of C storage are peat subsidence and greenhouse gas emissions (Couwenberg et al., 2010; Dhandapani et al., 2020a; Hergoualc'h and Verchot, 2011). Peat subsidence after drainage occurs via four possible routes: 1. lowering of the peat surface through heterotrophic loss of surface C due to greenhouse gas emissions; 2. shrinkage due to physical peat contraction after drainage; 3. consolidation of peat below the water table, due to the aeration of surface layers that results in loss of buoyancy; 4. physical compaction by activities in the converted land-use (Hooijer et al., 2012). Although carbon loss through subsidence and GHG emissions is mainly due to a switch from anoxic to aerobic conditions (Wakhid et al., 2017), this can be further influenced by multiple other factors such as the microbial community structure (Dhandapani et al., 2020b; Dhandapani et al., 2019c), nutrient concentrations (Dhandapani et al., 2021a), and peat physico-chemical properties (Couwenberg et al., 2010; Dhandapani et al., 2019a; Girkin et al., 2020a).

The North Selangor peat swamp forests have been drained and selectively logged like most other peatlands in Peninsular Malaysia (Dhandapani et al., 2019c). The presence of a large number of smallholder farmers in this area (Dhandapani et al., 2019b; Saadun et al., 2018), along with private and state owned industrial plantations, provides a typical range of peat land-uses (Cooper et al., 2019; Matysek et al., 2017; Tonks et al., 2017). Several occurrences of peat fire (Smith et al., 2018) and management interventions by local authorities (GEC, Personal communications) have further added to the diversity of peat land-uses and conditions (Charters et al., 2019). These characteristics make peatlands in the Selangor state of Malaysia a good representation of the main land-uses, management practices and associated issues occurring on peatlands in the Southeast Asian region. However, detailed peat properties and subsidence rates have not been reported for any of the land-uses in Selangor peatlands. Considering the extent of the peat cover in the region, accompanied by huge peat carbon storage, and alongside the diversity of peat land-uses, it is essential to understand the peat properties, subsidence rates and GHG emissions in the remaining secondary peat forest and the impact of different peat land-use changes on those properties and subsidence rates.

In this spatially extensive study of the Selangor peatlands, we explore the changes in peat properties, nutrient concentrations, subsidence rates, greenhouse gas emissions and their interactions across six different land-uses over a one-year period. The land-uses studied comprise Secondary Peat Swamp Forests, Burnt peatlands, Pineapple Plantations, Mixed Agriculture, Smallholder Oil Palm Monoculture plantations and Industrial Oil Palm Monoculture plantations. Specifically, we test the following set of hypotheses:

1. Land-use change significantly affects peat physico-chemical properties and nutrient concentrations, with lower carbon content, greater pH and greater nutrient concentrations in agricultural and burnt land-uses due to anthropogenic inputs and ash addition, respectively.
2. Peat subsidence rate increases with lowering of water table, with the land-uses that have the greatest degree of modification in peat properties relative to the Secondary Forest, having highest subsidence rates.
3. Total CO_2 emissions from peat will be highest in the Secondary Forest land-use owing to high autotrophic contributions, while total CO_2 emissions with insignificant autotrophic contributions from other land-uses will exhibit a positive correlation with increased drainage.

4. There will be negligible CH_4 emissions under all land-uses, with higher emissions in land-uses with a higher water table.

2. Materials and methods

2.1. Study sites

A total of 61 study sites of six different land-uses were spread across the peatlands in the State of Selangor, Peninsular Malaysia, to characterise peatlands of all major land-uses in the region. Site information and locations are given in Supplementary Information and in Fig. 1. Peatlands in Selangor comprise of two distinct peatland areas; North Selangor peatland and South Selangor peatland. The North Selangor peatland is the second largest peat dome in Peninsular Malaysia and covers an area in excess of 76,000 ha. A large proportion has maintained a land cover of secondary peat swamp forest that was historically drained and logged (Charters et al., 2019), and which is divided into four forest reserves that are protected and managed by different district authorities. These protected forest reserves are surrounded by industrial oil palm plantations and villages that are dependent on smallholder agriculture. This has resulted in a diversity of land-uses in and around the forest reserves. The South Selangor peatlands are relatively small in size but are even more diverse than the North Selangor peatland in terms of land-uses, including a large urban area and the Kuala Lumpur International Airport lying to the south. Of the 61 sites, a total of 21 representative sites were chosen (due to limitations of logistical capacity to do continuous measurements) across the North and South Selangor peatlands for more detailed monitoring. These selected sites were spread across the different land-uses and here intensive field sampling with additional analyses and field monitoring was undertaken. These selected sites with intensive sampling are hereafter referred to as ‘Supersites’. Such intensive sampling was not carried out in any sites under the Mixed Agriculture land-use due to logistical limitations, and hence the Mixed Agriculture land-use is excluded from water table and GHG measurements. Seasonal GHG measurements and monthly water table measurements were made in these Supersites, which were not measured in other sites. Weather data to indicate the wet and dry seasons (Kiew et al., 2018) of 2018 were obtained from the nearest towns to the North and South Selangor sites and are given in Table 1.

Table 1
Weather data for each greenhouse gas measurement periods in wet and dry season. Data obtained from World Weathers Online (2020) for Kuala Selangor, Malaysia (closer to North Selangor Peatland sites) and Banting (Closer to South Selangor peatland sites).

Weather	Dry season (Aug 2018)		Wet season (Dec 2018)	
Region	N.Selangor	S.Selangor	N.Selangor	S.Selangor
Rainfall mm	38	65	412	361
Rainfall days	18	20	28	27
Average temperature °C	28	29	29	30
Sun hours	302	300	230	202
UV scale	7	7	7	7
Average humidity %	68	68	80	79
Average cloud cover %	19	22	52	53

2.1.1. Drained secondary peat swamp forest

The Drained Secondary Peat Swamp Forest land-use (here after referred to as ‘Secondary Forest’) comprised of 25 site locations in the North Selangor peat swamp forests and five site locations in the South Selangor peat swamp forest. A total of five Supersites were selected for this land-use, with two located in North Selangor (one each in Sungai Karang and Raja Musa forest reserve) and three in South Selangor (two in South Langat and one in North Langat).

The North and South Selangor peatlands are remnants of a natural peat dome that once occupied most of the coastal area before land-use changes (Azhar et al., 2011). Despite having an extensive history of selective logging, the North Selangor peatlands are rich in biodiversity with 126 floral species and 262 faunal species (Adila et al., 2017). The Secondary Forest vegetation includes *Macaranga pruinosa* (Miq.) Müll. Arg, *Campnosperma coriaceum* (Jack) Hallier f., *Blumeodendron tokbrai* (Blume) Kurz, *Shorea platycarpa* F.Heim, *Parartocarpus venenosus* Becc., *Ixora grandiflora* Ker Gawl, *Pternandra galeata* Ridl., *Stenoclaena palustris* (Burm. f.) Bedd., *Asplenium longissimum* Baker, *Nephrolepis biserrata* (Sw.) Schott, *Cyrtostachys* sp., *Cyperus rotundus* L., and *Pandanus atrocarpus* Griff. (Yule and Gomez, 2009). Above ground biomass in the North Selangor peat swamp forests ranges between 127 and 443 Mg ha^{-1} with an average of 320 Mg ha^{-1} (Brown et al., 2018). The peatland is drained by the Bernam River in the north and the Tengi River that runs from east to west through the middle of the peatland. In addition, there is an

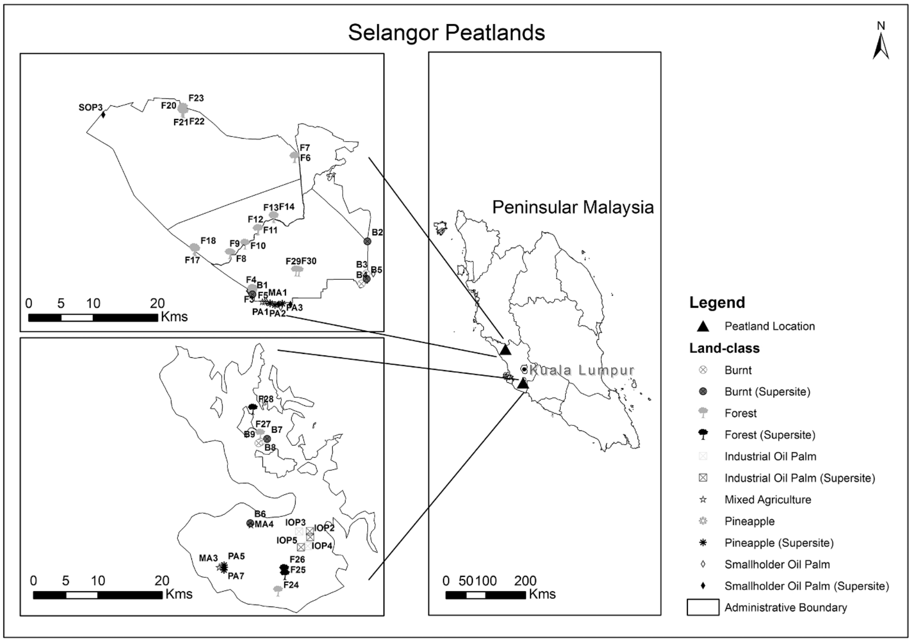

Fig. 1. Site map showing locations of Secondary forest (F), Burnt (B), Pineapple (PA), Mixed Agriculture (MA), Smallholder Oil Palm (SOP), and Industrial Oil Palm (IOP) site locations. The geographical co-ordinated and further site information are given in Supplementary Information.

extensive remnant canal network (comprising of approx. 600 km) present throughout the Secondary Forest; these canals were constructed for timber extraction and irrigation of neighbouring paddy fields (Irvine et al., 2013). The average peat depth is 3.6 m, but with a highest recorded depth of 10 m (Global Environment Centre, 2014).

The South Selangor peat swamp forest is relatively less well characterised compared to the North Selangor peat swamp forest. It is reasonable to assume that these peatlands have a similar species composition, considering their proximity and comparable geographical location, topography, and climatic conditions. However, it should be noted that the South Selangor peat swamp forests are smaller and more fragmented than North Selangor peat swamp forests, which may have impacted species diversity. Some of the larger tree species include *Koompasia malaccensis, Shorea teysmanniana*, *Tetramerista glabra* and *Gonystylus bancanus* (Global Environment Centre, 2014). The South Selangor peat swamp forest is drained by the Langat River (Waldron et al., 2019) and supplemented by drainage canals. The average peat thickness is estimated to be 3.3 m (Global Environment Centre, 2014).

2.1.2. Fire affected and forest trees replanted (Burnt) peatlands

The fire affected and forest tree replanted (here after referred to as 'Burnt') land-use consisted of nine sites that were burned down by fire within the last decade, prior to which they were all forested. All of the selected sites had been impacted by canal drainage, but these drains were subsequently blocked, and the burned areas were replanted with forest tree species as part of restoration and fire risk mitigation measures. The sites are now managed by the Global Environment Centre in collaboration with local communities. One of the North Selangor locations was near Kampung Raja Musa village, located between an industrial oil palm plantation and the Raja Musa forest reserve. Four site locations were on the western edge of the Raja Musa forest reserve, North Selangor; three on the edge of the North Langat peat swamp forest in South Selangor, and one location near the South Langat forest reserve in South Selangor. A total of five Supersites were selected for this land-use, with three in North Selangor and two in South Selangor. Burnt sites were covered with tall dense grasses after drain blocking, with native forest trees planted in rows in between these grasses. Peat depths were greater than 2 m for most sites of this land-use, except for one site in North Selangor which had shallow peat in the 0.3 – 0.5 m depth range.

2.1.3. Pineapple cropping systems

As a general practice, pineapples were planted under electric power lines running through oil palm plantations in smallholder villages. Pineapple was also commonly intercropped with young oil palm by some farmers. Pineapple land-use was located at three sites in the North Selangor and four sites in the South Selangor peatlands. Two sites in North Selangor were intercropping systems with young oil palm, while one site was monocropping. All four of the South Selangor sites of this land-use were pineapple monocropping, located in Kampung Kundang. The pineapple sites were usually bordered by drainage canals on each side, with no additional drainage canals running within a site. The pineapple and oil palm intercropping followed an alley cropping system, where the pineapple crop was densely planted in between the rows of young (1–2 years old) oil palm. The pineapple land-use was usually heavily managed and devoid of any other vegetation, possibly because of the high density of the pineapple crop and regular maintenance work carried out by the farmers. The peat depth for sites in North Selangor was between 1 and 1.5 m, while for sites in South Selangor the peat depth was greater than 1.5 m.

2.1.4. Mixed agriculture

Mixed agriculture land-use occupied a limited area in comparison to other land-uses and was usually located in residential areas of villages. A total of four sites were included in this study, with two each in North Selangor and in South Selangor. The North Selangor sites were located in between an industrial oil palm plantation and the southern edge of the Raja Musa forest reserve. These agricultural fields had been cultivated for the last 40 years with winter melon and other vegetable crops. The peat depth at these two sites was very shallow at around 0.2 m. One site in South Selangor was located in Kampung Kundang village and cultivated with cassava, whilst another site located in the same village was in between cropping cycles. The peat depth at both sites was greater than 1.5 m.

2.1.5. Smallholder oil palm monocropping

Oil palm was first introduced to Malaysia in the Thennamaran region of North Selangor, which is located on the Southern edge of the peat dome. Oil palm (OP) plantations gradually expanded to nearby peatlands, mostly through smallholder farmers. Thus, the region is important for oil palm research, and our selection of six different locations represent the smallholding oil palm practices in the Selangor state of Malaysia. All the studied Smallholder OP plantations were located in North Selangor peatlands, with four in Kampung Raja Musa village, one on the eastern edge of the Raja Musa forest reserve and one on the northern edge of the Sungai Karang forest reserve. Smallholder OP plants were unevenly planted and less intensively managed compared to industrial plantations, with considerable cover of understorey ferns. All field sites were about 2 ha in size, consistent with small holdings by farmers in this region (Dhandapani et al., 2019a). Only sites with mature oil palm plantations (>15 years) were chosen for this study, as most of the smallholder oil palm plantations in the region are at the end of their first-generation cropping cycle. Each oil palm small-holding farm was bordered by drainage canals, with an additional one or two drainage canals within a site. The peat depth for this land-use ranged from 1.5 to 3.5 m.

2.1.6. Industrial oil palm monocropping

The Industrial OP plantations studied for this research were owned by the Malaysian airport authority and located adjacent to the new terminal of the Kuala Lumpur International Airport. This area used to be part of the South Selangor peat swamp forest but has been converted to agriculture since 1977. Most of the area is in the second generation of oil palm plantations. Similar to other such industrial plantations, these plantations were intensively managed with regular maintenance under supervision from the management office located on the site. Thus, the whole industrial plantation area was homogenous, and we selected five different site locations spread over the plantations. The peat depth of this land-use ranged from 1 to 2 m.

2.2. Peat analyses

Peat cores down to a depth of 50 cm were collected between June and August 2018 from a plain surface within each site for analyses, carefully avoiding areas of hummock-hollow topography or water erosion. The 50 cm peat core was separated to 5 X 10 cm layers, and used for lab analyses. The procedures used for peat analyses were based on Dhandapani et al. (2019b) and Dhandapani and Evers (2020). Peat temperature was measured *in situ*, using a digital thermometer Cosmark PDT300 (Norwich, UK). For this, fresh peat was dried in an oven at 105 °C for 48 h. The gravimetric moisture was calculated as follows:

Gravimetric moisture (%) = (Mass of the water lost in oven drying/mass of oven dried peat) × 100

Bulk density was calculated by dividing the dry weight of a 50 cm peat core from a Russian corer in grams by the volume of the Russian corer in cm^3. For the sites that had peat depth lesser than 50 cm, only peat layers were used for bulk density calculations and the volume was adjusted accordingly. Mineral layers were not used for any of the analyses reported in this research.

For pH, redox and electric conductivity measurements, 5 mL volume of peat sample was diluted in 10 mL deionised water in a centrifuge tube and shaken on a table shaker for 2 h. The pH of the supernatant was then measured using a Eutech pH700 pH meter supplied by Thermo Scientific (Loughborough, UK). The redox potential and electrical conductivity were measured using Eutech Ion 2100 (Thermo Scientific, Loughborough, UK) and Groline HI98331 probe (Hanna, Leighton Buzzard, UK), respectively.

For analysing total carbon (C) and nitrogen (N) content, all samples were oven dried (105 °C for 48 h) and finely ground using a Fritsch mortar grinder pulverisette 2 (Brackley, UK). Approximately 70 mg of sample was weighed into a Skalar ceramic crucible and the exact weight was recorded. The samples were then transferred to an auto sampler in Skalar primacs series SNC100 TC TN analyser (Breda, The Netherlands) and analysed for total C and N content.

2.3. *Nutrient analyses*

The peat nutrient concentrations were analysed using inductively coupled plasma mass spectroscopy (ICP-MS). For this, approximately 0.15 g of oven dried (105 °C for 48 h) and ground peat were weighed in microwave digestion tubes (MARSXpress vessels, CEM Microwave Technology Ltd., Buckingham, UK.). The digestion tubes were sealed with a stopper and a screw lid, after adding 10 mL of nitric acid to each sample. The digestion tubes were then placed in a MARSXpress microwave (CEM Microwave Technology Ltd., Buckingham, UK.) and run at 1600 W & 100% power with a ramp for 20 min and held for 20 min at 170 °C. The tubes were left over night in the microwave to cool down. The digested samples were then filtered and made up to 30 mL using milliQ water. Then, 1 mL of each sample was transferred in to a 10 mL tube and further diluted with 9 mL of milliQ water. The samples were then analysed using 'Agilent Technologies (Milton Keynes, UK) 7900 ICP-MS fitted with 'SPS 4′ autosampler.

2.4. *Peat subsidence and water table levels*

To measure subsidence, metal poles (3 per site) were inserted through the peat and anchored into the underlying clay substrate. Pole height from the peat surface was measured quarterly for all 61 sites, whilst the monthly pole measurements were made for 21 selected Supersites. Metal pipes of five millimetre diameter supplied by Kindraco Hardwares (Kuala Lumpur, Malaysia) were used as poles for this purpose. The pipes, which were six metre in length, were cut to one metre pieces (poles) and threaded on each side. The sockets were then used to connect one metre poles during insertion. The poles were then inserted into the peat reaching the clay and then beneath the clay, until the pole reached a point where it was fixed and could not be physically pushed or hammered further. The depth of such insertion ranged from four to eight metres, with most locations having poles inserted at least up to five metres deep. For Secondary Forest sites, PVC pipes of five millimetre diameter were used instead of metal poles, because of logistical difficulty involved in carrying metal poles into the Secondary Forest. Extra care was taken to ensure that the poles were inserted vertically at a straight angle. Three poles were arranged in a roughly triangular pattern with a side length of about 15 m. A metal washer ring was put around the tube after the insertion process was complete (and left in place for the duration of the study), so that the length of the pole aboveground could be measured from the flat ring on the peat surface to the top of the pole. For the measurement to be more precise and consistent, the side on the top of the pole where the first measurement was made, was marked with paint, so that the same side could be used for subsequent measurement of the pole length. The pole lengths were measured quarterly (from August 2018 to August 2019) for all sites and every month (from August 2018 to September 2019) for selected 'supersites' within each of the land-uses. For the agriculture sites, the poles were inserted in areas that were not in the harvesting path or close to trees where workers needed to go to harvest the fruits. Some of the first-generation oil palm plantations, where the peat surface was not flattened, had a hummock-hollow surface topography, further eroded by rainwater flow. Such areas of rainwater erosion were also carefully avoided, to reduce the influence of such erosion in our subsidence measurements.

Water table levels were measured (from August 2018 to September 2019) using a dipwell made by inserting a perforated PVC pipe of 50 mm diameter and 2 m length, into peat down to a depth of 1.5 m, with open bottom. The dipwells were installed after the peat cores were removed using a Russian peat corer. One dipwell was installed in each of the 21 Supersites, and the measurements were made monthly.

2.5. *Greenhouse gas emissions*

The greenhouse gas (GHG) measurements were made at five random points within five metre radii of the dipwells to directly connect the gas emissions to water table changes. The GHG measurements were made in July and August 2018 for dry season, and in December 2018 for wet season. The gas measurement points were also more than three metres away from oil palm trees in oil palm plantations to account for only heterotrophic emissions (Dariah et al., 2014; Dhandapani et al., 2021b; Dhandapani et al., 2019b; Matysek et al., 2017). No measurement points in the Secondary Forest sites was more than a metre away from a nearby plant or tree due to dense vegetation structure in this land-use. Thus, all measurement points for GHG emissions in the Secondary Forest land-use were influenced by autotrophic contribution from nearby trees (Hergoualc'h et al., 2017). Some site locations were inaccessible for GHG measurements during the wet season measurement campaign, and there is no data for the industrial oil palm land-use because of a fault in the GHG analyser which could not be fixed during the remaining field measurement period.

CO_2 and CH_4 emissions from the peat surface were measured using a Los Gatos (San Jose, California, USA) ultraportable greenhouse gas analyser as described in Dhandapani et al. (2019c). The gas analyser works on the principle of laser absorption spectroscopy and gives readings of CH_4 and CO_2 ppm as well as gas temperature. The measurements were made using a closed dynamic chamber method using a chamber with a height of 15 cm and an inner diameter of 13.5 cm. The chamber had an inlet and an outlet port that were connected to the gas analyser, using a 6.35 mm outer diameter polytetrafluoroethylene (PTFE) tube. During each measurement about 1 cm of the chamber was carefully inserted into the ground until it was sealed to the ground surface, and gas measurements were taken over 3 min. There was no surface vegetation in any of the measurement points. The gas analyser was set to record gas flux every 20 s, resulting in at least six recorded measurement points for each plot. The first minute of each measurement was ignored allowing the gas flux to settle down after initial disturbance of placing the chambers. The gas measurements in ppm were converted to mg CO_2 m^{-2} hr^{-1} and μg CH_4 m^{-2} hr^{-1} for CO_2 and CH_4 respectively, using the ideal gas law $PV = nRT$, where: P = atmospheric pressure; V = volume of headspace; n = number of moles (mol); R = universal gas constant (8.314 J. $K^{-1}mol^{-1}$) and T = temperature in kelvin (K), with conversion factor, 1 mol of CO_2 = 44.01 g and 1 mol CH_4 = 16.02 g.

2.6. *Statistical analyses*

All the statistical analyses were carried out using Genstat® 19th edition (VSN international, Hemel Hempstead). The significance of differences between land-uses for GHG emissions, peat subsidence rates, nutrient concentrations and other physico-chemical properties were evaluated using two-way Analysis Of Variance (ANOVA) incorporating conditions 'land-use', and 'depth' or 'season' as fixed effects. For the data sets that were not normally distributed, the data were log transformed. Principal component analysis was performed using a correlation matrix for the dataset containing all the measured peat physico-chemical properties, nutrient concentrations, and subsidence, to identify difference between land-uses. Tukey's multiple comparison test was performed to identify pair-wise differences in subsidence between land-uses. Simple linear regression was performed with CO_2 and CH_4 as response variables and water table level as a fitted term. CO_2 and CH_4 emissions from the Secondary forest land-use were left out of the multiple regression because of significant root contribution to total emissions from this ecosystem. Simple linear regression was also carried out connecting changes in peat surface level every month to the corresponding changes in monthly water table level.

3. Results

3.1. Peat physico-chemical properties

The pH was significantly different between land-uses but did not vary significantly with depth (Table 2; Fig. 2a). The pH was highest and second highest at the Burnt (mean pH 3.73 – pH 4.25) and Mixed Agriculture (mean pH 3.64 – pH 3.96) land-uses respectively, for all depth ranges, and lowest at Secondary Forest (mean pH < 3.35) for almost all depth ranges. For other land-uses such as Pineapple, Smallholder and Industrial OP, pH was closer to that of Secondary Forest. The interaction between land-use and depth was significant as different land-uses exhibited a different trend of change with depth, notably pH slightly decreased with depth for Burnt land-use and slightly increased with depth for Secondary Forest and Industrial OP.

Gravimetric moisture was significantly different between different land-uses. All land-uses showed an increase in gravimetric moisture with depth, resulting in significant changes with depth, but no significant interactions between land-use and depth (Table 2; Fig. 2b). Moisture was highest at Burnt land-use with mean value for depths ranging from 453% (0–10 cm) to 910% (40–50 cm), closely followed by second highest moisture content at Secondary Forest land-use (mean 339% – 670%), and lowest moisture at Mixed Agriculture land-use for all depths (mean 115% – 209%). All the other land-uses i.e., Pineapple, Smallholder and Industrial OP had similar levels of moisture content in the range between Secondary Forest and Mixed Agriculture land-uses.

Electrical conductivity was significantly different between land-uses, and depths, however interaction terms were non-significant (Table 2; Fig. 2c). Electrical conductivity was highest in the Secondary Forest land-use (406 μS cm^{-1}) and lowest in the Burnt land-use (148 μS cm^{-1}) for the surface peat (0–10 cm) layer. Electrical conductivity slightly reduced with depth under the Secondary Forest land-use, while it stayed at the same level in the Burnt land-use and was lowest for most depth ranges. Other land-uses showed varying trends of change with depth with only slight variations and no clear pattern.

Redox potential significantly varied between land-uses, and depths, with no significant interaction between land-use and depth (Table 2; Fig. 2d). Redox potential in the surface peat layer (0–10 cm) was highest at the Pineapple land-use (292 mV), showed a slight increase with depth and stayed the highest at all depth ranges. All the other land-uses were grouped together with similar redox potential in the surface layer and exhibited slightly varying trends of change with depth.

Table 2
Two way Analysis of Variance (ANOVA) for peat physico-chemical properties and nutrient concentrations, showing statistical significance of the effects of land-use, depth and interactions between land-use and depth. Statistically significant figures are presented in bold italics.

	Land-use	Depth	Land-use*Depth
pH	***$F_{(5,247)} = 49.23, p < 0.001$***	$F_{(4,247)} = 1.39, p = 0.236$	***$F_{(20,247)} = 2.24, p = 0.002$***
Moisture	***$F_{(5,250)} = 14.20, p < 0.001$***	***$F_{(4,250)} = 15.11, p < 0.001$***	$F_{(20,250)} = 0.45, p = 0.980$
logEC	***$F_{(5,247)} = 16.09, p < 0.001$***	***$F_{(4,247)} = 6.94, p < 0.001$***	$F_{(20,247)} = 1.42, p = 0.112$
Redox	***$F_{(5,247)} = 19.92, p < 0.001$***	***$F_{(4,247)} = 14.08, p < 0.001$***	$F_{(20,248)} = 0.88, p < 0.608$
C	***$F_{(5,250)} = 32.80, p < 0.001$***	$F_{(4,250)} = 0.75, p = 0.557$	$F_{(20,250)} = 1.17, p = 0.281$
N	***$F_{(5,249)} = 26.48, p < 0.001$***	***$F_{(4,249)} = 25.13, p < 0.001$***	***$F_{(20,249)} = 1.69, p = 0.036$***
C:N	***$F_{(5,248)} = 13.82, p < 0.001$***	***$F_{(4,248)} = 27.53, p < 0.001$***	***$F_{(20,248)} = 1.99, p = 0.008$***
logMg	***$F_{(5,249)} = 4.80, p < 0.001$***	$F_{(4,249)} = 0.19, p = 0.945$	$F_{(20,249)} = 0.69, p = 0.838$
logP	***$F_{(5,247)} = 23.48, p < 0.001$***	***$F_{(4,247)} = 39.38, p < 0.001$***	$F_{(20,247)} = 1.11, p = 0.335$
S	***$F_{(5,247)} = 22.99, p < 0.001$***	$F_{(4,247)} = 0.93, p = 0.444$	$F_{(20,247)} = 1.16, p = 0.287$
logK	***$F_{(5,249)} = 10.25, p < 0.001$***	$F_{(4,249)} = 0.71, p = 0.588$	$F_{(20,249)} = 0.68, p = 0.851$
logCa	***$F_{(5,249)} = 24.83, p < 0.001$***	***$F_{(4,249)} = 7.39, p < 0.001$***	$F_{(20,249)} = 0.63, p = 0.892$

3.2. Peat carbon and nutrient content

Total peat carbon (C) content varied significantly between different land-uses, however the changes with depth and the interaction terms were not significant (Table 2; Fig. 3a). The Secondary Forest land-use had the highest (mean 50.3% – 56.9%) and the Mixed Agriculture land-use had the lowest C content (mean 17%- 24.7%) of all land-uses. All the other land-uses were grouped together with slightly lower C content than the Secondary Forest.

Total peat nitrogen (N) content varied significantly between different land-uses, with significant changes with depth, and significant interactions between land-use and depth (Table 2; Fig. 3b). The Secondary Forest land-use had the highest N content at the surface (1.87 %) and the Mixed Agriculture had the lowest N content at the surface layer (0.9 %). The Mixed agriculture also had the lowest N content throughout the studied depth ranges.

Peat C:N ratio was significantly different between different land-uses, varied significantly with depth, and exhibited significant interactions between land-use and depth (Table 2; Fig. 3c). All the rest of the macronutrients showed significant variations between different land-uses, with only phosphorus and calcium showing significant variations with depth, and all of them exhibiting no significant interactions between land-use and depth (Table 2; Fig. 3d-h).

3.3. Peat subsidence rates and bulk density

Peat subsidence from quarterly measurements across 61 sites showed that the subsidence rates varied significantly between land-uses ($F_{(5,608)} = 4.93$, $p < 0.001$), and between measurement periods ($F_{(3,608)} = 37.47$, $p < 0.001$). However, there was no significant interaction between land-use and measurement period ($F_{(15,608)} = 0.92$. $p = 0.543$), as all land-uses showed a significant reduction in surface level over time. Tukey's Multiple comparison results show that the Burnt land-use had undergone significantly greater subsidence than the Secondary Forest and Industrial oil palm land-uses, while all the other land-uses were not significantly different between each other (Table 3; Fig. 4a). Annual subsidence was highest in the Burnt land-use at 4.43 cm, and lowest in the Industrial oil palm land-use at 1.8 cm. The Secondary Forest land-use had annual subsidence of 2.1 cm with all the rest of the land-uses having an annual subsidence rate that was greater than that of the Secondary Forest.

Peat bulk density was significantly different amongst the studied land-uses ($F_{(5,60)} = 6.31$, $p < 0.001$). Tukey's multiple comparison shows that Mixed Agriculture (0.11 g cm^{-3}) was the only land-use to have significantly greater bulk density than Secondary Forest (0.04 g cm^{-3}; Table 3; Fig. 4b).

Despite its ongoing and historic drainage, Secondary Forest was assumed to be the closest representation of a near-natural set of peat properties due to minimal changes in the above ground cover and absence of any fertiliser inputs. Therefore, any deviation away from Secondary Forest in the principal component analysis (PCA) was taken to indicate the level of anthropogenic modification of the peat. All properties taken together in the PCA show both Smallholder and

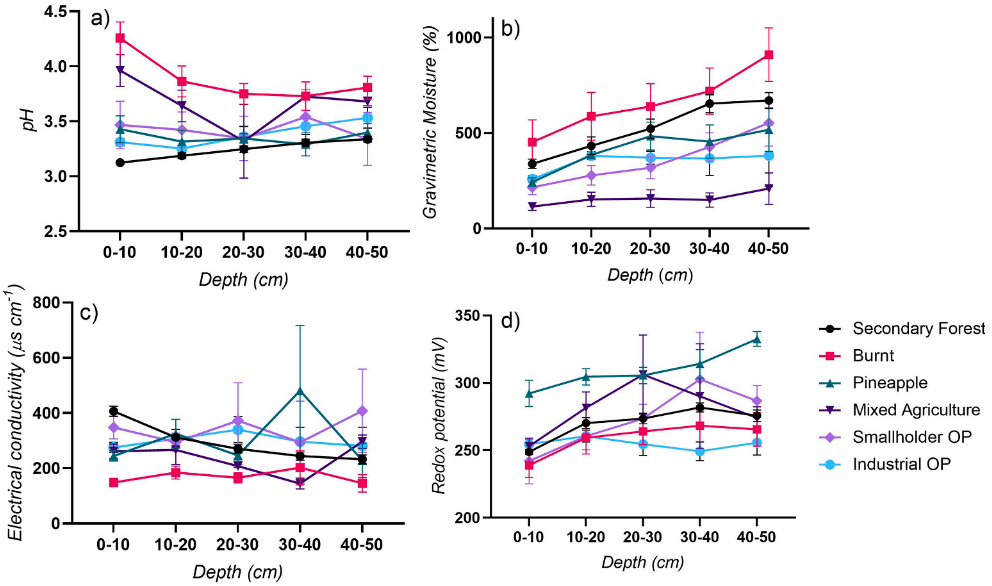

Fig. 2. Effect of land-use and depth upon a) gravimetric moisture, b) pH, c) electrical conductivity and d) redox potential. Points denote mean values (n varies, see text). Whiskers denote standard errors.

Industrial oil palm grouped together closer to Secondary Forest, while other land-uses were further away (Fig. 5). Principal Components (PC) 1 and 2 together accounted for 54.5 % of the variance. PC1 separated Secondary Forest from all the other land-uses that are clustered together except for the Mixed Agriculture land-use which was further separated from Secondary Forest and the other cluster. Separations in PC1 away from Secondary Forest were associated with high bulk density, high nutrient concentration and low peat organic matter content. PC2 grouped Secondary Forest, Smallholder and Industrial OP together, while it located both Burnt and Mixed Agriculture land-uses together furthest away from the Secondary Forest land-use. Separations in PC2 away from Secondary Forest were associated with high pH and Ca concentrations.

3.4. *Greenhouse gas emissions*

CO_2 emissions (with mean ranges from 492 to 1422 mg m^{-2} hr^{-1}) did not significantly vary between land-uses ($F_{(4,185)} = 1.48$, $p = 0.211$), nor between seasons ($F_{(1,185)} = 3.83$, $p = 0.052$) (Fig. 6a). The Pineapple land-use showed higher emissions in the wet season compared with the dry season, while there were no seasonal variations for other land-uses, resulting in significant interactions between land-use and season ($F_{(3,185)} = 8.22$, $p < 0.001$).

CH_4 emissions were all under 1 mg m^{-2} hr^{-1} and, as for CO_2 emissions, showed no significant variations between different land-uses ($F_{(4,105)} = 1.98$, $p = 0.103$) or between seasons ($F_{(1,105)} = 0.07$, $p = 0.797$) (Fig. 6b). The Burnt land-use exhibited higher CH_4 emissions in the wet season than in the dry season, whilst Secondary Forest showed decreased emissions in the wet season. For other sites there was no change in emissions between seasons, resulting in significant interactions between land-use and season ($F_{(3,105)} = 3.21$, $p = 0.026$).

3.5. *Influence of water table level on GHG emissions and peat subsidence*

Monthly water table level significantly varied between land-uses ($F_{(4,176)} = 12.56$, $p < 0.001$), and between months ($F_{(9,176)} = 7.32$, $p < 0.001$). However, Tukey's multiple comparison analyses showed that only the Burnt land-use had a significantly higher water table (-26 cm) than all the other land-uses. Smallholder oil palm (-68 cm) had a significantly lower water table than the Secondary Forest (-43 cm) and Burnt land-uses, while the water table level between other land-uses did not significantly differ (Table 4). The interactions between land-uses and months were not significant ($F_{(36,176)} = 0.77$, $p = 0.817$), showing that the water table level changes for different land-uses follow the same trend throughout the year.

The CO_2 emissions did not correlate with actual water table level ($F_{(1,136)} = 0.7$, $p = 0.403$), however CH_4 emissions were positively correlated with higher water table level ($F_{(1,81)} = 8.91$, $p = 0.004$, $r^2 = 0.09$). The peat subsidence was significantly correlated with decrease in water table level ($F_{(1,504)} = 4.78$, $p = 0.029$, Peat surface level = -0.29 + 0.0005 (water table level)). Further fitting subsidence as a function of changes in water table level for the individual land-uses showed that this relationship was significant only for the Burnt, Smallholder OP and Pineapple land-uses, while the Secondary Forest and Industrial OP land-uses did not exhibit any significant correlation between changes in water table levels and peat subsidence (Table 4; Fig. 7).

4. Discussion

Land-use changes at our tropical peatland study locations had a significant impact on all of the studied peat physico-chemical properties and nutrient concentrations (Table 2). Considering the complexity of natural tropical peat swamp forests and the dramatic above and below ground changes that accompany their conversion to agriculture, these subsequent differences in peat properties between different land-uses were anticipated. Peat pH was consistently lowest in the Secondary Forest (mean pH 3.1 at 0–10 cm depth) and highest at the Burnt land-use (mean pH 4.3 at 0–10 cm depth), with other land-uses between this range. Fire is known to increase pH in tropical peat in the immediate aftermath of burning because of the release of cations in peat after fire (Dhandapani and Evers, 2020; Sazawa et al., 2018), as observed in most other soil systems (Chungu et al., 2019; Heydari et al., 2017; Kennard and Gholz, 2001; Scharenbroch et al., 2012; Zaccone et al., 2014). Similarly, the conversion of tropical peatland to oil palm and other agricultural systems is also known to increase peat surface pH (Cooper et al., 2019; Dhandapani et al., 2019a; Tonks et al., 2017), although not by the same amount as fire (Dhandapani and Evers, 2020).

All the studied land-uses were drained to some extent. Drainage is being actively reduced in some forest restoration areas and particularly in burnt focal areas in an effort to prevent fires as part of ongoing restoration. This work is proving successful with significantly higher water tables recorded at the Burnt land-use. However, for much of the

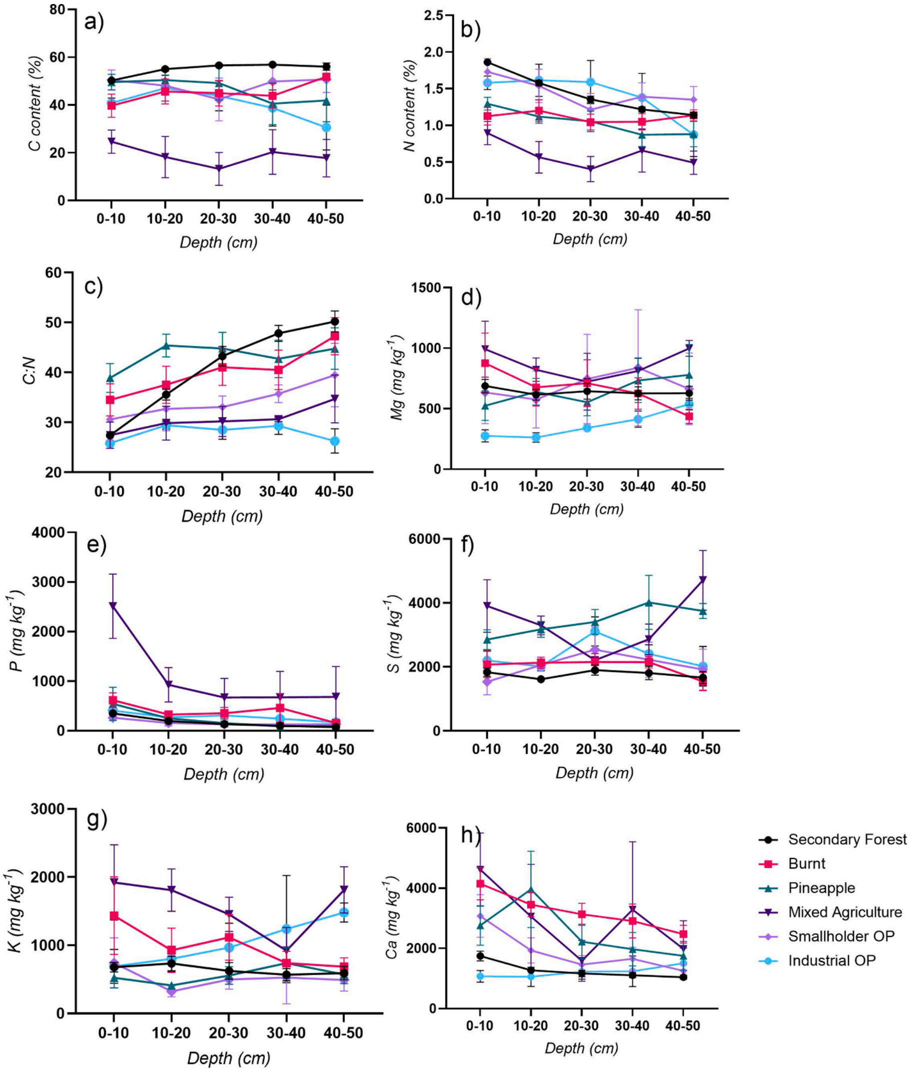

Fig. 3. Effect of land-use and depth upon a) C content, b) N content, c) C:N ratio, d) Mg concentrations, c) P concentrations, d) S concentrations, e) K concentrations, f) Ca concentrations. Points denote mean values (n varies, see text). Whiskers denote standard errors.

Table 3
Tukey's multiple comparison for quarterly subsidence rate, peat bulk density (0–50 cm) and water table level in each land-use, showing means and letters to denote significant difference between land-use pairs. Land-use pairs with any shared alphabet in Significance column is not significantly different from each other.

Land-class	Peat quarterly subsidence rate (cm)		Peat bulk density (g cm^{-3})		Water table level (cm)	
	Means	Significance	Means	Significance	Means	Significance
Burnt	−2.25	A	18.2	A	−26.25	C
Smallholder OP	−1.59	AB	44.3	C	−67.15	A
Mixed Agriculture	−1.54	AB	55.2	C	NA	NA
Pineapple	−1.06	AB	41.9	BC	−57.38	AB
Forest	−0.98	B	24.7	AB	−43.14	B
Industrial OP	−0.58	B	29.4	ABC	−56.92	AB

remaining reserve, there remains an ongoing legacy of drainage resulting from the previous timber production activities. All the other agricultural peatlands were actively drained. Differences in drainage intensity are also reflected in gravimetric moisture values, with the Burnt and Secondary Forest land-uses having the highest moisture values (Table 2; Fig. 2b). Moisture increased with depth for all land-uses. Lower moisture in the surface is possibly due to increased temperature and exposure for evapotranspiration in surface layers in open agricultural land-uses.

Electrical conductivity and redox potential are important properties which influence nutrient and GHG dynamics in peat or soil systems (Dhandapani and Evers, 2020; Niedermeier and Robinson, 2007; Pezeshki and DeLaune, 2012; Søndergaard, 2009; Visconti and De Paz, 2016). Electrical conductivity shows a rough estimate of peat nutrient profile, and it is unsurprising that it was significantly different between land-uses that also showed significant differences in macronutrient concentrations (Fig. 2&3). Redox potential values also indicate aerobicity in all studied land-uses, consistent with water table level results. The Burnt land-use had the highest mean water table levels due to drain blocking, and also had the lowest redox potential in the surface peat

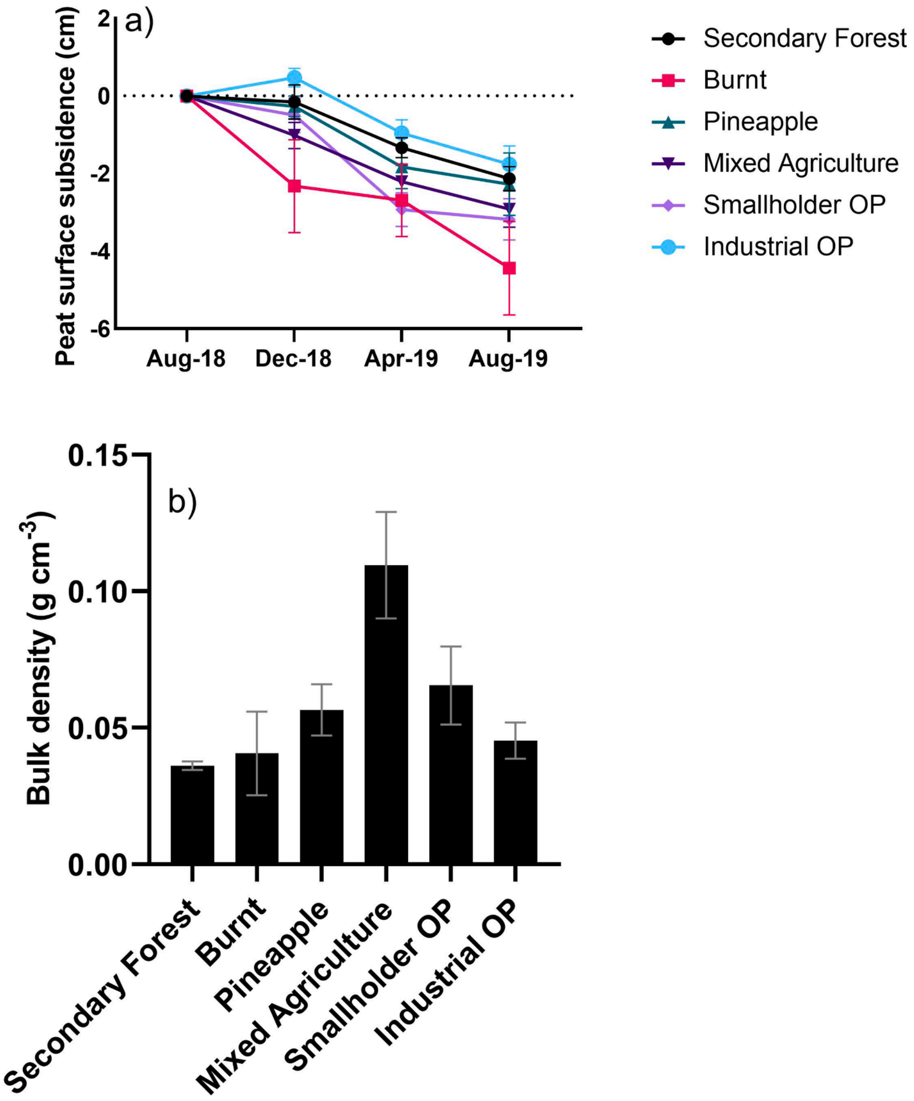

Fig. 4. a) Effect of land-use and measurement periods upon peat subsidence, bars denote mean values (n varies, see text). Whiskers denote standard errors. b) Effect of land-use upon peat bulk density, bars denote mean values (n varies, see text). Whiskers denote standard errors.

layer, consistent with our previous findings that showed that incidence of fire had reduced redox potential in fire affected layers of peat (Dhandapani and Evers, 2020). It should be noted that the Pineapple land-use (with some sites intercropped with young oil palm) is the most densely planted and hence most intensively managed agricultural system amongst the agricultural land-uses reported in this study. This combination of increased human activity causing increased peat disturbance, and the requirement for high productivity in this system resulting in greater peat microbial activity, may explain the observed high redox potential in the Pineapple land-use.

Peat macronutrient concentrations also significantly varied between land-uses. This is possibly influenced by a few different parameters: 1. Legacy effect of historic species distribution of peat forming forest trees both influencing and being influenced by macronutrient concentrations (Krishna and Mohan, 2017; Paoli et al., 2008; Rodrigues et al., 2016; Xi et al., 2017); 2. use of fire in land-management or -conversion (Dhandapani and Evers, 2020); 3. quantity and quality of management inputs in agricultural landscapes (Chapin et al., 2003); and 4. varied levels of leaching, nutrient run off and landscape topography (Adhikari et al., 2018; Bah et al., 2014; Zhang et al., 2011). The management inputs in agricultural landscapes are not known for the sites used in this study. Mixed Agriculture showed signs of greater fertiliser usage compared with other land-uses, with very high concentrations of phosphorus and potassium in the surface peat layers which then decreased with depth. Peat, by definition, comprises semi-decomposed plant organic material and thus nutrient concentrations are heavily dependent on the peat forming material aboveground. The Selangor peatlands are biodiversity rich ecosystems (Adila et al., 2017; Yule, 2010), and the legacy of the historic distribution of peat forming plant species aboveground and their spatial variations would have likely impacted the nutrient concentration of these current land-uses (Girkin et al., 2020b; Sjögersten et al., 2011), which are further affected by anthropogenic activities. Though there is not one single clear explanation for changes in peat nutrient concentrations between land-uses, peat nutrient content is known to significantly vary between different oil palm cropping systems (Dhandapani et al., 2021a), and even spatially vary within land-uses such as oil palm monoculture (Dhandapani et al., 2021b) and in secondary forests (Dhandapani et al., unpublished). It is also known to be impacted by disturbance such as fire (Dhandapani and Evers, 2020). The results from our current study show that all the studied peat physico-chemical properties and nutrient concentrations were significantly affected by land-use change, validating our first hypothesis. These findings clearly show that with land-use change, peat properties are appreciably altered from their relatively near-natural state as represented by the Secondary Forest land-use. Considering that such land-use changes are widespread across the region, there is a further need to understand the interactions

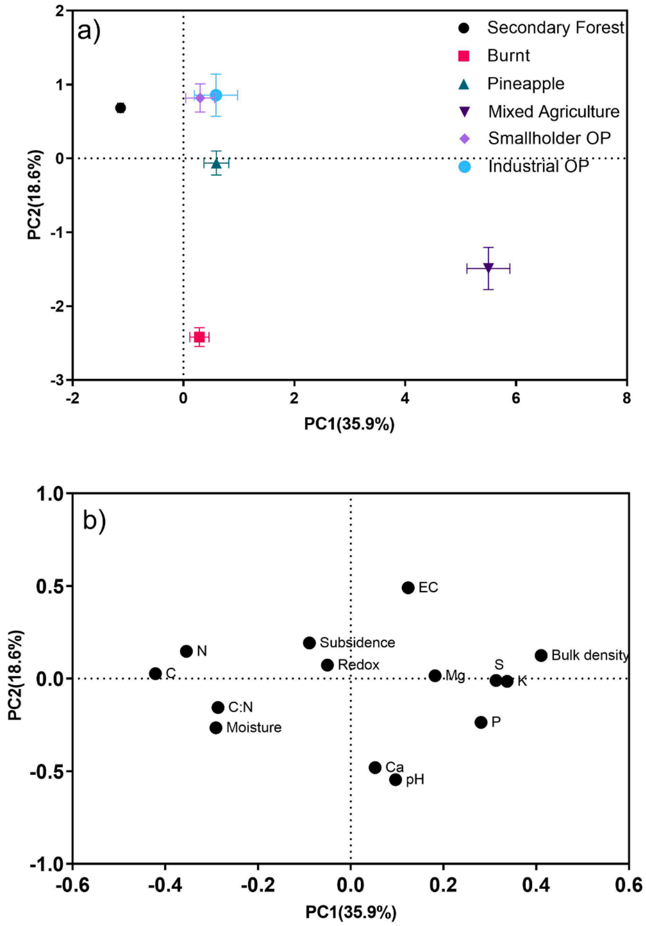

Fig. 5. Effect of land-use and depth upon peat physico-chemical properties and macronutrient concentrations, as shown by Principal Components (PC) analysis. a) ordination of PC1 and PC2 discriminating land-use, b) associated loading for individual physico-chemical properties and macronutrient concentrations. Whiskers denote standard errors.

between changes in different peat properties and biogeochemical cycling with controlled experiments alongside field observations. Such studies would also improve our understanding of the impact of land-cover change on peat ecosystem services such as carbon and water storage.

All studied land-uses showed a similar trend of significant subsidence with time, but only the Burnt land-use (4.4 cm yr^{-1}) had a significantly greater subsidence than Secondary Forest (2.1 cm yr^{-1}). The Secondary Forest sites studied here were historically drained, with drainage canals present throughout this land-use. This legacy drainage has resulted in reduced water-logging and increased peat decomposition rather than accumulation. Subsidence rates in the other agricultural landscapes were in a similar range to that of the Secondary Forest land-use. This result may well reflect the short duration of the study (one year), which limits our ability to assess longer-term trends. However, it is also the case that the water table at forest sites is below surface for most of the year, a clear indication of widespread forest degradation. If these trends were to persist longer term, it is likely they would impact the structural integrity of the peat profile, and its natural ability to respond to changing water table levels (Marshall et al., 2022). They would also potentially affect other important peat functional ecosystem services such as water and carbon storage. It is therefore vitally important that legacy and current drainage networks are blocked to prevent on-going degradation of forested peatlands.

In the agricultural land-covers, subsidence can be partly attributed to peat compaction during land-use conversion and preparation for planting, as indicated by high values for peat surface bulk density (Table 3; Fig. 4b). Some of the Mixed Agriculture sites had been under cultivation for the last 40 years and had lost most of the peat, with depths of<0.2 m remaining at some sites. These degraded peats had a low C content even in the surface layers (Supplementary Table 1; Fig. 3a). Hence, the subsidence rate in this land-use is low (2.9 cm yr^{-1}) owing to the loss of most of the soil organic layer. The significant subsidence rates across all land-uses are in line with a recent study which observed that 90 % of peatlands in Southeast Asia, including forested peatlands, are undergoing subsidence (Hoyt et al., 2020). Hoyt et al. (2020) also found that subsidence rates in forests were highest across a range of land-uses that included industrial and smallholder plantations, burnt areas, urban areas, tall and small shrubs. The field observed average subsidence rates for most land-uses in Selangor peatlands in our study (means 1.8 ± 0.47 to 4.4 ± 1.2 cm yr^{-1}) match with the average rate of subsidence of 2.2 cm yr^{-1} across all land-covers reported by Hoyt et al. (2020). Our annual subsidence rates are also consistent with those from other studies of forested and agricultural peatlands in this region (Evans et al., 2019; Hooijer et al., 2012). Secondary peat swamp forests constitute almost all of the remaining peat forest land cover in Peninsular Malaysia. These findings of significant subsidence in this land-use emphasise the fragility of these ecosystems, and affirm the need for management to improve peatland hydrological and ecological integrity.

Peat surface level changes were positively correlated with a decrease in water table level, corroborating previous observations in peatlands (Carlson et al., 2015; Wösten et al., 1997), even though the actual water table level did not significantly correlate with subsidence rates. This may be because all the studied land-uses had a water table level well below the peat surface for all or most of the study period, and the study sites were under varying management practices, including those resulting in peat compaction, which overrode the direct relationship of peat subsidence with site water table level. Nevertheless, the significant relationship between the decrease in water table level and subsidence across land-uses indicates the importance of maintaining a higher water table level to reduce subsidence and peat carbon loss. Principal component analyses placed the Burnt and Mixed Agriculture land-uses at greatest distance from the Secondary Forest land-use, suggesting that these two land-uses have substantially different peat properties to those of the Secondary Forest (Fig. 5). In addition, Tukey's multiple comparison for subsidence indicated that the Burnt land-use had a significantly different subsidence rate to all other land-uses. This supports our second hypothesis that land-uses with the most different peat properties to those of Secondary Forest have the highest subsidence rate, and that this rate will increase with increasing drainage.

Total CO_2 emissions did not significantly differ between land-uses or seasons. However, it should be noted that for Secondary Forest, the total CO_2 emissions will have included significant autotrophic contributions from the forest trees which can account for around 50% of the total CO_2 emissions from the peat surface (Hergoualc'h et al., 2017; Murdiyarso et al., 2017). For other land-uses, the total emissions will have arisen almost completely from heterotrophic respiration, in other words from the decomposition of the peat (Dariah et al., 2014). In Smallholder and Industrial oil palm, all GHG measurements were taken away from the oil palm root influence zone, which is more than 3 m from the stems (Dariah et al., 2014; Matysek et al., 2017), and thus will have had minimal autotrophic contributions. All GHG measurement points in the Pineapple land-use were close to the pineapple crop, as pineapple fields are densely planted with minimal space in between plants. However, pineapple root systems have not been found to significantly contribute to an increase in total CO_2 emissions (Dhandapani et al., 2022; Dhandapani et al., 2019b). Thus, the results suggest high carbon loss in all non-forest land-uses relative to the Secondary Forest land-use, but with no clear, observed relationship between water table level and CO_2 emissions. Our third hypothesis was therefore not supported.

CH_4 emissions were all under 1 mg m^2 hr^{-1}, consistent with previous observations that CH_4 emissions are minimal from Southeast Asian

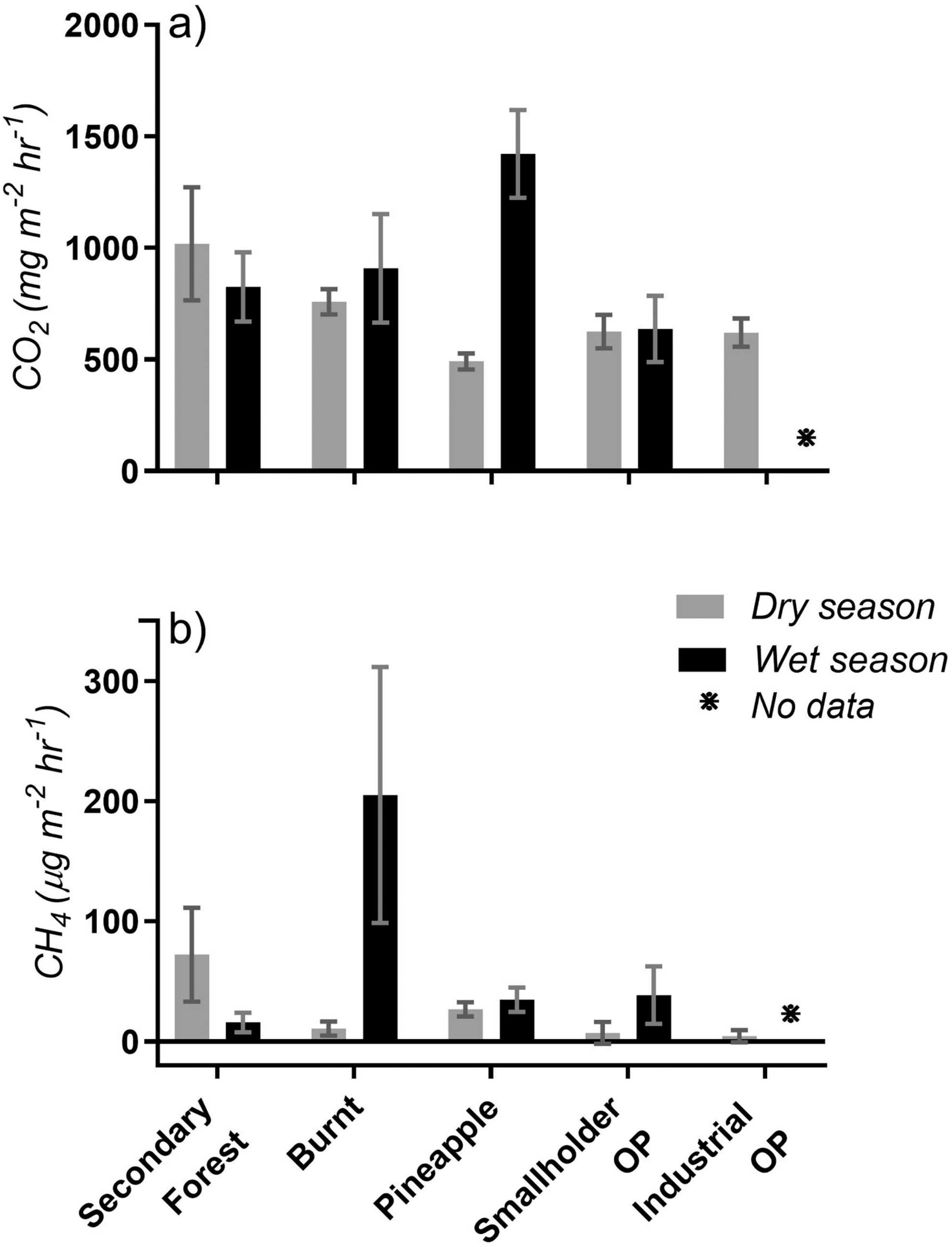

Fig. 6. Effect of land-use and season upon a) CO_2 emissions, b) CH_4 emissions during dry (grey) and wet (black) season. Bars denote mean values (n varies, see text) and whiskers denote standard errors.

Table 4
Simple linear regression equation for subsidence (cm) in each land-use for every cm change in water table.

Land-class	F and p value	R^2	Constant	Change
Forest	$F_{(1,95)} = 0.23$, p = 0.634	Not Significant		
Burnt	$F_{(1,114)} = 10.11$, p = 0.002	0.073	−0.392	+0.01637
Pineapple	$F_{(1,156)} = 5.35$, p = 0.022	0.027	−0.3282	+0.00598
Smallholder OP	$F_{(1,81)} = 5.35$, p = 0.023	0.051	−0.1832	+0.00688
Industrial OP	$F_{(1,53)} = 2.37$, p = 0.130	Not Significant		

peatlands across different land-uses (Couwenberg et al., 2010; Dhandapani and Evers, 2020; Dhandapani et al., 2019a; Hatano et al., 2016). This can be explained by low water tables, with a mean water table level deeper than 25 cm for all studied land-uses (Table 4), and individual water table levels deeper than 30 cm for most sites during the measurement period (Fig. 7). In addition, the measured redox potential (Fig. 2d) indicates that redox levels at the study sites were not in the suitable range to facilitate methanogenesis. The microbial reduction of CO_2 to CH_4 occurs under water saturation, when the redox potential is below −200 Mv, which is well below the observed redox potential at all of our sites. CH_4 emissions were notably higher in Burnt peatlands compared to other land-uses during the wet season, and can be directly related to the above ground water level in this land-use during this season. Dhandapani et al. (2019a) observed a similar exponential increase in CH_4 emissions with increase in moisture over a certain level in surface peat, associated with above surface water table level. This increase in CH_4 emissions is as expected, as water-logged conditions are a prerequisite for anaerobic decomposition and methane production in tropical peatlands (Couwenberg et al., 2010). This increase in CH_4 emissions was further aided by the effect of fire, as fire in peatlands is known to negatively impact methanotrophic activity (Danilova et al.,

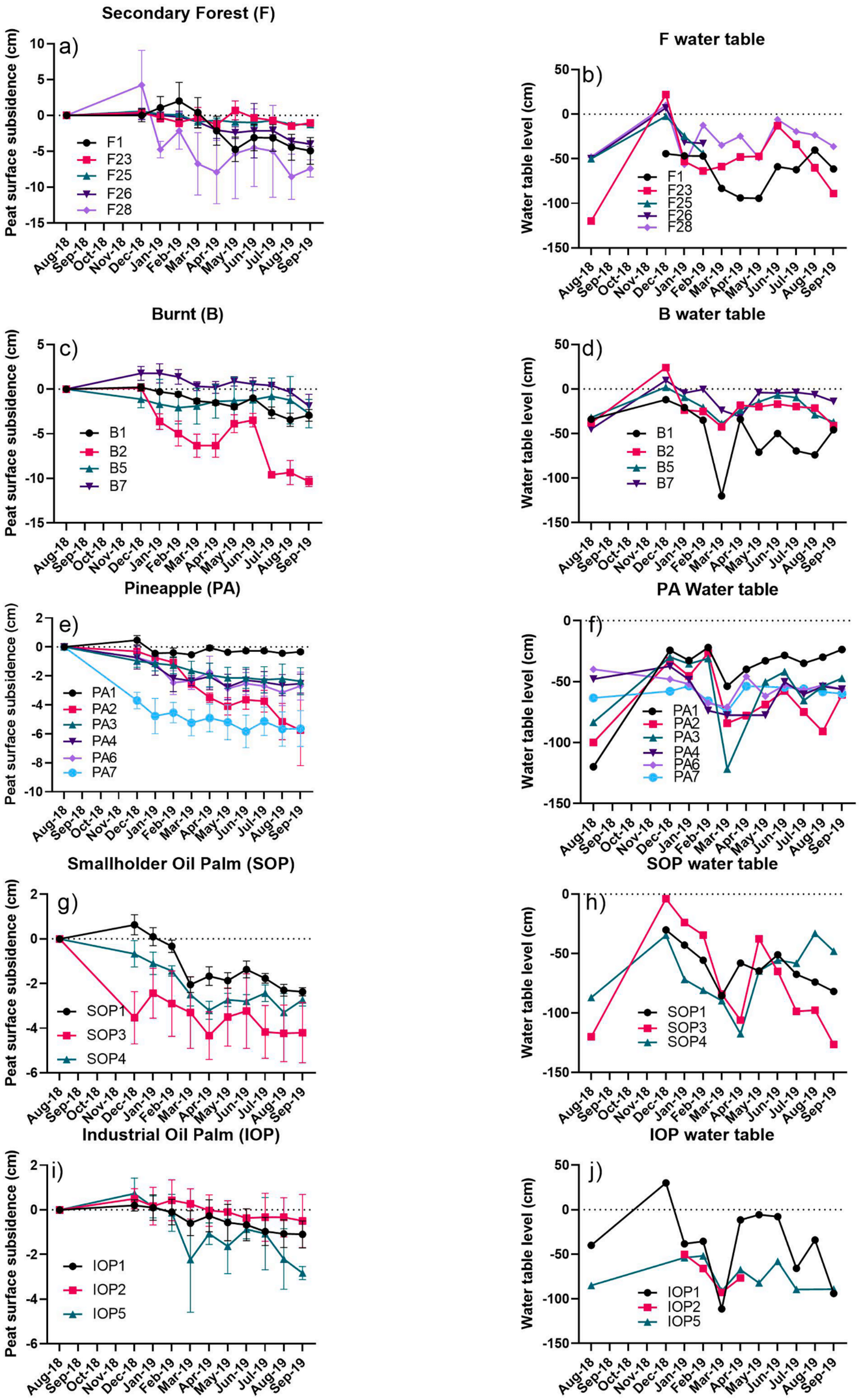

Fig. 7. Monthly changes in peat surface levels (n = 3) and associated water table levels (n = 1) across sites within each land-use; a & b) Secondary Forest, c & d) Burnt, e & f) Pineapple, g & h) Smallholder OP, i & j) Industrial OP.

2015). On the basis of these results, the first part of the fourth hypothesis that CH_4 emissions varied amongst different land-uses was not supported, whilst the second part, that CH_4 emissions decrease with increased drainage, was validated.

5. Conclusion

Taken together, the results of this study, extensively covering a large area of peatlands in Selangor state of Malaysia, show that land-use change as a result of anthropogenic activity significantly impacts peat physico-chemical properties, nutrient content and generally results in carbon loss through increased peat subsidence and GHG emissions. Even though the total CO_2 emissions did not significantly vary between land-uses, higher autotrophic emissions from Secondary Forest reported in several other studies suggest that there may be greater carbon loss through GHG emissions in disturbed peatlands compared to Secondary Forest. CH_4 emissions were minimal in all land-uses as expected, and unlike CO_2 emissions, CH_4 emissions were significantly correlated with water table levels, showing an increase in CH_4 emissions with increase in water table. The peat subsidence rate, was highest in the Burnt land-use, and across all land-uses demonstrated a positive correlation with increased drainage. This correlation shows the importance of improving current management practices to maintain a high water table across all peat land-uses, including secondary forest, to reduce subsidence and associated carbon loss in tropical peatlands. However, the results for Burnt peatlands need to be regarded with caution, as the Burnt peatlands used in this study are currently undergoing restoration and there are indications in our results that some sites where the drain blocking had been successful in maintaining a higher water table, have relatively minimal subsidence. Therefore, there is a need for longer term monitoring to understand the impact of restoration efforts on peat subsidence in heavily degraded land-uses.

CRediT authorship contribution statement

Selva Dhandapani: Conceptualization, Investigation, Methodology, Formal analysis, Data curation, Visualization, Writing – original draft, Writing – review & editing. **Stephanie Evers:** Conceptualization, Funding acquisition, Investigation, Methodology, Writing – review & editing. **Doreen Boyd:** Conceptualization, Funding acquisition, Writing – review & editing. **Chris D Evans:** Conceptualization, Funding acquisition, Formal analysis, Writing - review & editing. **Susan Page:** Conceptualization, Funding acquisition, Writing - review & editing. **Faizal Parish:** Conceptualization, Funding acquisition, Writing – review & editing. **Sofie Sjogersten:** Conceptualization, Funding acquisition, Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

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