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A Comparative study of Peat Soil Properties and Humification in Oil Palm Plantation and Forest Reserve at Pekan, Pahang

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Comparative Study of Peat Soil Properties and Humification in Oil Palm Plantation and Forest Reserve at Pekan, Pahang

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DECLARATION

I declare that the work in this thesis was carried out in accordance with the regulations of Universiti Malaysia Sarawak. Except where due acknowledgements have been made, the work is that of the author alone. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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ABSTRACT

The cultivation of oil palm plantation on tropical peatlands raises concerns on land use. To address these concerns, this study investigates the properties and humification degree of peat soil in both the oil palm plantation of Ladang Amanah Saham Pahang and Pekan Forest Reserve in Malaysia. Peat samples were collected from different depth of 0-50 and 50-100 cm at both sites. The samples were analysed for pH, electrical conductivity, moisture, elemental compositions, momentary carbon dioxide. The humification degree was assessed using CN ratio and Geographical Information System (GIS) was employed to map the spatial variation of peat characteristics. Pekan forest was found to have a high degree of humification as the CN ratio was reported as 20 ± 6 while the oil palm plantation was 35 ± 5. The forest peat was also characterised with high moisture (89 ± 1%) and pH (3.7 ± 0.1), but low electrical conductivity (179 ± 91 µS) as compared to the plantation with soil moisture (81 ± 4%), pH (3.3 ± 0.3) and electrical conductivity of 220 ± 51 µS. The results indicated that the plantation peat was more acidic and drier, along with higher salinity than the forest, likely due to the conventional usage of nitrogen fertiliser. Within the plantation, soil moisture and pH were found to increase with depth while electrical conductivity and nitrogen content decreased with depth. Such occurrence is likely due to the low humification of peat where peat structures are still intact to hold water within the pore spaces. Nitrogen is likely to leach out in water or being intensively harvested through oil palm growth. The GIS mapping indicated that the northern side of the plantation had a high CN ratio, suggesting low humification and less nutrient availability would require extra attention for nutrient supply. These findings highlight the significant influence of agricultural land use on peat properties, with notable differences between forest and plantation peat.

Keywords: GIS, humification degree, oil palm plantation, primary forest reserve

Pencirian sifat dan tahap penguriaian tanah gambut dari Ladang kelapa sawit Amanah Saham Pahang serta Hutan Simpan Primer Pekan

ABSTRAK

Penanaman kepala sawit di tanah gambut tropika telah didapati mempunyai isu pengunaan tanah yang tidak lestari. Demi mengurangkan kesan negatif, ciri-ciri tanah gambut di ladang kepala sawit dan hutan simpan dikaji bagi memantau perubahan dari penggunaan tanah pertanian. Tujuan projek ini adalah untuk mengetahui ciri-ciri tanah gambut dengan tahap penguraiannya di Ladang Amanah Saham Pahang dan Hutan Simpan Pekan di Malaysia. Sampel tanah gambut telah dikumpul dari kedua-dua kawasan kajian tersebut berserta kedalaman 0-50 dan 50-100 cm. Sampel tanah telah dianalisa untuk menperolehi data seperti perlembapan tanah, pH, kekonduksian elektrik, komposisi unsur dan pelepasan karbon dioksida sementara. Nisbah CN telah digunakan sebagai petunjuk bagi tahap penguraian tanah gambut. Pemetaan variasi spatial telah dihasilkan melalui Sistem Informasi Geografi (GIS). Hutan Simpan Pekan telah didapati mempunyai tahap penguraian tanah gambut yang tinggi dengan nisbah CN 20 ± 6 manakala ladang kelapa sawit adalah 35 ± 5. Tanah gambut hutan juga menunjukkan sifat perlembapan tanah (89 ± 1%) dan pH (3.7 ± 0.1) yang tinggi sebaliknya kekonduksian elektrik yang rendah (179 ± 91µS) berbandingan dengan ladang kelapa sawit bersama nilai perlembapan tanahnya (81 ± 4%) dan pH (3.3 ± 0.3) dengan kekonduksian elektrik yang tinggi (220 ± 51µS).Keputusan tersebut menunjukkan bahawa tanah gambut ladang lebih berasid dan kering serta kemasinan yang tinggi daripada hutan, kemungkinan tinggi disebabkan oleh penggunaan konvensional baja nitrogen. Selain itu, perlembapan tanah dan pH didapati menurun dengan kedalaman manakala kekonduksian elektrik dan kandungan nitrogen meningkat dengan kedalaman di ladang. Peta tanah bagi tahap penguraian telah menunjukkan bahawa *kawasan Utara ladang didapati mempunyai nisbah C/N yang tinggi memerlukan lebih perhatian terhadap pembekalan nutrisi. Kesimpulannya, penggunaan tanah pertanian mempengaruhi ciri-ciri tanah gambut, dengan perbezaan data yang ketara di antara tanah gambut daripada hutan dan ladang.*

Kata kunci: *GIS, hutan simpan primer, ladang kelapa sawit, tahap penguraian*

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LIST OF ABBREVIATIONS

GIS	Geographic Information System
GHG	Greenhouse Gas
EC	Electrical Conductivity
CEC	Cation Exchange Capacity
LASP	Ladang Amanah Saham Pahang
PFR	Pekan Forest Reserve

CHAPTER 1

INTRODUCTION

1.1 Study Background

Soil properties convey useful information about the soil itself. Having that information is important in making well informed decision on land use to make better use of the limited resources available. In the case of peat, having soil knowledge in proper evaluation of land use potential could ensure more successful utilisation of peatland for any purpose it was intended (Andriesse, 1988). Aligning with the Sustainable Development Goals where Independent Group of Scientists appointed by the Secretary-General (2023) advocated for sustainable food systems along with scaled up agro-ecological practices that protect soil fertility and biodiversity. From agricultural perspective, soil and water are the most important resource where they are the foundation of crop growing (National Research Council, 1991). Hence, terms such soil health and soil quality emerge as indicators depending on different viewpoint. Scientists preferred soil quality where it is related to soil function or what it does while farmers used soil health to represent the soil as a finite and dynamic living soil resource and is directly related to plant health. Though both terms are similar, they are not to be used interchangeably (Lal, 2016). The concept of soil health is closely related to sustainable agriculture, seeking to secure/balance food security without environmental degradation (Tahat et al., 2020).

Distinct peat characteristics are also indications of peat formation and how due to certain attributes enabled functions and services it provides as part of the environment (Page et al., 2006; Page and Rieley, 1998). For example, hydrology is a very important component of peat ecosystem where the waterlogged conditions created anaerobic conditions that prevents litter decay which then accumulates into peat. Due to the woody debris and high lignin content, the peat material is structured to have high porosity which then are capable of holding water aside from the topographic factor that trapped water flow (Liu and Lennartz, 2019). Such phenomena demonstrated the capability of peat swamp forest regulating water control during drought or monsoon season. Moreover, due to the accumulation of organic matter with high carbon content that did not undergo the decomposition process also resulted in peatland ecosystem becoming a huge terrestrial carbon sink where all accumulated carbon is stored within its waters (Charman, 2009). This has also helped with keeping majority of the carbon inland instead of overloading the atmosphere and becoming greenhouse gas. Also, peat swamp forest is a biodiversity hotspot as the habitat of endemic species adapted to the unique peatland ecosystem condition (Meijaard et al., 2018).

As for soil properties usage in agriculture, soil is the growing media of crops which will influence the crop production. Therefore, it is important to carry out soil survey and land suitability assessment before cease operation also to draft suitable management practices to tackle the requirement of the crop planting while maintaining the soil health (Boafo et al., 2020; Jaroenkietkajorn and Gheewala, 2021). Furthermore, with the call of sustainable agriculture, the extra effort of monitoring farmland in the long run would be beneficial in guaranteeing food security while reducing environmental degradation (Independent Group of Scientists appointed by the Secretary-General, 2023).

As previously mentioned, hydrology is peatland key characteristics along with high acidity, low nutrient and dissolved oxygen levels. Peat is also characterised as organic soils due to its high percentage of organic matter, typically more than 65% where microbial decomposition is subdued by anaerobic conditions along with recalcitrant properties in litter material from vegetation (Paramananthan, 2016; Parish et al., 2021; UNEP, 2006; Wetlands International, 2010).

Peatland was estimated to be 7.45% of Malaysia's total land area with Sarawak having the largest area of peatland in the country. However, only 20% of the area remained as forest with canopy cover. Whereas within Peninsular Malaysia, Pahang state remains as the largest undisturbed peatland area which is the South-East Pahang Peat Swamp consisting of four blocks of forest reserve (Omar et al., 2022; UNEP, 2006; Wetlands International, 2010). A lot of peat swamp forest has been converted into agricultural use, especially due to the rapid expansion of oil palm plantation in the 90s (Miettinen et al., 2012).

According to the Ministry of Economy (2023), crude palm has the highest production among the major commodities of rubber, crude oil and natural gas. Also, crude palm oil accounted 4.9% of the total gross export, which is the 3rd largest contributor among the major economic sectors of Malaysia. With the increasing market demand for oil palm, the industry is set to expand and grow more in the future (OECD/FAO, 2022). Among the oil palm production, 40% was contributed by smallholder farmers (Rahman, 2020). This showed that oil palm is capable of generating ample revenues and income to eradicate poverty, empower local communities and boost rural development (Tejuddin, 2023).

Oil palm cultivation on peatland can lead to significant environmental impacts such as peat subsidence, GHG, enhanced fire risk and loss of critical biodiversity (Dohong et al., 2017). The impacts are brought by the land use change of forested peatland into monoculture oil palm plantation. Firstly, the removal of local vegetation species is no longer within the area to function as a habitat provision where peat swamp forest exists as a biodiversity hotspot for various endemic fauna. This reduces its potential as a genetic bank and medicinal resource with the loss of undiscovered plants (Azhar et al., 2011; Dislich et al., 2017; Yule, 2010). Although there are arguments whether oil palm plantation with their forest-like structure suggested the possibility of replacing forest functions with wildlife friendly plantations, Azhar et al. (2011) and Azhar et al. (2014)showed disappointing results of lesser species adapting into the plantation landscape. It is better to leave the forest areas untouched for wildlife while acting as a buffer zone around the plantation (Edwards et al., 2010).

Next, the preparation of oil palm cultivation that involves logging, drainage, compaction and the cultivation itself eventually wean out the peat as agriculture depletes the soil resource. Peat is not resilient against these activities that alter the preset conditions, especially when water is removed from the ecosystem (Yule, 2010). When water is drained off peat, the protective layer of anoxic condition is no longer there to stop microbial activity that decomposes the organic matter. The sped-up decomposition along with the compaction would result in subsidence where peat structure and texture are destroyed (Wetlands International, 2010). This in turn alters peat properties, increasing bulk density and losing porosity which weakens water holding capacity (Tonks et al., 2017). Exposed peat also increases the risk of forest fires in degraded landscape and fragmented areas during drought season. Dry peat is highly combustible due to the woody debris being the parent material, which poses as a fire hazard in the wild (Nuruddin et al., 2006). The cultivation causes agricultural depletion of soil which would degrade and further decompose the peat material. Cultivation practices such as water table control, fertilisation and weeding are the activities that hit exactly on the right spot where these are right on the factors that influences peat decomposition (Andriesse, 1988; Cooper et al., 2019; Swails et al., 2018). The low moisture and excess nutrient promote microbial breakdown even more and facilitate GHG emissions, turning the carbon sink into the source (Dhandapani et al., 2019; Hashim et al., 2018;

Jauhiainen et al., 2012). SEPSSF is found to have rich and unique ecosystem and floristics diversity, having the potential to be gene bank as there exist useful varieties of plant species (Jusoff et al., 2007). Its forest provisions support the livelihood of the indigenous community living close to the area (Abraham et al., 2021; UNEP, 2006). Azmi et al. (2009) supported that the potential economic value of its existence is high, therefore it is better to be preserved rather than being exploited into other usage.

1.2 Problem Statement

The land use change from the conversion of peatland to oil palm plantation has resulted in peatland degradation (Dohong et al., 2017). The market demand for oil palm has caused the rapid expansion of oil palm plantation onto peatland, though it has already slowed down in recent years (Miettinen et al., 2012). Comparative studies between oil palm plantation and peatland were done for other states but not in Pahang (Sangok et al., 2017; Tonks et al., 2017). Therefore, there is a lack of comparative studies between oil palm plantation and forest reserve. The knowledge pertaining peat soil characteristics and humification degree in oil palm plantation versus forest would provide a picture on the extent of alteration on the ecosystems as a result of land use changes.

Cultivation of oil palm onto peatland alters soil properties which could affect soil quality and its capability to provide optimum conditions for oil palm to flourish (Andriesse, 1988; Corley and Tinker, 2016). To improve soil quality and ensure adequate nutrient for plant growth, there is currently insufficiency information on specific properties and characteristics of peat soils in the area cultivated for oil palm plantation, making it challenging to understand how peat properties change over time with continuous agriculture uses.

1.3 Objectives

Hence, the objectives of this study are:

1. i. to characterise the peat soil properties such as soil moisture. pH, Electrical conductivity, elemental composition, humification degree, momentary carbon dioxide emission and soil temperature in oil palm plantation of Ladang Amanah Saham Pahang and Pekan Forest Reserve;
2. ii. to map the spatial variability of these peat soil characteristics of Ladang Amanah Saham and Pekan Forest Reserve using GIS.

1.4 Chapter Summary

This thesis is organised in five chapters. The introduction provides readers the background, problem statement, and objectives of the study. The second chapter is the literature review; this chapter discusses the past studies on relationship between the oil palm industry, peat issues and their complex interconnection towards the environment. The third chapter, Materials and Methods, discusses the samples, experimental design and methods of analyses. Chapter 4 discusses the data and the result with the final chapter provides conclusions on the major findings, limitations and suggestions for future reference.

CHAPTER 2

LITERATURE REVIEW

2.1 Peat

Peatland definition is important in quantifying peat, and it is not an easy task due to its variety found around globally. Peatland is a general term for land with a naturally accumulated layer of peat near the surface that include both ecosystems that are actively accumulating peat and degraded peatlands that no longer accumulate but in contrast lose peat. Peat itself consists of partially decomposed vegetation at various degree in decomposition (Andriesse, 1988; United Nations Development Programme (Malaysia), 2006). From the definitions, the condition of partially decomposed is strongly emphasised in peat, which also explained its characteristics and attributes of the material. Though the general argument around peat involves the variation in thickness of peat and the minimum percentage of organic carbon (Lourenco et al., 2023). In Malaysia, peat is defined as having more than 65% organic matter and a minimum depth of 50cm (Hajon et al., 2018; Paramananthan, 2016; Wetlands International, 2010).

2.1.1 Peat Properties

Undisturbed peat is often characterized by high organic content, high acidity and low nutrient content (Osaki et al., 2021; Page et al., 2006; Wetlands International, 2010). These are just distinct attributes that stands out greatly among other properties which are less focused on, but it offers more insight into the nature of peat and possibilities of reclamation. More often, peat properties could be studied from physical and chemical component as to diversity its possibilities from different purposes. For agricultural usage, physical properties such as the structure, texture, bulk density, porosity, water retention capacity and permeability are studied for hydrological management since water is an important component for both the peat and crop growing.

Peat with its high organic matter derived from woody debris provided the structure and texture of the material in which exhibits low bulk density and high porosity (Liu and Lennartz, 2019). These are characteristics that affects hydraulic properties in peat. High porosity has a lot of pore spaces to retain moisture within while connected pores allow permeation within itself (Rezanezhad et al., 2016). Therefore, soil moisture is highly depending on degree of decomposition. It is capable to serve as a warning in peat condition if abnormality persisted during monitoring.

Chemical properties of peat to be evaluated are pH, electrical conductivity, Cation exchange capacity (CEC), redox potential and nutrient content. These are criteria could further determine if the peat is a suitable growing media with sufficient nutrient reservoir for cultivation. pH and electrical conductivity are closely related parameters that can be easily obtained as soil quality indicators. pH could determine solubility, nutrient availability and also affecting microbial activities (Carmo et al., 2016; Smith and Doran, 2015). As for electrical conductivity, though it is commonly associated with soil salinity, it also capable to measure soluble nutrient in forms of cations and anions. However, it is also affected by soil texture, density, temperature, moisture and CEC which made it an ideal indicator for early change detection in spatial mapping (Corwin et al., 2003; Heiniger et al., 2003). As for CEC, it is due to the decomposition of organic matter into humic substance that exhibits exchange properties which could bind cations and thus are able to hold nutrients and reduce leaching (Andriesse, 1988; Melling, 2016; Mohamed and Sim, 2007). Whereas redox potential is used to assess decomposition in peat through the detection of oxygen content in peat (Oishi, 2020; Zubov et al., 2022).

2.1.2 Humification of Peatland

Peat is made of organic matter that did not breakdown completely where it tends to accumulate as organic compounds such as proteins, polyuronides, lignin-like substances and humic acids (Blodau, 2002; Kaila, 1956). If carbon did not successfully retain as organic matter and accumulate as peat, further decomposition would result in the production of carbon dioxide. However, within the peat, there are various pathway which are capable of transforming carbon into other compounds depending on the factors. Under anoxic conditions, methane is more likely to form while if it small enough to dissolve in water, it becomes Dissolved Organic Carbon (Horwath, 2007).

Peat humification is dependent on factors such as temperature, moisture, aeration, plant decomposition invertebrate community and microbial activity, since it is mostly carbon, it shares similar factors that influence its transformation and compound state. (Blodau, 2002; Bu et al., 2011)

Humification could be represented by bulk density and the CN ratio of the soil. Frolking et al. (2010) supported that bulk density is often used as proxy for degree of decomposition and mainly affects the water balance through its influence on both the growth rate of peat column and on peat hydraulic conditions and the capacity to shed water. CN ratio though is typically used to describe the degree of humification but, it is more suitable for as the indicator of the elemental mobilisation and immobilisation during the decomposition as it is observed that nitrogen release in soil is relative to CN ratio (Jakusné Sári & Forró, 2008; Kaila, 1956).

Peat humification is found to be related to soil fertility where higher degree of humification affects oil palm yield greatly (Veloo et al., 2015). On the other hand, where peat humification decreases with increasing depth, sago planted in deep peat showed stunted growth as compared to shallow peat (Sim et al., 2017; Umaru and Samling, 2018).

2.1.3 Roles and Functions of Peat

Peat swamp forest, due to their carbon density and considerable thickness, hold more carbon per hectare on average than all other ecosystems, making them the largest carbon stock of the entire terrestrial biosphere (Temmink et al., 2022). Tropical peatland may account for only 10-12% of the global peatland resource by area but they contain between 50 and 70 Gt (16-21%) of the peat soil carbon store and 2-3% of the total soil carbon pool (Gorham, 1991; Immirzi et al., 1993; Page et al., 2002). These characteristics has effectively made peat swamp forests as significant carbon stores and sink of terrestrial nature. If the carbon in peat is rapidly released into the atmosphere, it would contribute to the greenhouse effect and climate change (Wetlands International, 2010).

Peat swamp forest with their unique conditions has nurtured species that are adapted specifically to the habitat. Despite having unfavourable conditions, peat swamp forest is one of ecosystems with considerable biodiversity. Although a large number of animals and plants has been identified, most areas of the peat swamp forest have not been investigated (Rieley et al., 2016). Moreover, it is also a refuge for certain endangered species as some of them are endemic to peat swamp forest (Yule, 2010; UNEP, 2022).

Hydrology of peatland is greatly emphasized as it plays a key role in the development and maintenance of all peatland systems (Page and Rieley, 1998). If disrupted, it could bring disastrous chain reaction that affects carbon cycle, upsetting the delicate balance of ecosystem. United Nations Development Programme (2006) explained that peat functions in regulating water resources, which includes flood mitigation, water storage and maintenance of base flow in rivers. These are crucial to maintain the integrity of downstream ecosystems and to prevent economic losses of low lying areas.

Aside from the ecological functions and services, peat swamp forest is important from the socio-economic point of view. Page et al. (2006) asserted that peat swamp forest has contributed to the way of life and economy of indigenous people through provisions of resources for food, shelter, medicine and cultural wellbeing. There are also potential for tourism and recreational purposes. Peat swamp forest is the main resource for forestry and agriculture, even though controversial, it is currently an ongoing occurrence of exploitation activity in Malaysia (Wetlands International, 2010). If properly managed and maintained, this sector would be beneficial in supporting livelihoods of local communities, contributing to the economy of the nation.

2.1.4 Peat Accumulation

Peat formation process is a series of existing favourable conditions and complex mechanisms that contributes to the accumulation of peat. Omar et al. (2022) refers the existence of tropical peatlands as a paradox and its formation involves a complex combination of factors.

Charman (2009) pointed out that peat accumulation is the result of an imbalance between plant productivity and decay. Peat can accumulate even the plant productivity is relatively low as the decaying rate is reduced in waterlogged, low oxygen, and nutrient-poor conditions. As moisture and temperature play important roles in regulating peat decay, the impending climate change renders peat vulnerable to climate variability. Climate warming would enhance peat respiration more than net primary production, turning carbon sinks into carbon sources (Leng et al., 2019).

2.1.5 Peat Degradation Drivers

Peatland has always been exploited by mankind, but certain usage has caused irreversible damages to the ecology and functioning of the peat accumulating system. Peatland are often in use for agriculture and forestry along with peat extraction for fuel and other commercial applications (Charman, 2009).

Dohong et al. (2017) and Parish et al. (2021) reviewed those activities of logging conversion to industrial agriculture plantation, drainage and repeated fires are the major drivers of peatland deforestation and degradation in the Southeast Asian region. Conversion of peat swamp forest into degraded and fragmented landscapes, resulting in deterioration of peatland ecosystem, loss of biodiversity loss and significant increase in carbon emission.

Reclamation of peat often involve drainage of water table and drying up the surface. However, water is a vital component for the ecology and carbon cycling of a peatland ecosystem (Charman, 2009). As the peat dries out, the environment is no longer anoxic; the organic matter is subjected to break down by bacteria in which causes excess emission of carbon dioxide and subsequently peat subsidence. Moreover, dried up peat is very susceptible to fire and would further release smog and haze that pollute the atmosphere if a fire outbreak were to occur. Also, when peat is no longer retaining water, the excess rainwater from heavy downpour could potentially flood the residences and infrastructures as it exceeded the drainage capacity of lowland cities (Wetlands International, 2010).

2.1.6 Mitigation Strategies

The most severe impact that garner attention from the public and pressuring the authorities on taking immediate action was nonetheless the notorious transboundary haze affecting Southeast Asian region. The haze affected various countries and for weeks the many has suffered as the haze has brought upon air pollution that affects respiratory health and low visibility in the sky (Mai, 2023). The issue was brought onto the ASEAN meeting and the member states agreed to address the issues of peatland management to reduce transboundary haze pollution and climate change impact. The ASEAN Peatland Management Strategy 2006-2020 was endorsed by the ASEAN Ministers Meeting on Environment (ASEAN, 2023).

In Malaysia, policies such as National Action Plan for Peatlands covers prevention of peat fires and loss of biodiversity whereas the National Commodities Policy was formulated to guide the Malaysian palm oil industry (Padfield et al., 2016; Shehu et al., 2020). Integrated management plan were created for states with peat for conservation and sustainable use of the peat swamp forests (Efransjah et al., 2006; Global Environment Centre, 2019). Under the support of local authorities and NGOs, rehabilitation and restoration efforts were carried out on peat swamp forests with promising results of success, though it is costly and proper planning is required for a successful outcome (Ismail et al., 2007, 2012).

On the other hand, the Malaysian palm oil industry is also striving for sustainability, seeking alternatives and innovation to balance on improving oil palm yield and minimising environmental impacts (Kadir and Parveez, 2022). In commercial agricultural practices, business can either opt for intensification of production or expansion outwards. Due to law restrictions, Malaysian stakeholders have chosen on the path of intensification while their Indonesian counterparts opted expansion as they have the land resource to do so (Varkkey et al., 2018).

Non-governmental Organisations such as Roundtable on Sustainable Palm Oil (RSPO) has developed a set of environmental and social criteria which companies must comply for Certified Sustainable Palm Oil (CSPO) to satisfy international markets. They are supportive in peatland conservation and rehabilitation while ensuring existing plantation on peatlands are managed responsibly (Parish et al., 2021). The most recent declaration is the "No Deforestation, No Peat and No Exploitation (NDPE)" commitments by major corporates to remove peatland destruction and worker exploitation from supply chain (Lyons-White and Knight, 2018).

In addition, integrated management practices in plantation play a crucial role in determining the sustainability of the oil palm industry (Foong et al., 2019). Land and water management are top priority in sustaining oil palm yield (Rhebergen et al., 2019). There are a few theories of agricultural management practices in oil palm plantation that has strong emphasis towards making sustainable decisions. Fairhurst et al. (2003) explained on Precision Agriculture where various integrated management technologies were used to increase nutrient use efficiency, productivity and for environmental monitoring. They supported on soil maps that could be used as overlays to relate productivity and nutrient status to soil characteristics. Following this idea, the theory of spatial variation came into picture where samplings at multiple geographical locations are intended to give a pattern or picture on the changes of variables over the surface terrain or field. Alam et al. (2015) and Subramaniam and Hashim (2018) recommended the implementation of Good Agricultural Practices to obtain the best outcome both in yields and reduced economics and environmental burdens. It also focused on key elements of integrated land, water and fertiliser management. In RSPO, the Best Management Practices (BMP) set critical priorities on water management, nutrient, pest and disease management as well as fire prevention. These priorities are important for enhancing management of existing oil palm cultivation on tropical peat while reducing environmental impacts especially GHG emissions and subsidence (Parish et al., 2021).

2.1.7 Monitoring and Assessment of Peat

Cultivation involves alteration of peat properties so that the soil is more suitable for plantation. This, however, has resulted in peat degradation. For this reason, it is important to constantly monitor and assess the soil condition to ensure the quality and fertility of soil. Additionally, evaluating soil quality is beneficial for the enhancement of agricultural soil management and use. The adoption of strategies that allow continuous and intensive cultivation of lands without depleting soil quality would be helpful in supporting long-term food security and environment quality, as part of the sustainable movement (Boafo et al., 2020). In reference to peat characteristics and oil palm optimum growth conditions, certain soil parameters and indicators could be collected for inferencing useful information.

2.2 Pekan Forest Reserve

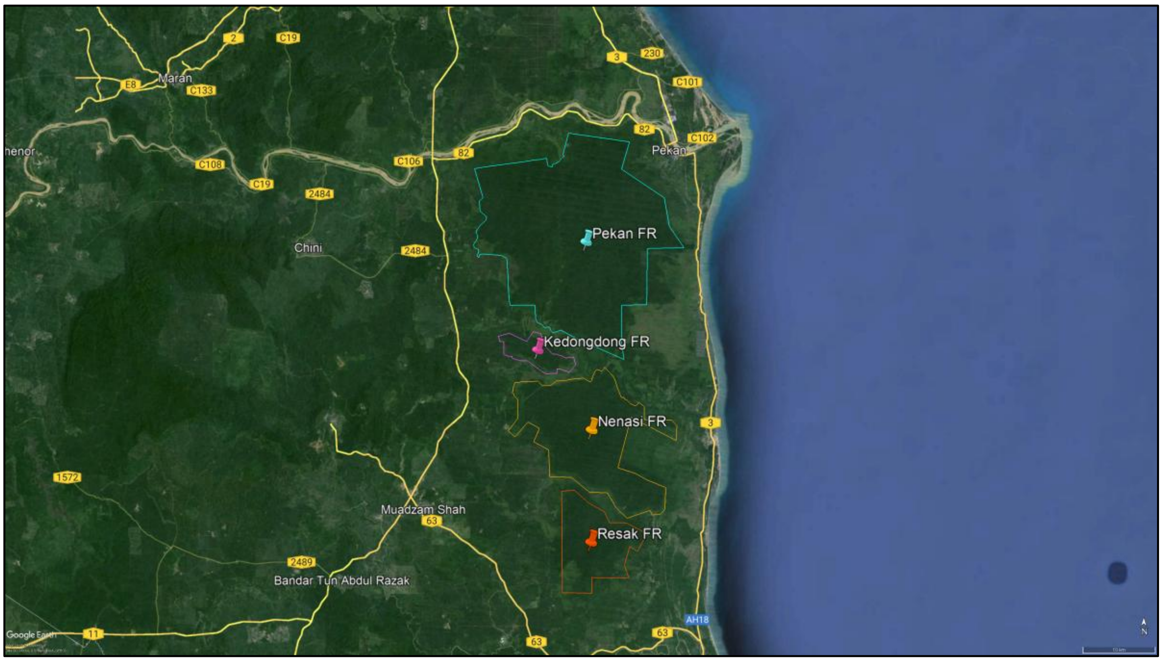


Figure 2.1: The map of Southeast Pahang Peat Swamp Forest (SEPPSF)

The remaining undisturbed peat swamp forest area in Peninsular Malaysia is found in the Southeast of Pahang, covering the Forest Reserves of Pekan, Kedondong, Nenasi and Resak (Efransjah et al., 2006). Jusoff et al. (2007) assessed the Southeast Pahang Peat Swamp Forest (SEPPSF) and found out rich diversity in both the ecosystem and floristics diversity. This showed that the SEPPSF is a biodiversity hotspot with preservation value that is hard to be monetise in economic values. Moreover, there are indigenous community of Orang Asli still relying on the provisions of peat swamp forest though they were relocated to a government settlement (Abraham et al., 2021; UNEP, 2006).

Efransjah et al. (2006) had suggested the integrated management plan for conservation and sustainable use of the peat swamp forest at the Southeast Pahang. This plan addresses challenges such as balancing different stakeholder interests, including land use for agriculture versus conservation, and proposes land zonation to mitigate conflicts. The unique approach of consultative planning which consider various stakeholders' opinions and multidisciplinary knowledge on the forest features. The management team included government agencies, NGOs and the private sector along with local communities so that all needs could be included in drafting the management plan that satisfies everyone's expectations. The principal strategy from the outcome is dividing the area based on zonation approach, depending on the different physical environment profiles and varied land-use interests. Such arrangements have resolved a win-win situation for both conservation of peat swamp forest while land maintaining landscape integrity.

Abdul-Rahim et al. (2006) tried to balance timber production through sustainable harvest practice while solving flooding issues from the forest that affects the logging operations. Incorporating the knowledge of hydrological properties within the forest, alternative remedies such as surface water diversion and creation of water congestion zone were able to reduce flooding on the road system. This showed the possibility of working the solution around the environment properties instead of altering it through anthropogenic interventions. Moreover, understanding the ecosystem would be helpful in cases of future restoration on degraded areas.

2.2.1 Review of Research on Pekan Forest Reserve

Table 2.1: A summary of Research on Pekan Forest Reserve and its key findings

Studies conducted in Pekan	Key findings
Firdaus and Philip (2009)	Quantification of nutrient conducted on surface waters from drained peat swamp forest showed that Calcium and Magnesium were leaching while Nitrogen and Potassium persisted. The result suggested possible phenomena of nutrient loss and leaching would occur in the water draining from peat swamp forest.
Azahari et al. (2013)	A multi-spectral image segmentation method combining spectral and shape features was proposed for landcover classification identified 94470.02 ha of peat swamp forest. The distribution could be used for restoration and management activity.
Othman et al. (2019)	The use of satellite image and land use model successfully assessed the forest degradation status and forest land exploitation in Rompin and Pekan.

	Geospatial techniques approaches are useful in forest monitoring to detect land use changes.
Roslan et al. (2015)	Bacteria originating from peat swamp forest flourished better with peat water and showed lignin degradation abilities. Endemic bacteria species may not do well with changes in peat swamp forest.
Hj. Parlan (2017)	Above and belowground carbon stock in the vegetation peat swamp forest area was quantified and estimated to be 70.6 tC/ha whereas soil carbon was estimated to be 247.2 tC/ha. It was lesser than the virgin PSF in Compartment 100 of Pekan Forest Reserve. Low carbon stock indicated degraded peatland.
Afzanizam et al. (2016)	Tree biomass at Compartment 75 of Pekan Forest Reserve was quantified and estimated to be 415.18 t/ha, value similar to Compartment 100. Peat swamp forest has the potential as a carbon sink compared to other forest types.

Afzanizam et al. (2018)	Litterfall and deadwood at Compartment 75 in Pekan Forest Reserve was evaluated, carbon stock was estimated at 11.79t/ha while total dry biomass was 0.023 t/ha. This suggested deadwood could be a significant contributor to the total aboveground biomass.
Wahab et al. (2022)	The physical properties of undisturbed tropical peat in Pekan were examined and found unsuitable for construction due to its weak properties for construction stability.

2.3 Oil Palm

Oil palm originates from Africa, and it is widely used as food since the early days of mankind. As time progressed with human development, there are historical evidence of oil palm in trade and goods (Corley and Tinker, 2016). At the modern age and time, palm oil could be found in everyday life situation. The low production cost along with its high availability and easy affordability in the market has resulted in increasing demands from developing countries (Meijaard et al., 2018; Precedence Research, 2023). Moreover, palm oil has a much higher yield than the alternatives. It demonstrates the highest yield of vegetable oil crop by producing about 2.9 tonnes of palm oil from each hectare of land. Along with its high versatility and various applications, oil palm has risen to the top with its various benefits and advantages as a vegetable oil.

Oil palm as a pioneer species is capable to survive on the edges of the forest is highly adaptive to the humid tropical climate. It could withstand high precipitation, high solar radiation and warm temperatures of 24-32 ˚C. Oil palm is not demanding in its requirements to thrive; however, it does not tolerate salinity or stagnant water above the soil surface. Hence, during peat reclamation, the drainage and land compaction are necessary to sustain oil palm growth. Not only would the drainage and land compaction contribute to peat degradation, the cultivation practices such as fertilizer application and control of the water table could further increase the oxidation process, promoting microbial activity which in turn speeding up the peat decay (Andriesse, 1988). Neutralisation of the soil acidity and enrichment of ash content also promote the decomposition of the soil organic matter (Murayama and Bakar, 1996a).

CHAPTER 3

METHODOLOGY

3.1 Study Area

The study areas, located in Pekan district of Pahang in Peninsular Malaysia, include the oil palm plantation of Ladang Amanah Saham Pahang at E 03˚ 26’15.23” N 103˚ 23’20.43” and the primary peat swamp forest of Pekan Forest Reserve at E 03˚ 25’38.64” N 103˚ 21’59.28”. Figure 3.1 shows the locations of LASP plantation and Pekan Forest Reserve.

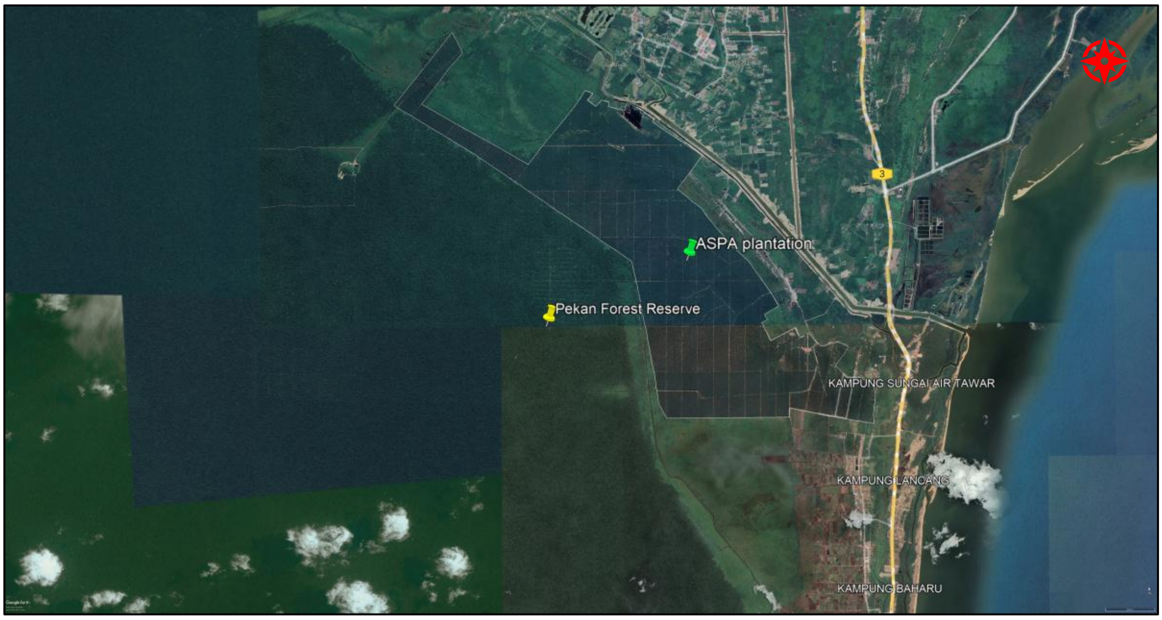


Figure 3.1: The location of the study area of LASP oil palm plantation and Pekan Forest Reserve

3.1.1 Ladang Amanah Saham Pahang (LASP)

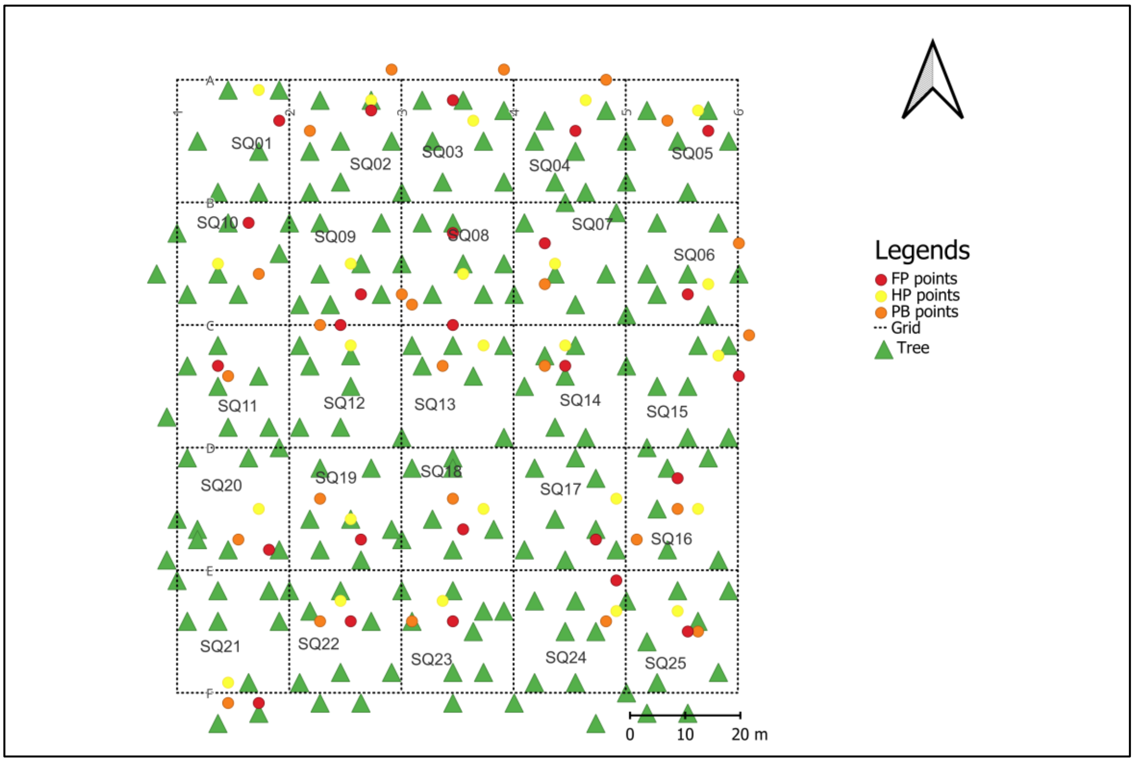


Figure 3.2: The study area and subplots in LASP plantation

The site of oil palm plantation was an established 1-hectare plot divided into 25 subplots of 20 m × 20 m each with 189 oil palm trees scattered across the study area (Figure 3.2).The peat depth in this area was found between < 150 cm (shallow peat) to 300 cm (150 - 300 cm, moderate peat) (Paramananthan and Omar, 2008). Due to the peat nature, most palm trees in this area were found slanted and crooked as they struggle to support itself growing upwards (Figure 3.3).

Figure 3.3: A photo of the LASP plantation

3.1.2 Pekan Forest Reserve (PRF)

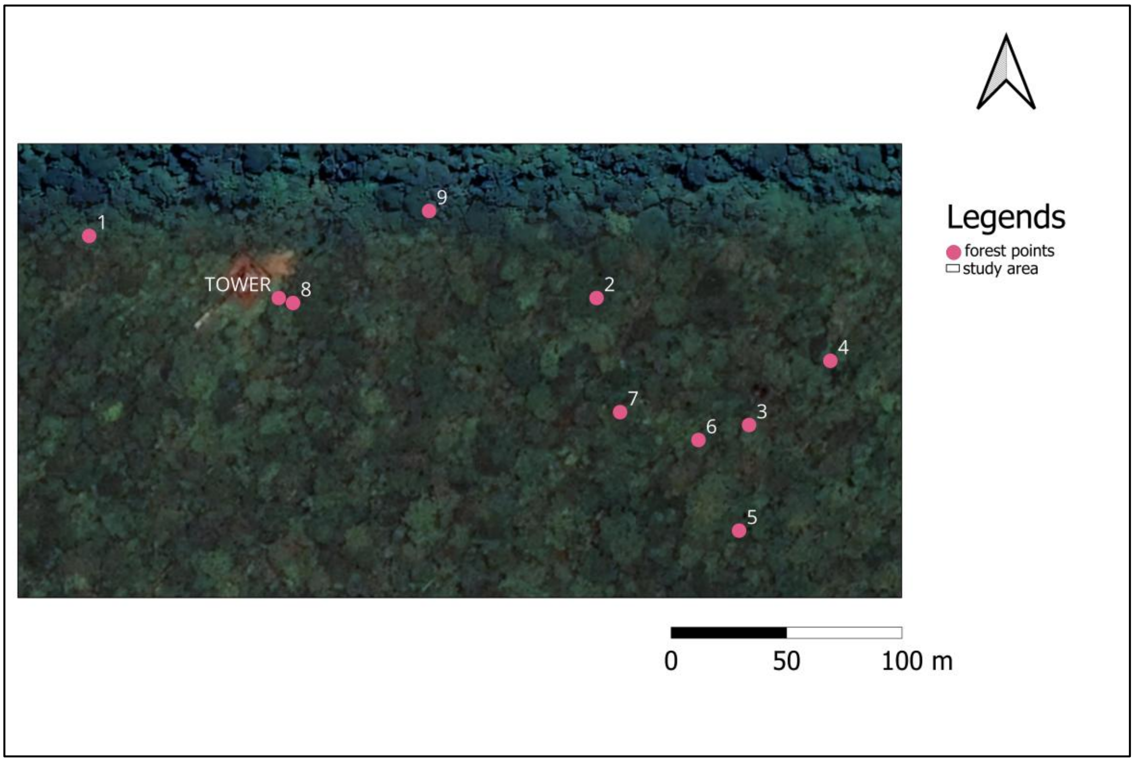


Figure 3.4: The study area and sampling locations in Pekan Forest Reserve

Pekan Forest Reserve did not have an established study site or plot. The area was an undisturbed primary forest of flourishing wildlife and posed certain hazards to untrained personnel entering the area. The Pekan Forest Reserve was also categorized under the Environmental Sensitive Area where it was strictly close off from any activities (Efransjah et al., 2006). The conditions in the forest could be illustrated as mostly submerged peat with thick foliage and forest floor litter.

3.2 Peat Soil Properties of LASP and PFR

3.2.1 *In-situ* Measurements

The GPS of each sampling point was recorded using the GPSMAP64s device. Surface soil moisture, soil temperature and air temperature were collected using the soil probe of ML3 ThetaProbe Soil Moisture Sensor with a HH2 moisture meter readout and the digital thermometer of Hanna Instruments. Carbon dioxide flux, or soil respiration of momentarily emission was collected using the Environmental Gas Monitor (EGM-4). The pipes, also known as collars were installed on ground at intended sites and soil respiration chamber was air-flushed to the collars on ground to collect emission data. The measurement was conducted according to method described by Marthews et al., (2012).

3.2.2 Soil Sample Collection

A random design was employed for soil sampling based on the three management zones within each subplot: Frond Pile (area where fallen fronds accumulate), Harvest Path (space between palm trees), and Palm based (area at the base of palm tree) (Anuar et al., 2008; Law et al., 2009). The peat soil samples were collected from 0 - 50 cm and 50 - 100 cm depth. The Eijkelkamp peat auger with core diameter of 52 cm and 50 cm in length, equipped with extension rod, was used for soil sampling. The soil samples were collected and sealed in plastic zip lock bag so that their fresh wet weight could be recorded before drying.

Random design was employed at along the walking trails of PFR. A total of nine soil samples at 0 – 50 cm depth were collected using the Eijkelkamp peat auger. Similar operation procedures were done towards the collected samples in PFR.

After the completion of sample collection, the samples were shipped to laboratory for preparation and analysis.

3.2.3 Sample Preparation for Soil Analysis

Soil samples were oven dried at 50 ˚C for 5 days to strip out the moisture entirely (Dettmann et al., 2021; Murayama and Bakar, 1996). The dry mass of the samples was recorded. Then, the soil samples were grinded using mortar and pestle into fine powder and sieving of 2 mm size.

3.2.4 pH and Electrical Conductivity Measurement

Soil pH and electrical conductivity were measured using the pH and conductivity meter (ExTech ExStik Ⅱ). Finely grinded soil samples were prepared in a 1:10 soil-to-water suspension (Gandois et al., 2013; Sim et al., 2019). The soil water mixture was shaken and stirred until it was homogenised and allowed to stand overnight before measurement. All measurements were performed in triplicates.

3.3 Humification Degree in LASP and PFR

3.3.1 CHNS Elemental Analysis

Elemental composition of CHNS were obtained using FLASH EA 1112 series elemental analyser. Finely grinded soil samples (2.5 - 3.0 mg) were precisely weighted and fed into the instrument. The samples underwent combustion in oxygen and the products were carried by helium gas to respective furnaces that oxidise into gaseous state. Later, the gases were distinguished by the thermal conductivity detector and a chromatogram was produced to calculate the elemental contents. The samples were run in triplicates.

3.4 Statistical Analysis

The collected data were analysed using R software. Due to the imbalance of samples between LASP and PFR, non-parametric test of Man Whitney U test was used to determine significant differences in soil moisture, pH, electrical conductivity, elemental composition of C, N, H and O and elemental ratios of CN, HC and OC.

Two-sample t-test was used to determine significant differences in between plantation depth of LASP for soil moisture, pH and electrical conductivity, elemental composition of C, N, H and O along with elemental ratios of CN, HC and OC. One way ANOVA was used to determine significant differences among collar zones at different depth of 0-50cm and 50-100cm respectively in soil moisture, pH, electrical conductivity, carbon dioxide, temperature, elemental compositions of C, N, H, O along with elemental ratios of CN, HC and OC followed by Tukey's Honestly Significant Difference (HSD) test to significant differences among sample means.

3.5 Peat Soil Characteristics Mapping

The soil data obtained from analysis and measurement along with the geo-reference data were fed into the Quantum Geographic Information System (QGIS) software. The soil data were interpolated using Inverse Distance Weighted spatial interpolation for full coverage of study area and the prediction of in-field situation.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Peat Soil Properties LASP and PFR

Table 4.1: The summary of peat soil properties

Properties	n	Soil Moisture Content (%)	pH	Electrical Conductivity (µS)	CO_2 (g CO_2 m^{-2} hr^{-1})	Temperature (°C)
PFR	9	88.6±1.1	3.72±0.12	178±91	-	-
LASP						
0-50cm						
Collar Zone						
Frond Pile	25	82.2±2.8	3.25±0.28	213±46	0.566±0.315	27.3±0.7
Harvest Path	25	81.5±3.2	3.25±0.24	214±47	0.591±0.200	37.9±0.6
Palm Based	25	78.5±5.7	3.27±0.28	232±58	1.051±0.929	38.4±0.5
Total(n)/ Average	75	80.7±4.4	3.26±0.26	220±51	0.597±0.303	27.9±0.7
50-100cm						
Collar Zone						
Frond Pile	25	85.8±2.8	3.33±0.29	181±45	-	-
Harvest Path	25	86.7±2.1	3.39±0.28	162±41	-	-
Palm Based	25	84.2±3.2	3.37±0.33	190±44	-	-
Total(n)/ Average	75	85.6±2.9	3.36±0.30	178±44	-	-

Table 4.2: Summary of statistical analysis

Mann Whitney U test for PFR and LASP			
Properties	Soil Moisture Content	pH	EC
W value	661	644.5	128
P value	$2.99 \times 10^{-6*}$	$9.30 \times 10^{-6*}$	0.0025*
Two-sample t-test for depth comparison			
Properties	Soil Moisture Content	pH	EC
t value	8.0406	2.2846	-5.4601
P value	$2.63 \times 10^{-13*}$	0.024*	$2.30 \times 10^{-7*}$

Table 4.1 showed the summary of soil properties while Table 4.2 showed the summary of statistical analysis. Asterisk values within Table 4.2 indicate $p<0.05$

One way ANOVA was performed to compare the effect of collar zones for both depths on the soil properties. It is revealed that there was a statistically significant difference in soil moisture of 0-50cm depth between at least two groups, F (2, 72) =5.56, p=0.006. Tukey's HSD test for multiple comparisons found that the mean value of soil moisture was significantly different between PB and FP (p=0.006, 95% C.I = -6.46, -0.87) with PB and HP (p=0.035, 95% C.I =-5.76, -0.17).

There is also another statistically significant difference found in temperature between at least two groups, F (2, 72) =22.14, p $=3.21 \times 10^{-8}$.Tukey's HSD test for multiple comparisons found that the mean value of temperature was significantly different between PB and FP (p=0.00006, 95% C.I = -0.436, -0.136) with PB and HP (p=0.0001, 95% C.I =-0.424, -0.124).

As for the collar zones of depth 50-100cm, only soil moisture showed significant difference between at least two groups, F (2, 72) = 5.46, p=0.006. Tukey's HSD test for multiple comparisons found that the mean value of soil moisture was significantly different between PB and HP (p=0.005, 95% C.I = -4.36, -0.66)

Aside from the natural occurring waterlogged conditions in the forest, the early drainage and management practices of controlling water table at the plantation, along with the compaction would further breakdown the peat structure and reduces the porosity within (Liu et al., 2020; Oleszczuk and Truba, 2013). Lesser water pore spaces reduce the water retention of peat and thus reducing the water supply capacity within peat (Zhao et al., 2017), Less moisture also means more oxygen space in which further promotes microbial breakdown of peat matter. This may be bad news for peat as the organic matter are decomposing rapidly and losing structure, but the breakdown of carbon along with excess nitrogen input could improve soil fertility (Veloo et al., 2015), though there is also a possibility of carbon decomposing into its final form as carbon dioxide, contributing to GHG emission in the atmosphere instead (Ishikura et al., 2018; Jauhiainen et al., 2012; Tonks et al., 2017).

Soil moisture at PB showed significant differences in both depths. PB is the area of oil palm trees growing, with evapotranspiration taking place actively due to living roots may have led to low soil moisture along with the lack of vegetation cover around the base of palm trees exposed it to direct solar radiation (Ribeiro et al., 2021). Here, soil temperature happened to be the highest among the collar zones as the soil surface is exposed and being heated up by solar radiation (Gusmayanti et al., 2019).

Malaysian climate is stable with the constant shine and rain though climate change may bring in longer draught and wetter monsoon seasons which would produce extreme fluctuations of the soil moisture. In cases of prolonged dry season, water shortage may impair oil palm growth and reduces nutrient intake which then would affect crop yield if left unattended (Afandi et al., 2022; Farrasati et al., 2022).

The soil samples from LASP demonstrated lower pH with high electrical conductivity as compared to those from PFR. The high acidity and electrical conductivity are likely due to fertiliser application, high probability of the fertiliser being nitrogen based as oil palm requires nutrients such as Nitrogen and Potassium, which is lacking naturally in peatland due to its characteristic of low mineral availability (Corley and Tinker, 2016; Kee et al., 1995). Moreover, the decomposition of organic matter where peat have been decomposing since the drainage of water along with nutrient leaching from fertiliser would also have acidified the soil (Mahmud and Chong, 2022). Possible weak acid groups such carboxylic and phenolic acids from breakdown of peat organic matter would also have contributed to the acidity (Kumar et al., 2020). Moreover, fertilisers are direct input of cation and anion in which increases salinity, coupling with low moisture at the plantation, would have increased the electrical conductivity (Farrasati et al., 2022). Although electrical conductivity is easily affected by soil texture, moisture and salinity, frequent collection of electrical conductivity is able to easily detect changes within the peat, whether if it is for measuring soil density or checking for abnormality in soil nutrient and moisture, it would be useful as early and simple tool for soil monitoring within the plantation (Carmo et al., 2016; Heiniger et al., 2003; Lund et al., 2015).

4.2 Humification Degree in LASP and PFR

Table 4.3: Summary of elemental composition and ratio

Properties	n	Elemental Composition				Elemental Ratio		
		C	N	H	O	CN	HC	OC
PFR	9	49.1± 0.9	3.0± 0.8	5.3± 0.2	42.7± 1.2	20.1± 5.6	1.27± 0.05	0.65± 0.03
LASP								
0-50cm								
Collar Zone								
Frond Pile	25	49.9± 1.3	1.82± 0.2	5.2± 0.4	43.1± 1.3	32.4± 4.4	1.25± 0.10	0.65± 0.03
Harvest Path	25	49.3± 1.6	1.81± 0.2	5.1± 0.6	43.8± 1.7	38.9± 4.7	1.19± 0.17	0.64± 0.07
Palm Based	25	49.3± 1.4	1.79± 0.2	5.2± 0.3	46.7± 1.6	32.6± 3.9	1.26± 0.10	0.67± 0.04
Total (n)/ Average	75	49.5± 1.4	1.8± 0.2	5.2± 0.4	43.5± 1.5	34.6± 5.3	1.24± 0.12	0.65± 0.05
50-100cm								
Collar Zone								
Frond Pile	25	49.2± 3.4	1.55± 0.2	5.1± 0.6	44.2± 3.8	37.5± 4.9	1.22± 0.13	0.68± 0.13
Harvest Path	25	50.4± 1.8	1.53± 0.2	5.1± 0.8	43.0± 2.4	32.3± 4.6	1.22± 0.14	0.67± 0.05
Palm Based	25	49.7± 2.4	1.54± 0.2	5.2± 0.4	43.6± 2.7	38.2± 5.1	1.25± 0.10	0.66± 0.08
Total(n)/ Average	75	49.8± 2.6	1.5± 0.2	5.1± 0.6	43.6± 3.0	36.0± 5.5	1.23± 0.11	0.67± 0.09

Table 4.4: Summary of statistical analysis

Mann Whitney U test for PFR and LASP							
Properties	Elemental Composition				Elemental Ratio		
	C	N	H	O	CN	HC	OC
W value	229	655	353	257	23	391	344
P value	0.118	$4.55\times10^{-6*}$	0.828	0.247	$5.60\times10^{-6*}$	0.44	0.93
Two-sample t-test for depth comparison							
Properties	C	N	H	O	CN	HC	OC
t value	0.4027	-4.918	-0.6789	0.2230	4.676	-0.9512	0.1853
P value	0.6878	$2.30\times10^{-6*}$	0.4983	0.8238	$6.54\times10^{-6*}$	0.3431	0.8533

Table 4.3 showed the summary of elemental composition and ratio while Table 4.4 showed the summary of statistical analysis. Asterisk values within Table 4.4 indicate $p<0.05$.

One way ANOVA was performed to compare the effect of collar zones for both depth on the elemental compositions and ratios. It is revealed that there was a statistically significant difference in nitrogen of 0-50cm depth between at least two groups, F (2. 72) = 13.34, p= 1.18×10^{-5}. Tukey's HSD test for multiple comparisons found that the mean value of nitrogen was significantly different between PB and FP (p=0.00006, 95% C.I = -0.436, -0.136) with PB and HP (p=0.0001, 95% C.I =-0.424, -0.124).

There was another statistically significant difference in CN of 0-50 depth at least two groups, F (2,72) = 13.16, p=1.34×10^{-5}. Tukey's HSD test for CN showed significant differences between PB and FP (p=0.0001, 95% C.I =2.65, 8.99) with PB and HP (p=0.00008, 95% C.I =2.79,9.14).

As for the collar zones of depth 50-100cm, no significant difference is found among the collected data.

In Table 4.4, the CN ratio varied significantly between samples collected from LASP and PRF areas, indicating differences in humification and nutrient mobilization. This align with sim 2019 where low CN ratio was found at LASP. Despite the practice of continually excess nitrogen being supplied onto the plantation, Nitrogen is found to be low at LASP when compared to PRF (Ariffin et al., 2020). Nitrogen fertilisation in plantation caused the inorganic N being easily loss through leaching and gas emission, while Swails et al. (2018) suggested nutrient export through crop harvest. While within the plantation, PB showed significant differences among the collar zones. The conditions of high acidity and low moisture content has created the ideal condition for nitrification to occur further enhance nutrient absorption at the root base (Ariffin et al., 2019; Mahmud and Chong, 2022). As for the PRF having humification and greater N mobile reserve, maybe due to the nature of nitrogen being highly associated with microbial processes within the peat of PRF. Espenberg et al. (2018) and Yin et al. (2022) has observed possible nitrogen input pathways to peat ecosystem through microbial community that does biological nitrogen fixation and nitrogen mineralisation. Excess nitrogen is beneficial to promote growth and yield for the oil palm, however it also encourage greenhouse gas emissions of nitrous oxide and methane (Lau et al., 2023).

Carbon don’t have significant difference in between forest and plantation, highly due to the recalcitrant of parent material in peat where the woody debris and leaves have lignin resistant to microbial breakdown (Hodgkins et al., 2018; Yule et al., 2016). The outcome from molar ratios of OC and HC indicates possible organic carbon compounds of tannins and lignin (Mann et al., 2015; Wu et al., 2022). From Figure 4.3, both forest and plantation show similar range of molar ratio, scattered between 1.2-1.6 (HC) and 0.6-0.8 (OC). The similarity in molar ratios showed that the origin of peat materials in both the plantation and forest are closely associated as they are of the same region with similar parent plant material input before land use change. However, the slight differences exist in the types of organic carbon compounds found in both areas where it is greatly affected by moisture due to peat humification. Swails et al. (2018) found out that drained peatlands have a higher proportion of aromatic compounds as compared to aliphatic compounds. Aromatic compounds are recalcitrant organic matter that resisted decay due to lesser net energy yield for microbes Hodgkins et al. (2018) as opposed to carbohydrates that are part of the labile carbon pool where it is preferentially decomposed anaerobically (Gandois et al., 2013; Sangok et al., 2017).

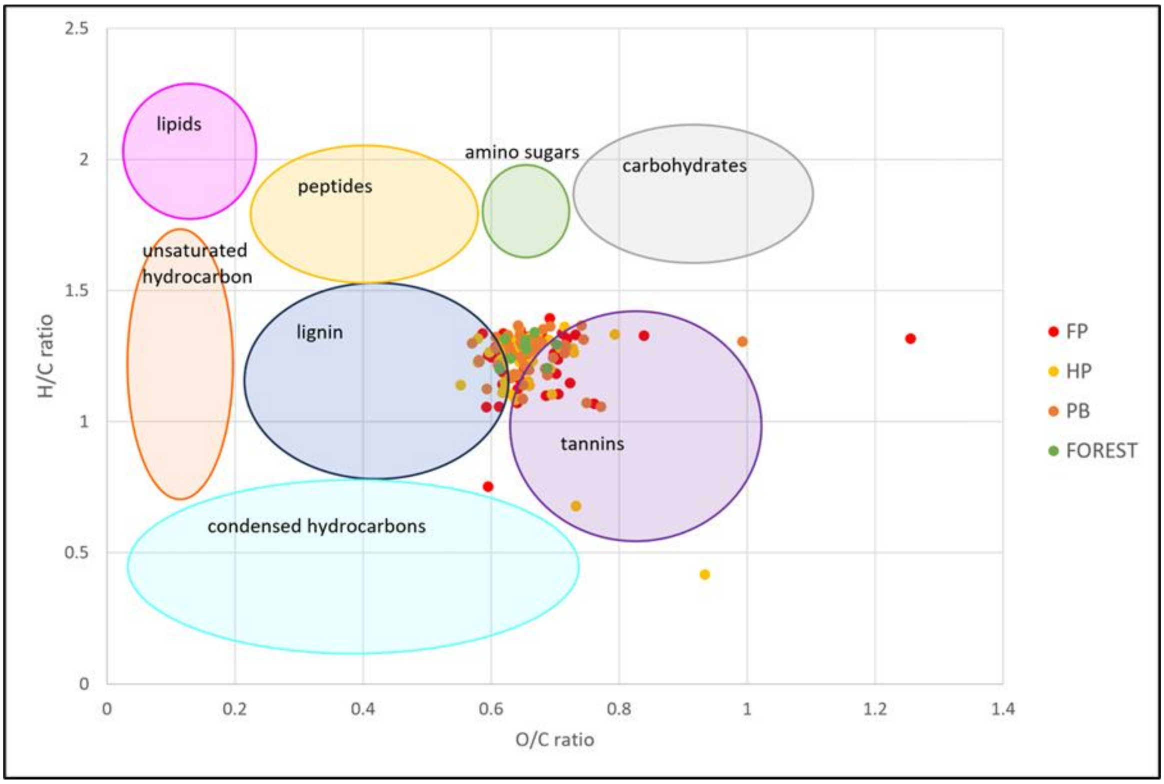
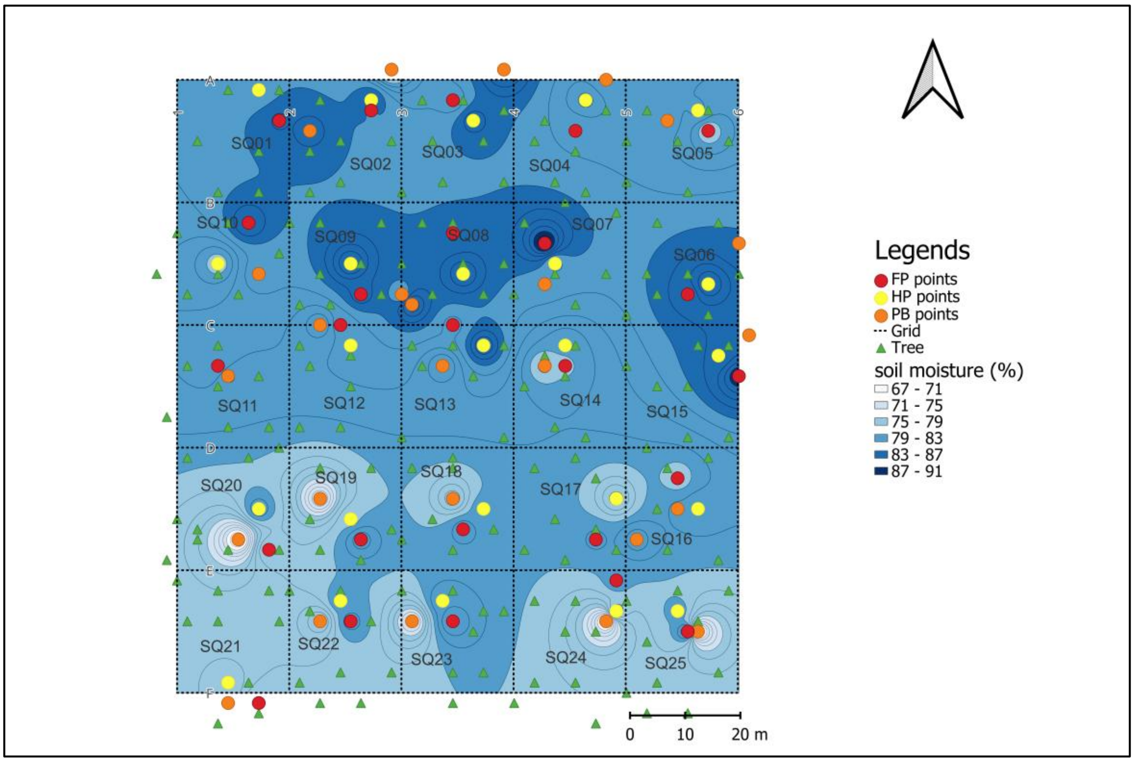
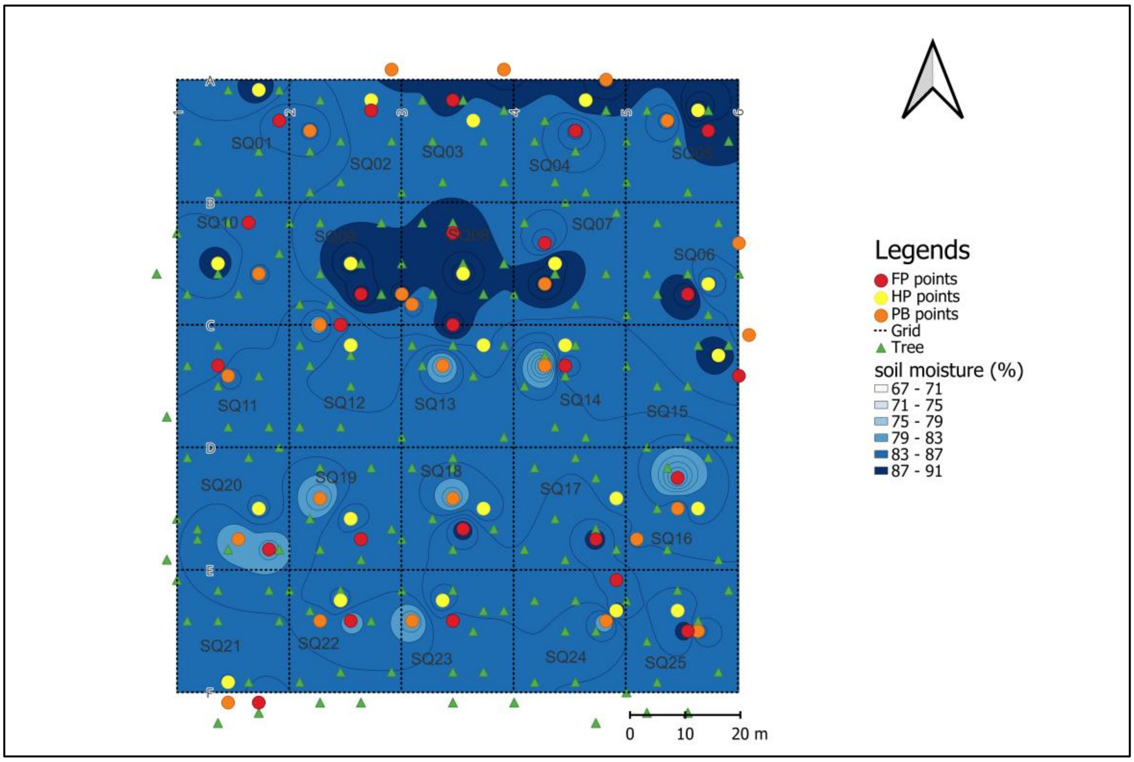


Figure 4.1: Van Krevelen Diagram of HC ratio and OC ratio

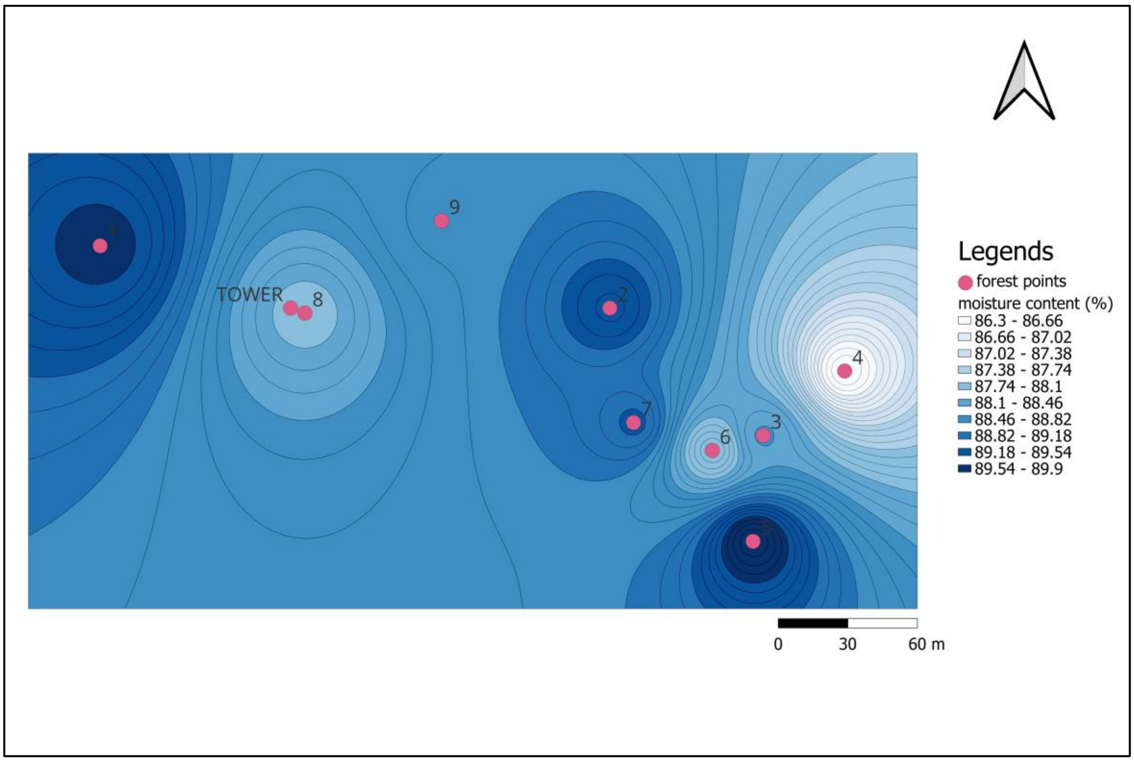
4.3 Peat Soil Characteristics Mapping



LASP plantation (0-50cm)



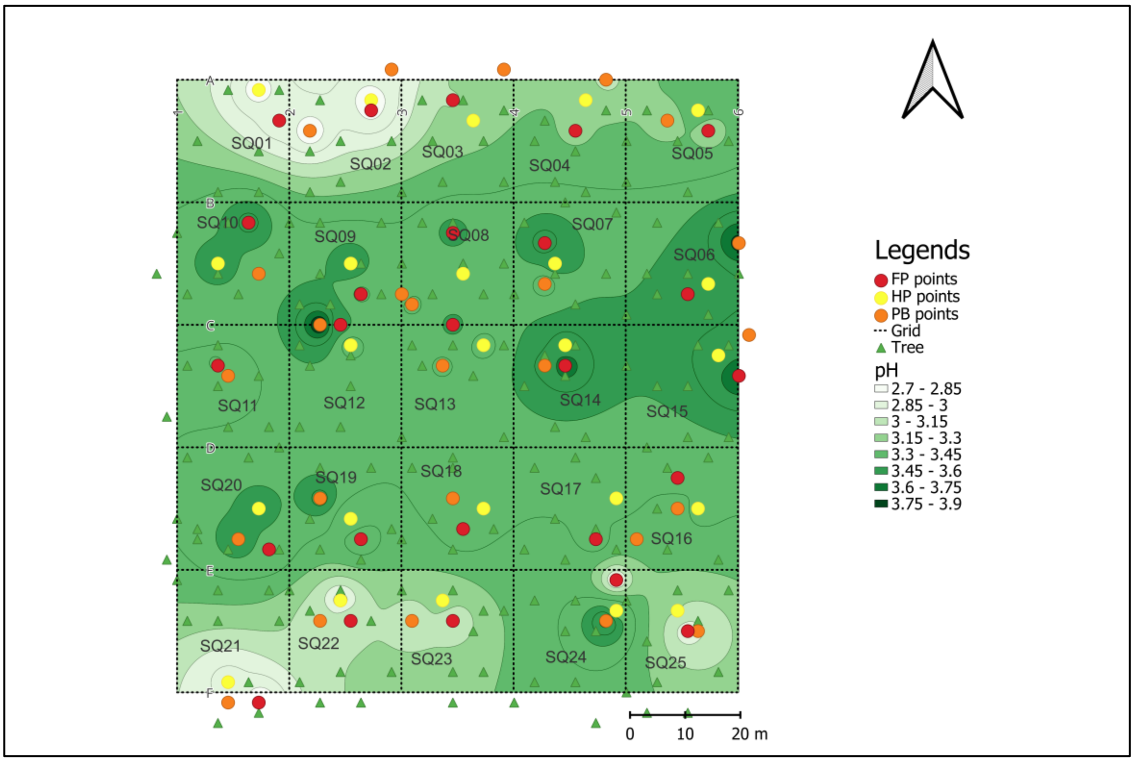
LASP plantation (50-100cm)



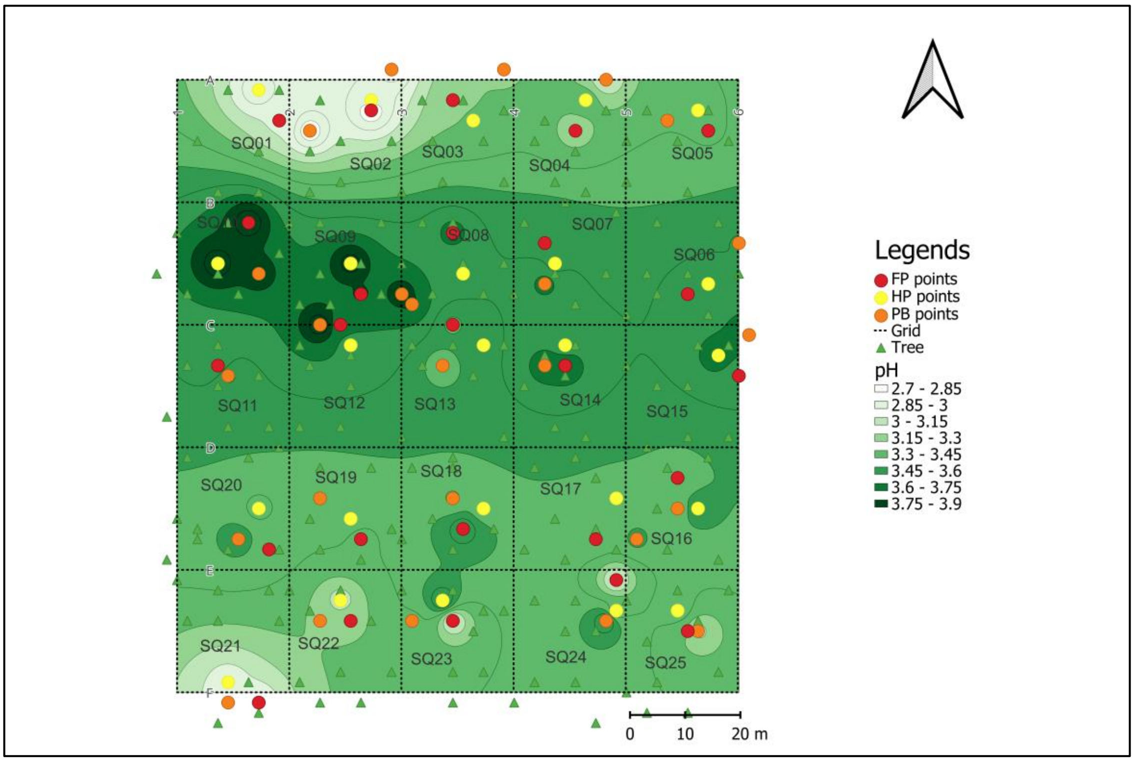
Pekan Forest Reserve

Figure 4.2: Spatial distribution map of soil moisture in LASP and PFR

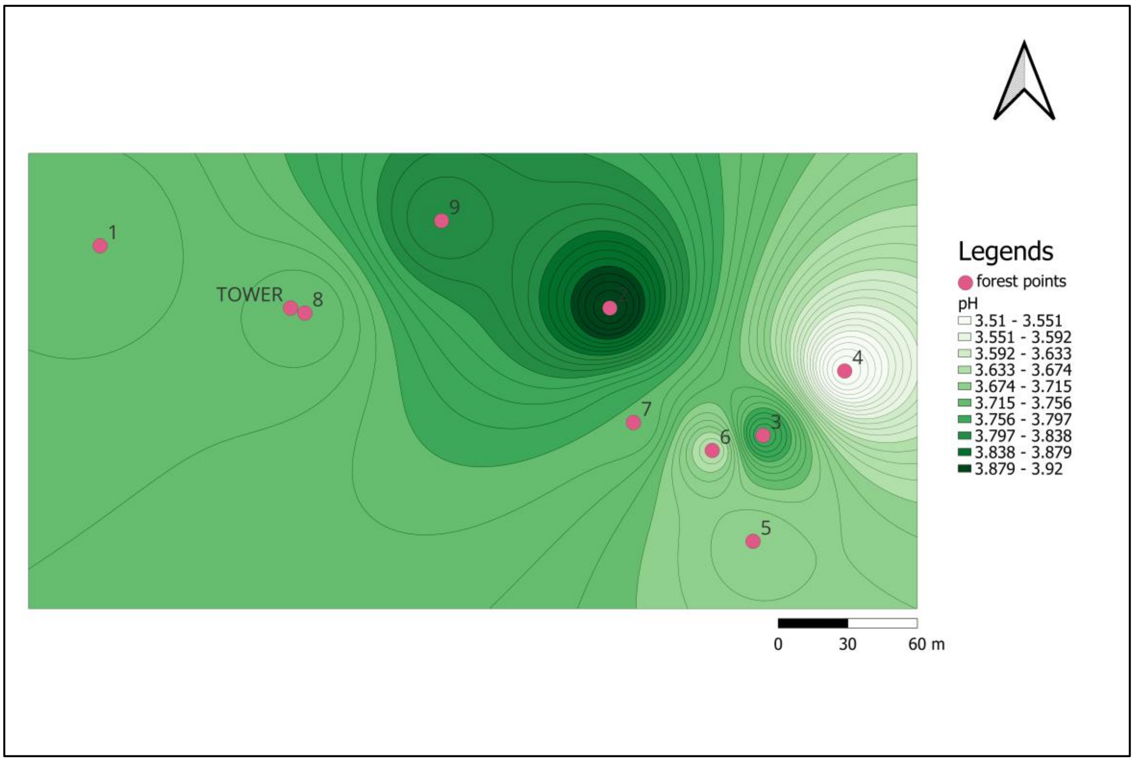
The soil moisture was mapped using GIS according to depths and sites (Figure 4.2). The map shows that soil moisture was higher on the Northern part of the plantation at 0-50 cm, drier in the South. Similar observation was obtained at 50-100 cm. As for the forest, sampling point no. 4 shows the lowest moisture content while the highest moisture is found at both sampling points no. 1 and 5.



LASP plantation (0-50cm)



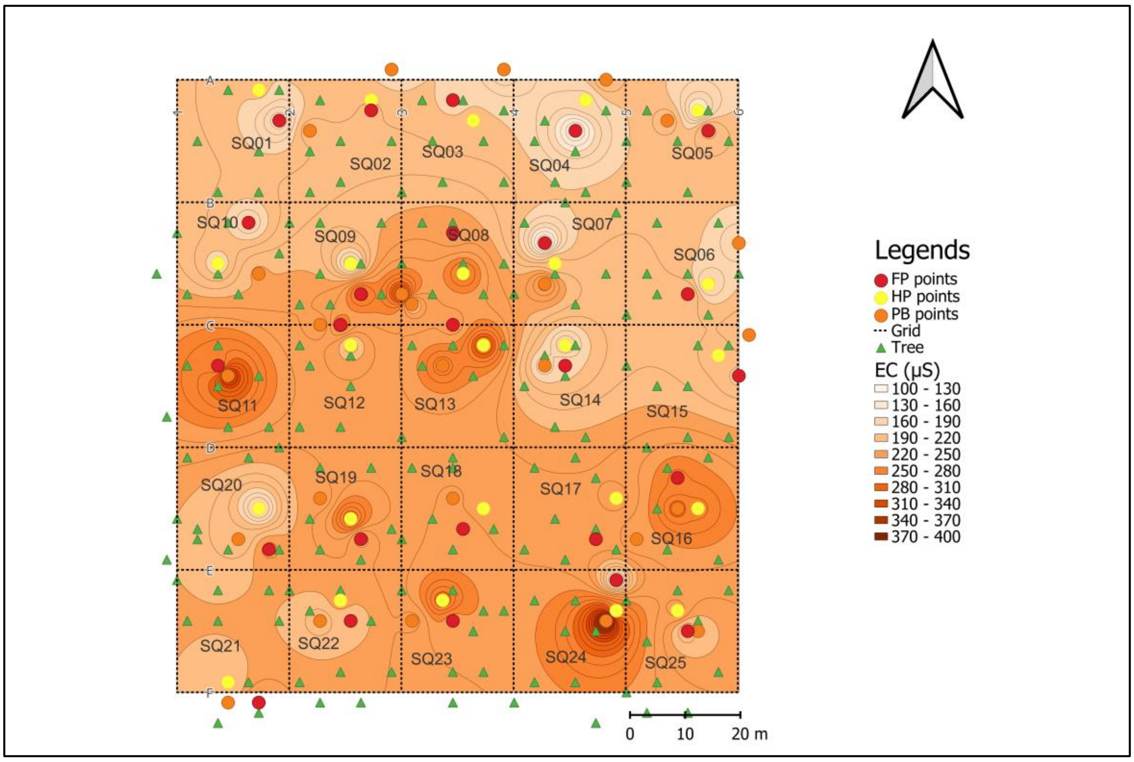
LASP plantation (50-100cm)



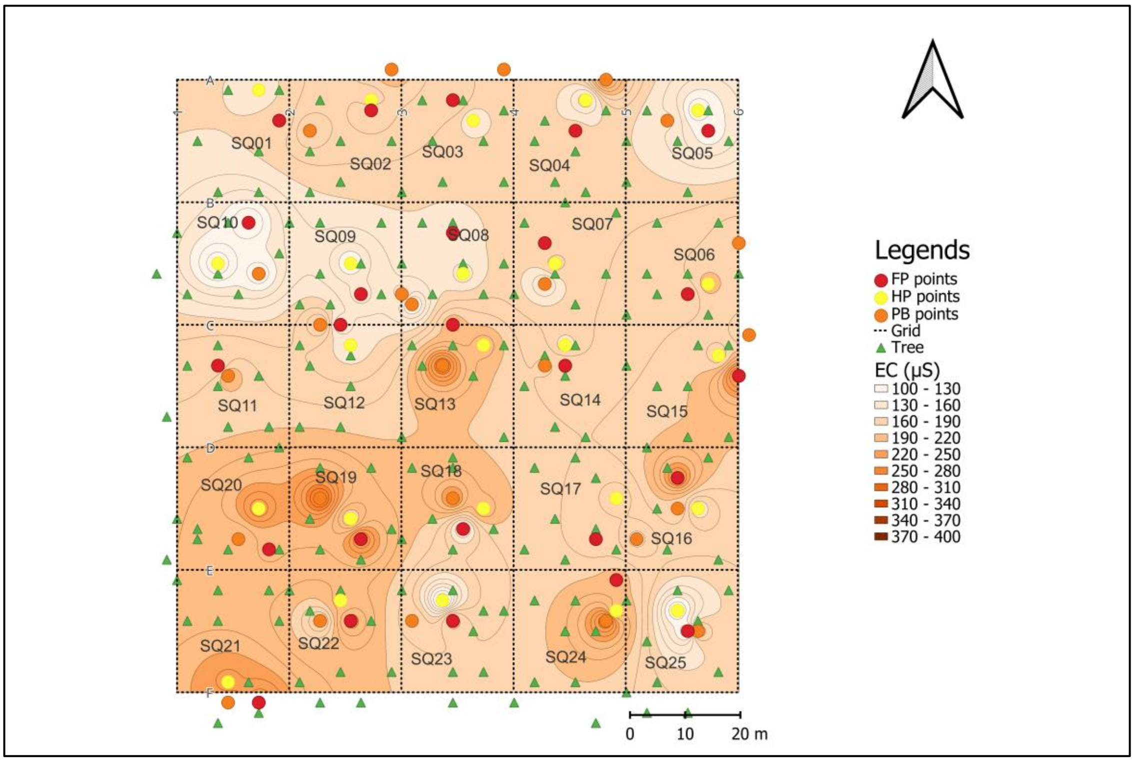
Pekan Forest Reserve

Figure 4.3: Spatial distribution map of pH in LASP plantation and PFR

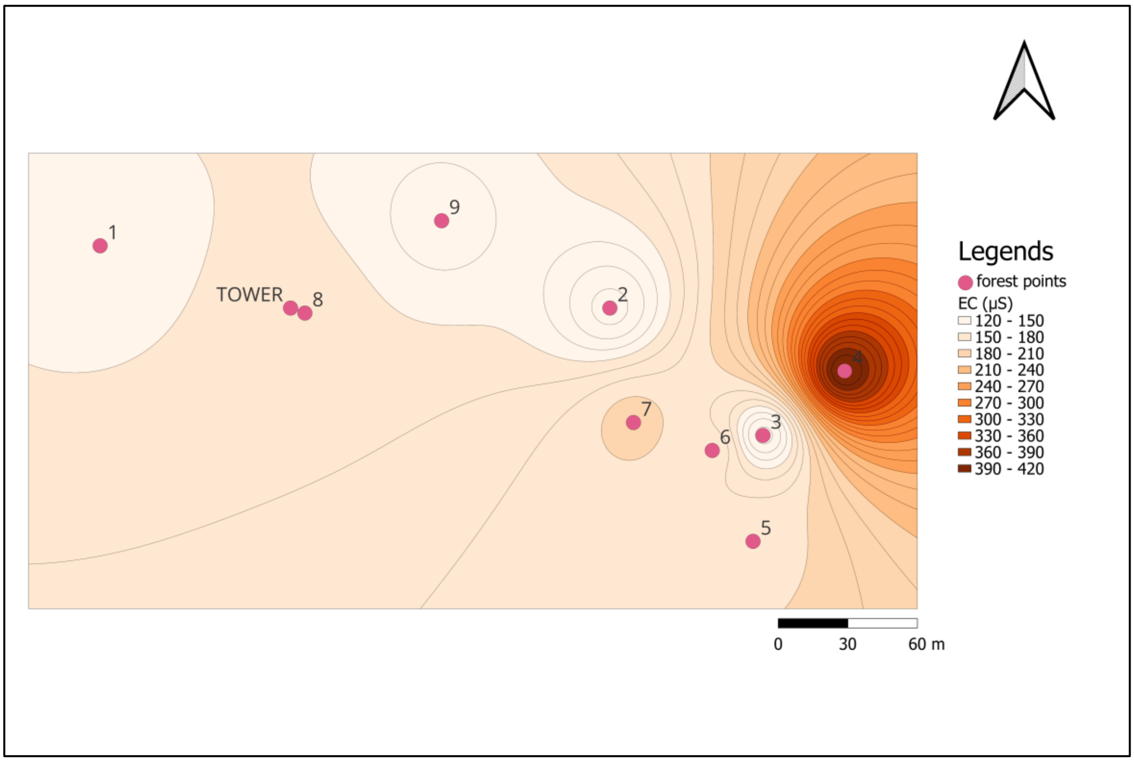
The pH and electrical conductivity of soil are mapped according to depths and sites (Figure 4.3). Soil pH was lower in the Northern and Southern edges of the plantation. The spatial distribution of soil pH at 50-100cm showed similar trend as that of 0-50cm, with higher values attained around plots of SQ09 and SQ10. The forest map showed that pH value was the highest at sampling point no. 2 and the lowest at sampling point no.4.



LASP plantation (0-50cm)



LASP plantation (50-100cm)



Pekan Forest Reserve

Figure 4.4: Spatial distribution map of EC (µS) in LASP plantation and PFR

For electrical conductivity (Figure 4.8, Figure 4.9 & Figure 4.10), the measurements were lower in the Northern area of the plantation. The lowest EC was recorded around SQ05, SQ10 and SQ25 with SQ15, and SQ18-SQ22 demonstrated relatively higher values. The overall colour intensity (in which represents EC values) was much lesser than 0-50cm. From the forest map, the highest value of electrical conductivity was found on sampling point no.4 whereas the rest having similar values.

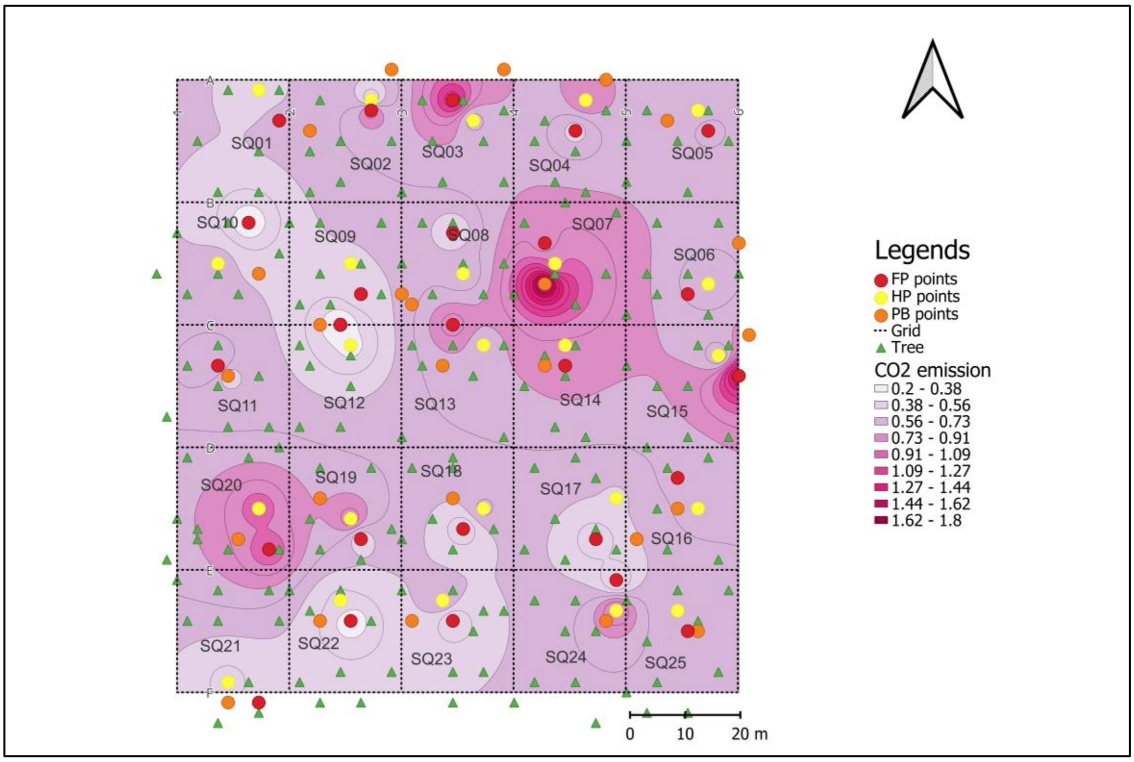


Figure 4.5: Spatial distribution map of momentality CO_2 emission (g CO_2 $m^{-2}hr^{-1}$) in LASP plantation

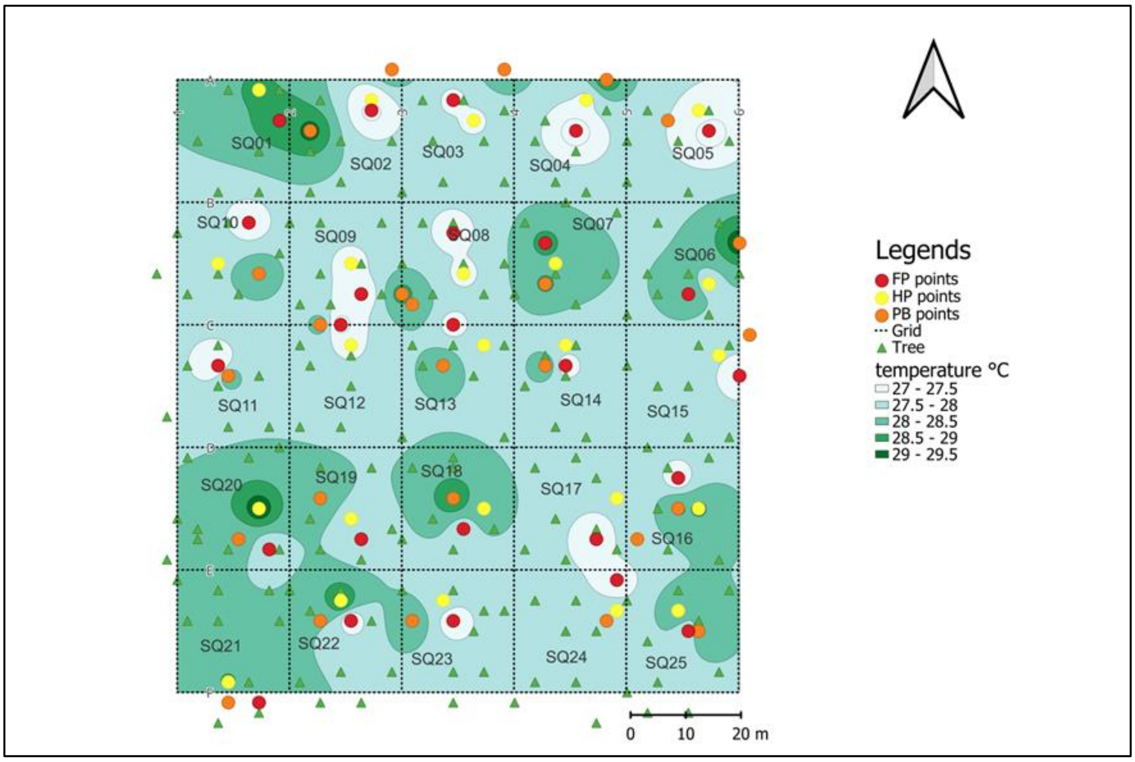
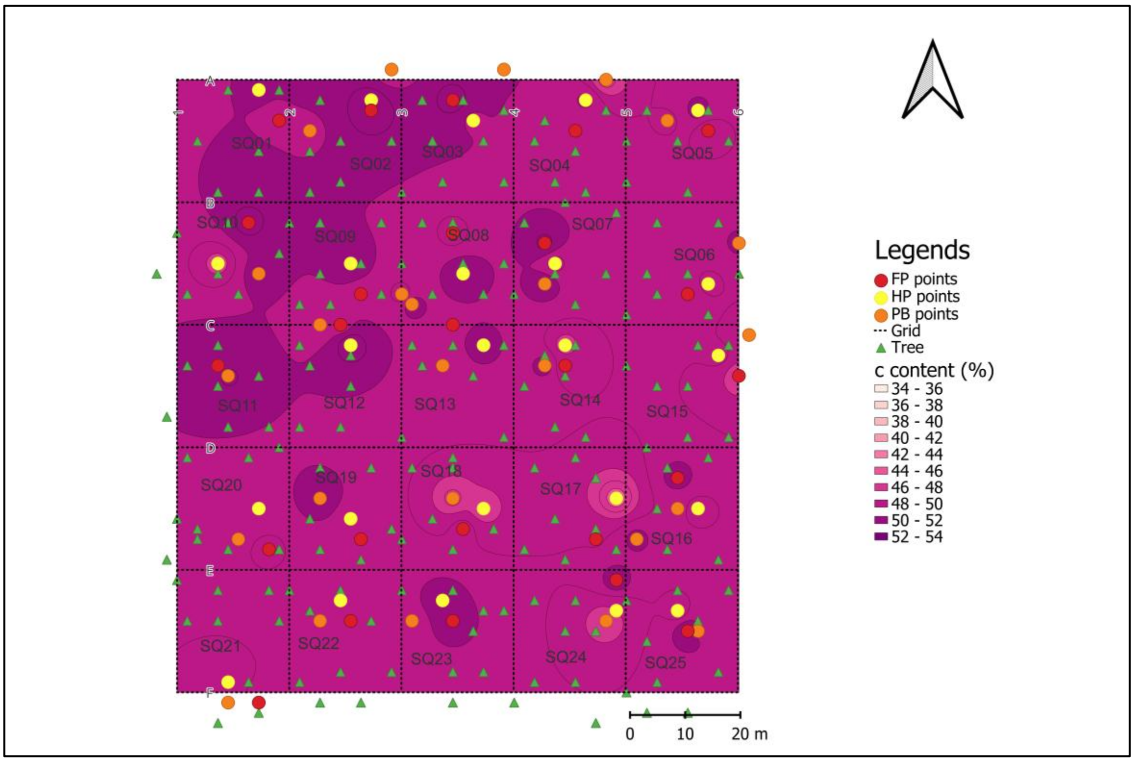
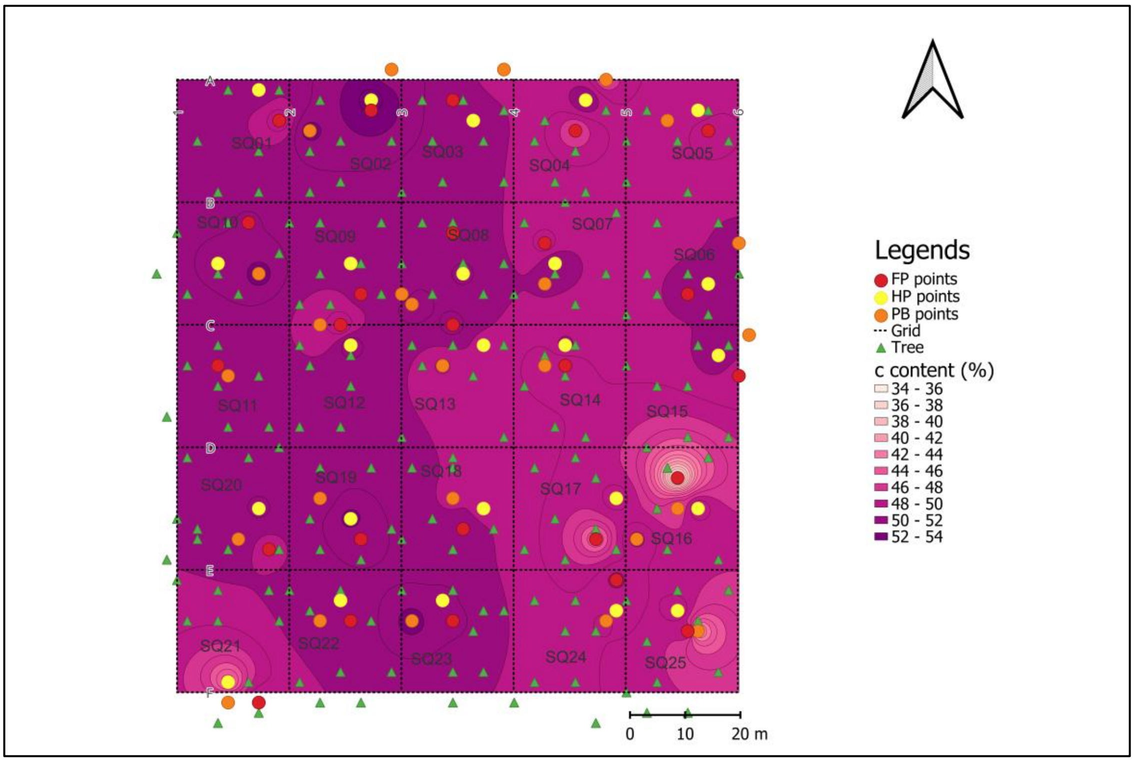


Figure 4.6: Spatial distribution map of soil temperature (°C) in LASP plantation

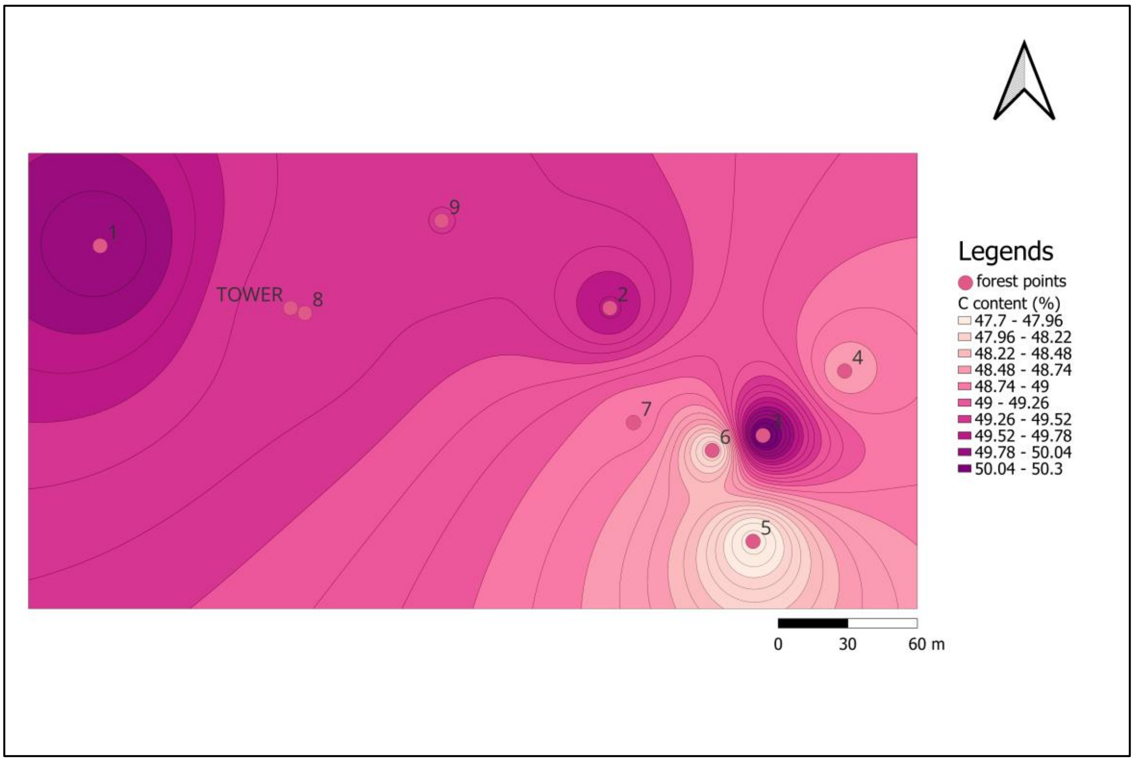
Figures 4.5 and 4.6 show the spatial map of momentary CO_2 emission and temperature in the plantation. High values of temperature (˚C) are scattered around on SQ01-SQ02, SQ06-SQ07, SQ16, SQ18-SQ22 and SQ25. Low values are distributed on SQ02-SQ05, SQ08-SQ12, SQ14-SQ15, SQ17 and SQ22-SQ24.



LASP plantation (0-50cm)



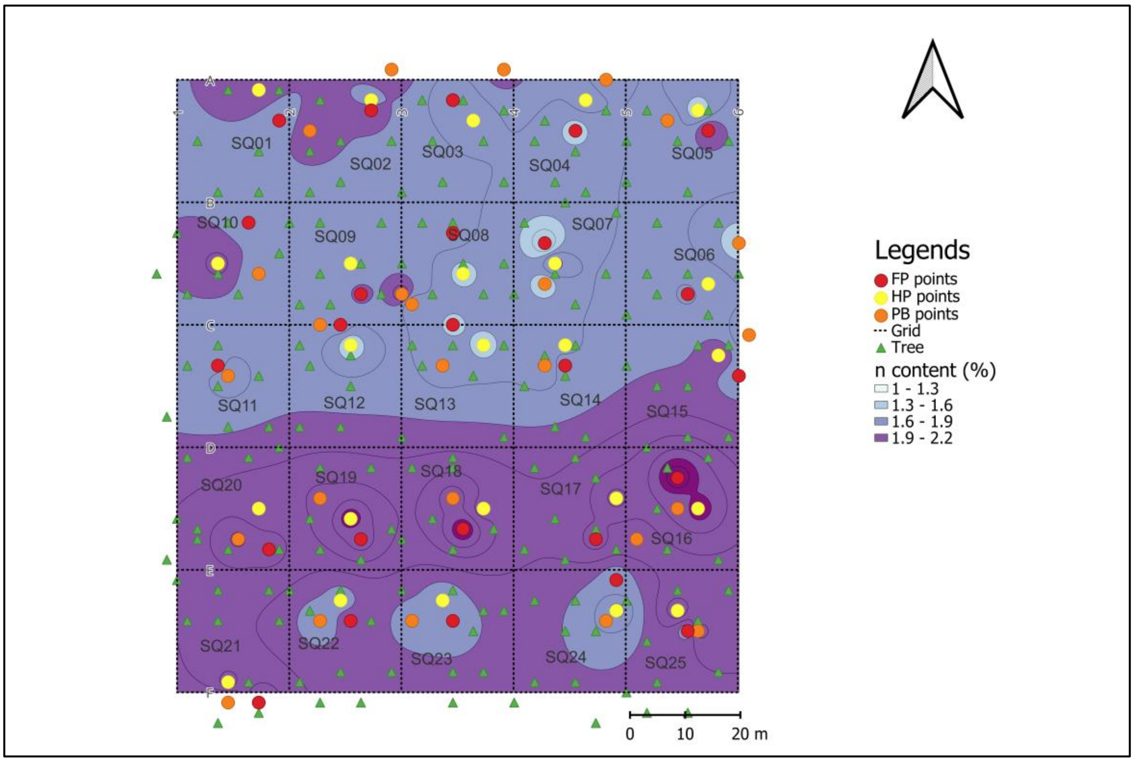
LASP plantation (50-100cm)



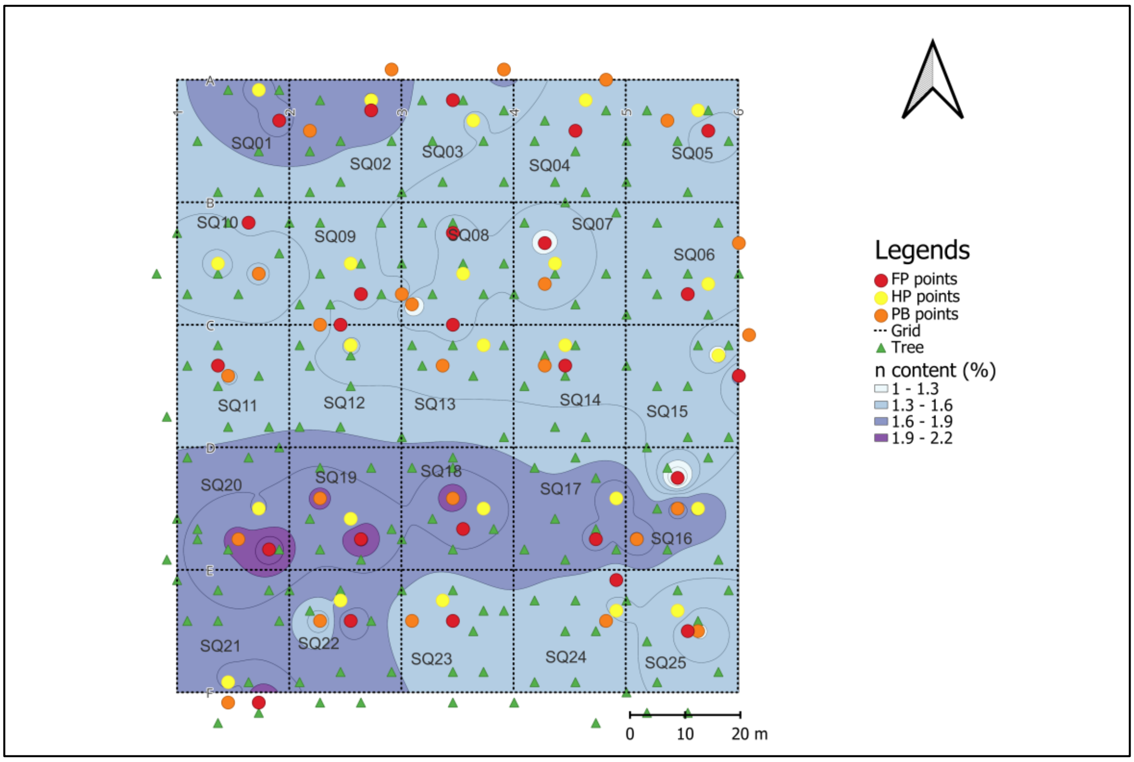
Pekan Forest Reserve

Figure 4.7: Spatial distribution map of carbon in LASP plantation and PFR

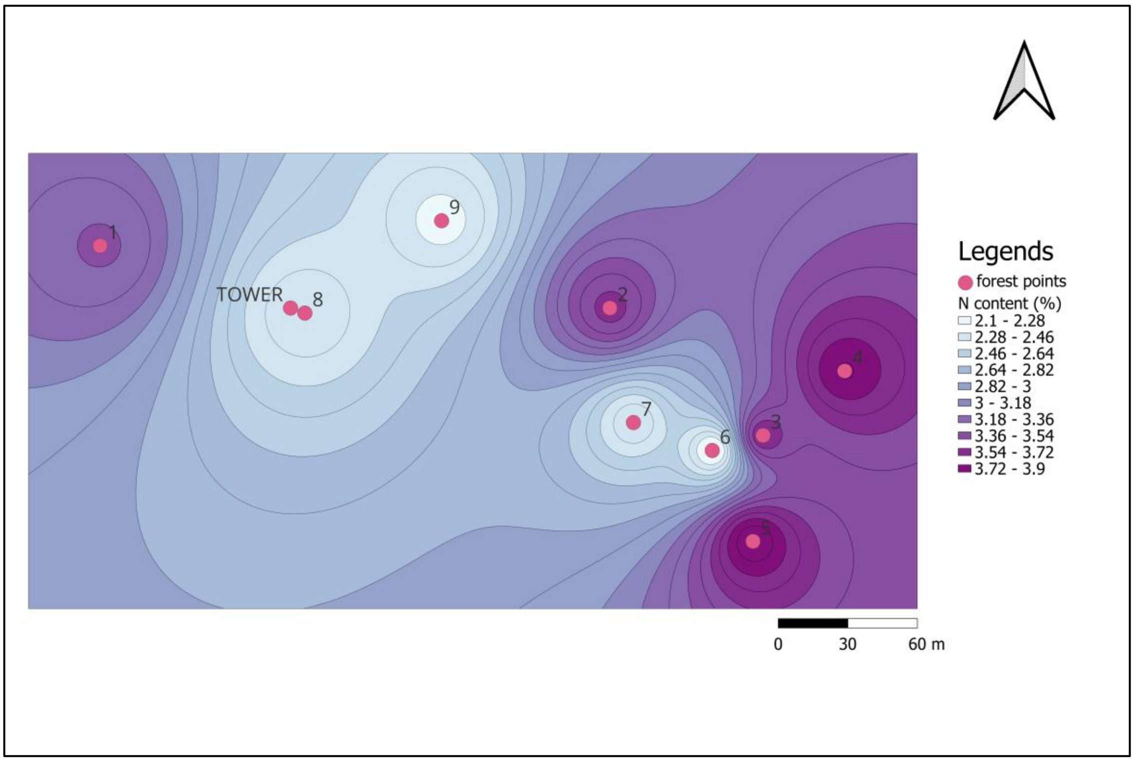
The spatial map of C content in Figure 4.7 shows that the C concentration is higher on the left corner. Soil carbon content is found to be higher on almost half of the area of the left side of the map. Similar ranges of C concentration are recorded between 0-50 cm and 50-100 cm. As for the forest, the scale is slightly different but close in range. The highest C content is found at sampling no.1 and no.3 while sampling points no.5 and no.6 are found to be the lowest in forest map.



LASP plantation (0-50cm)



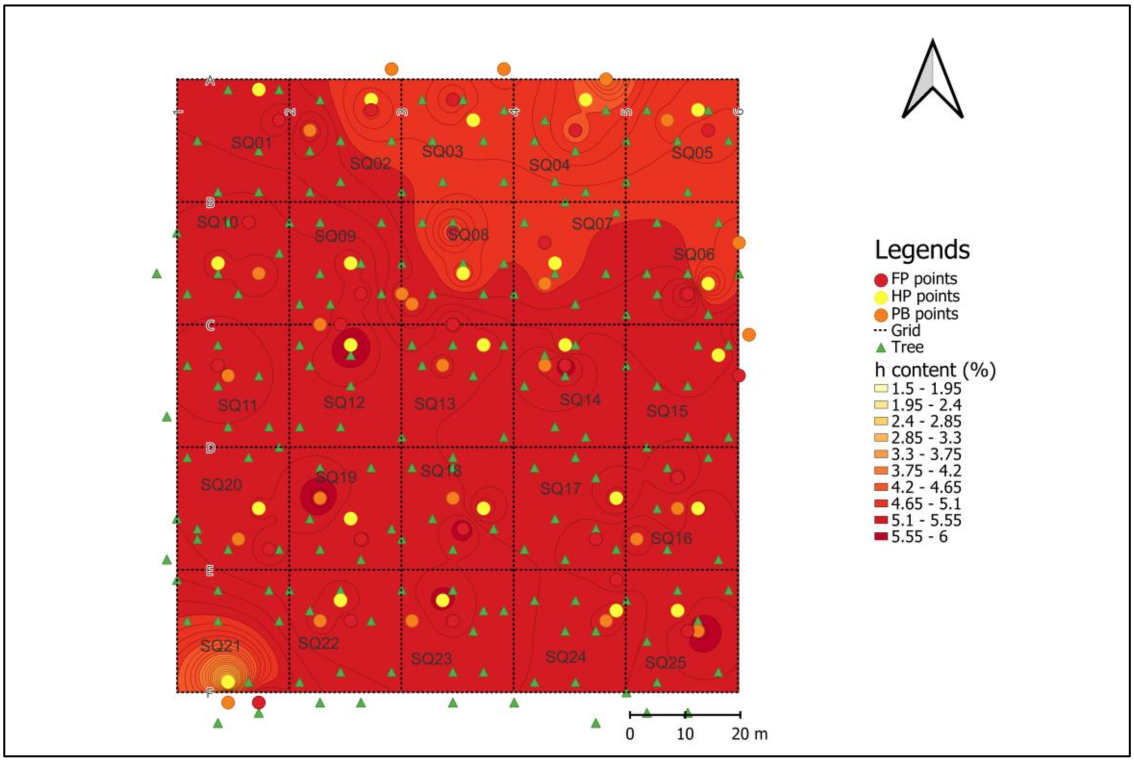
LASP plantation (50-100cm)



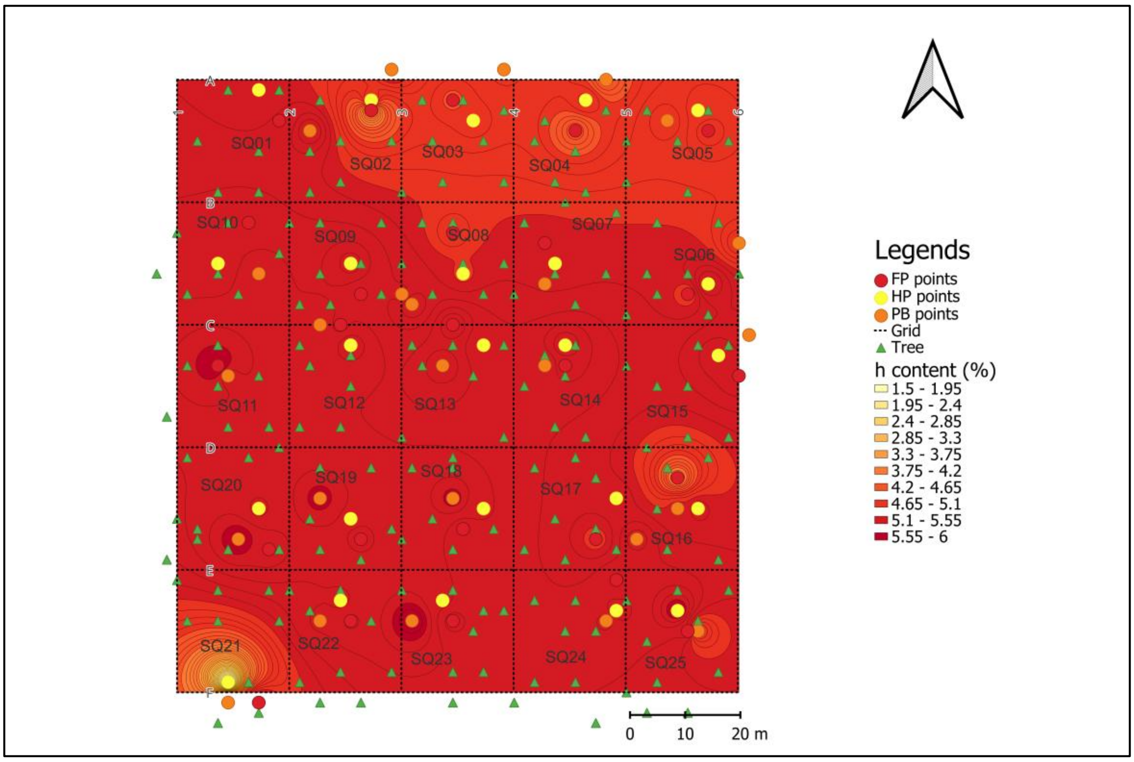
Pekan Forest Reserve

Figure 4.8: Spatial distribution map of nitrogen in LASP plantation and PFR

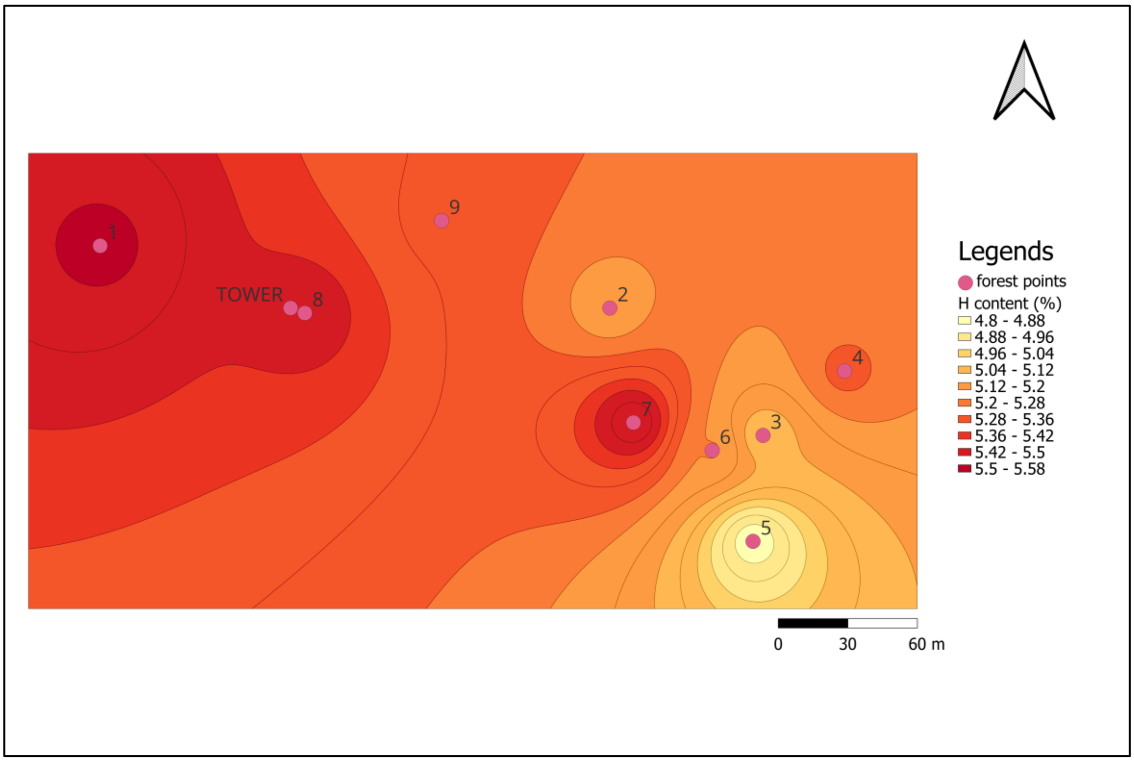
For N, a high N content is distributed on the Southern part, covering almost half of the map, with the highest concentration identified in SQ16, SQ18 and SQ19. Most N content of high value were recorded along SQ16 to SQ20 (Figure 4.8) The forest map shows N content is lower among sampling points of 6-9, sampling point no.1 till 5 were shown to have high values.



LASP plantation (0-50cm)



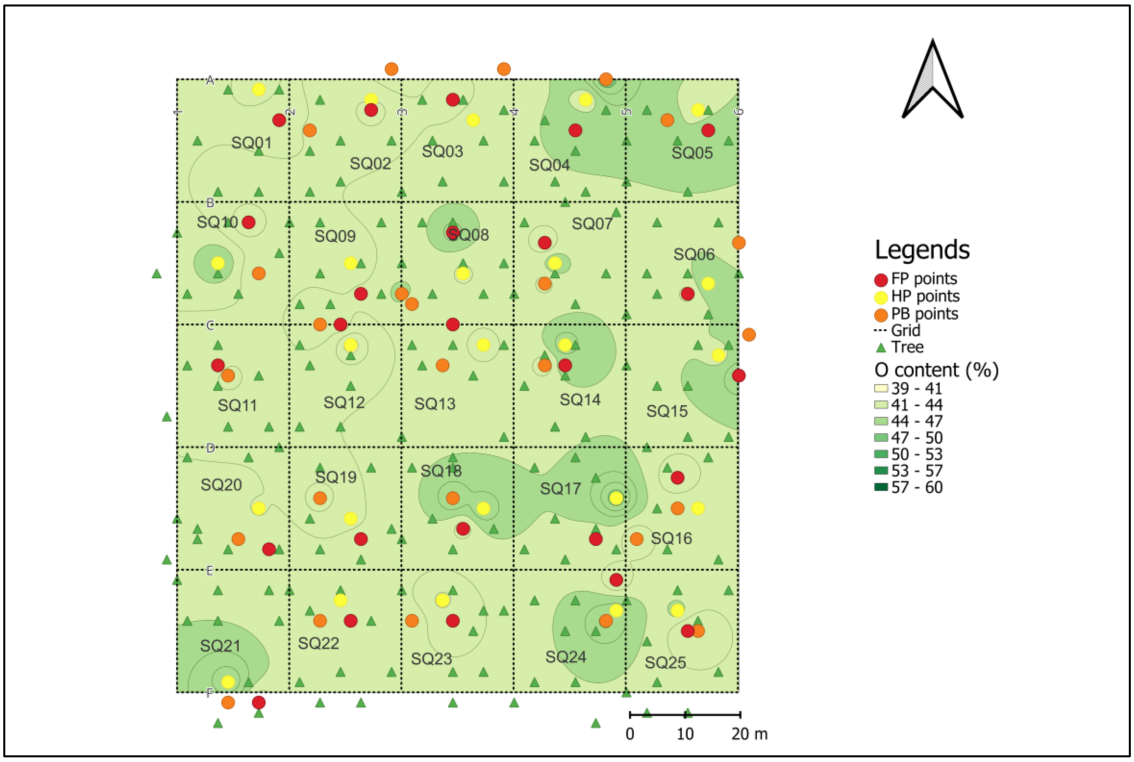
LASP plantation (50-100cm)



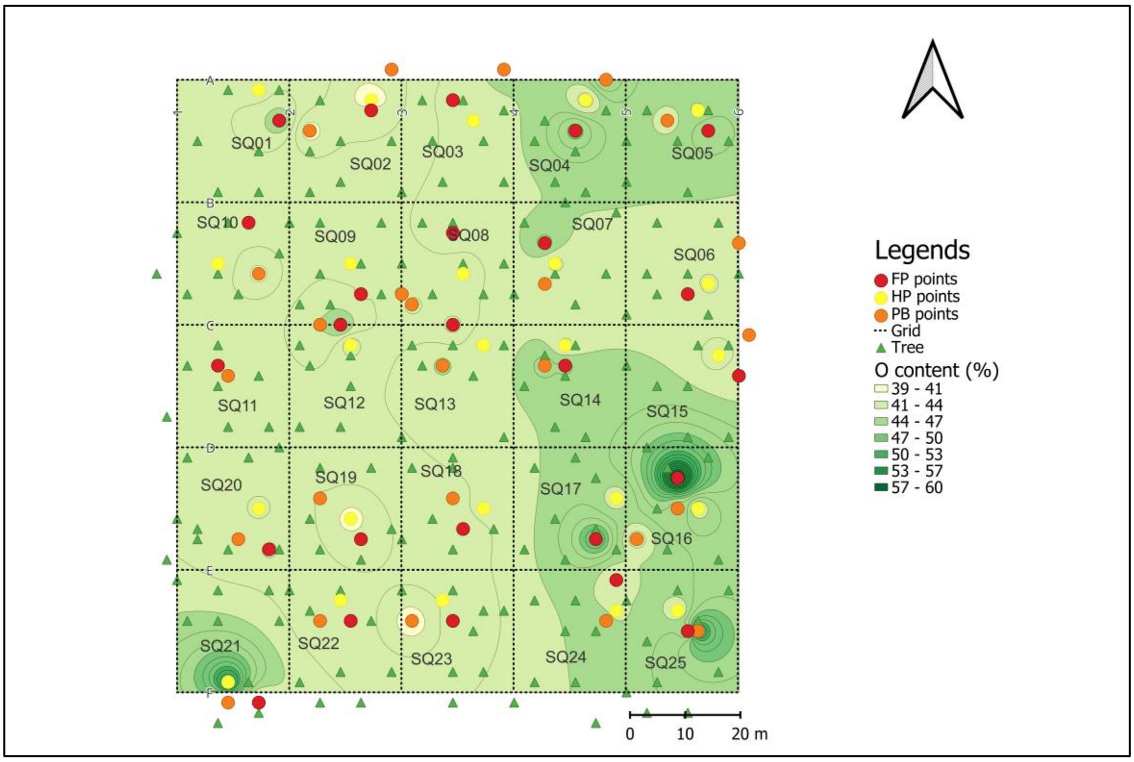
Pekan Forest Reserve

Figure 4.9: Spatial distribution map of hydrogen in LASP plantation and PFR

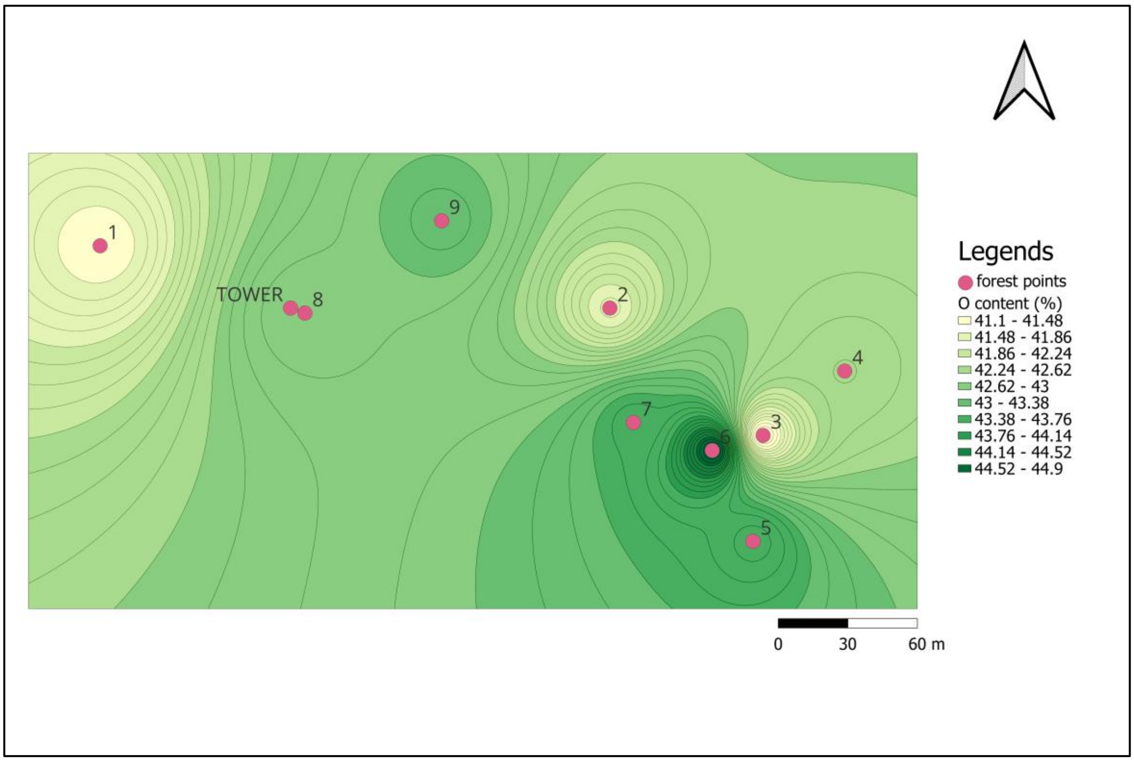
For hydrogen, a lower intensity of values is found around SQ03-SQ06 and SQ21. The overall map value range is quite consistent. At the lower horizon of 50-100 cm, similar trend as the surface layer is observed with lower values determined across SQ02-SQ05, SQ08, SQ16, SQ 21 and SQ25 (Figure 4.9). From the forest map, sampling points of 1, 7, 8 are having higher H content as opposed to sampling point no.5.



LASP plantation (0-50cm)



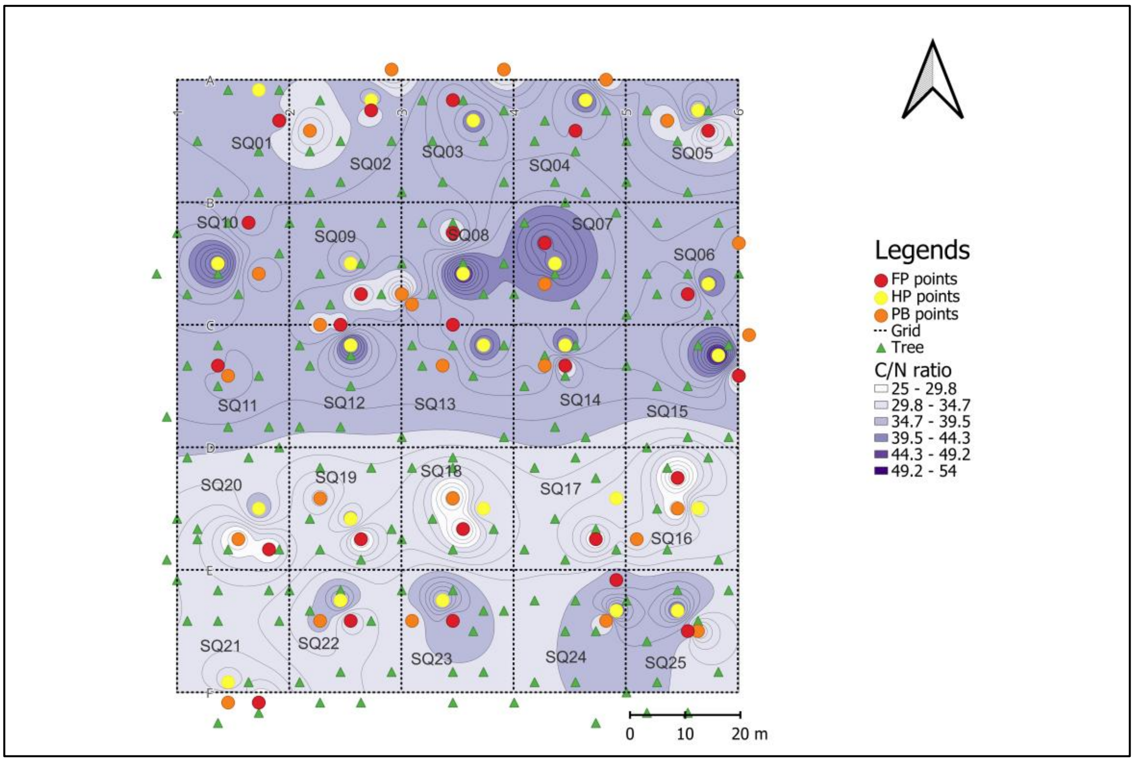
LASP plantation (50-100cm)



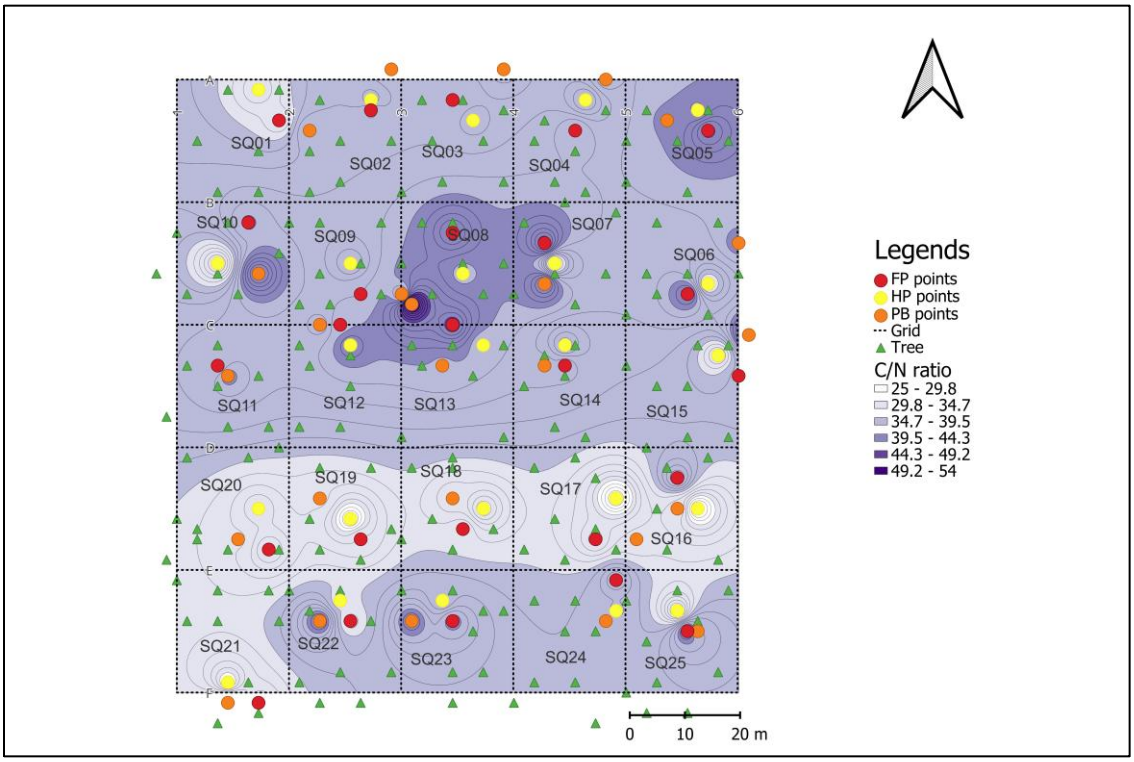
Pekan Forest Reserve

Figure 4.10: Spatial distribution map of oxygen in LASP plantation and PFR

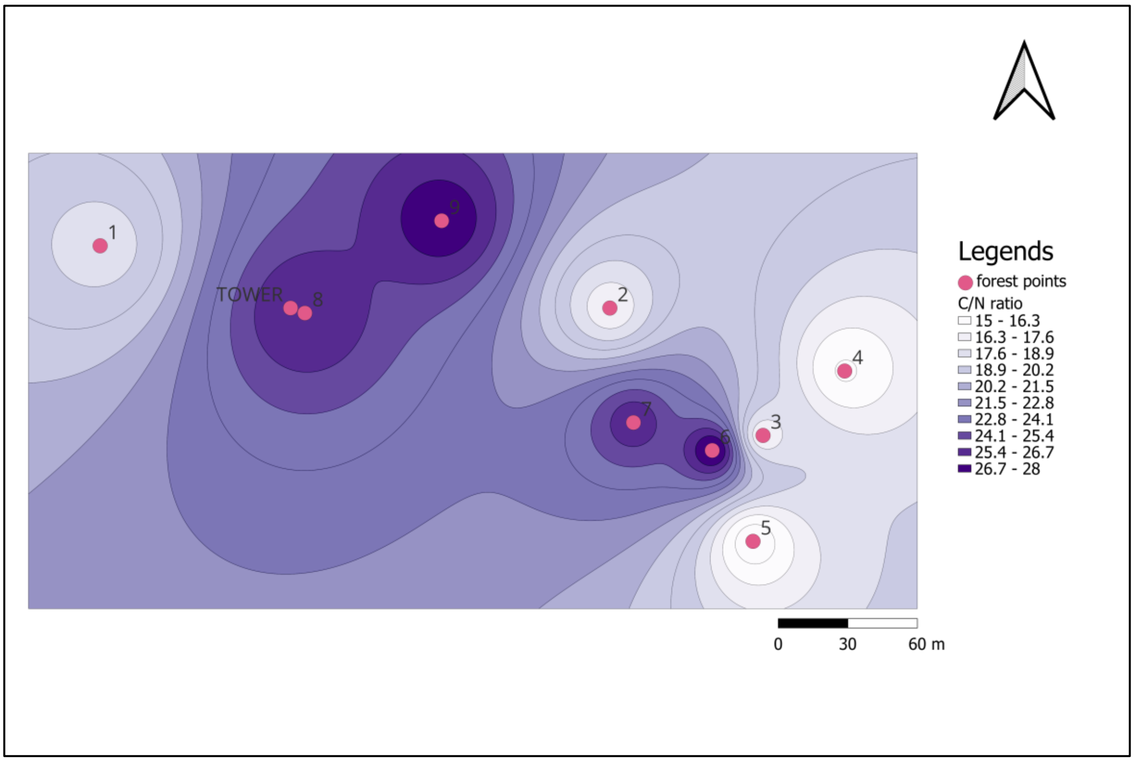
For O as shown in Figure 4.10, high values of O content were scattered across the map in SQ04-SQ06, SQ08, SQ10, SQ14, SQ17-SQ18, SQ21 and SQ24. At the deeper layer, O content is uniformly distributed. As for the forest, highest value of O content on sampling point no.6, while lower values were shown on sampling points 1-3.



LASP plantation (0-50cm)



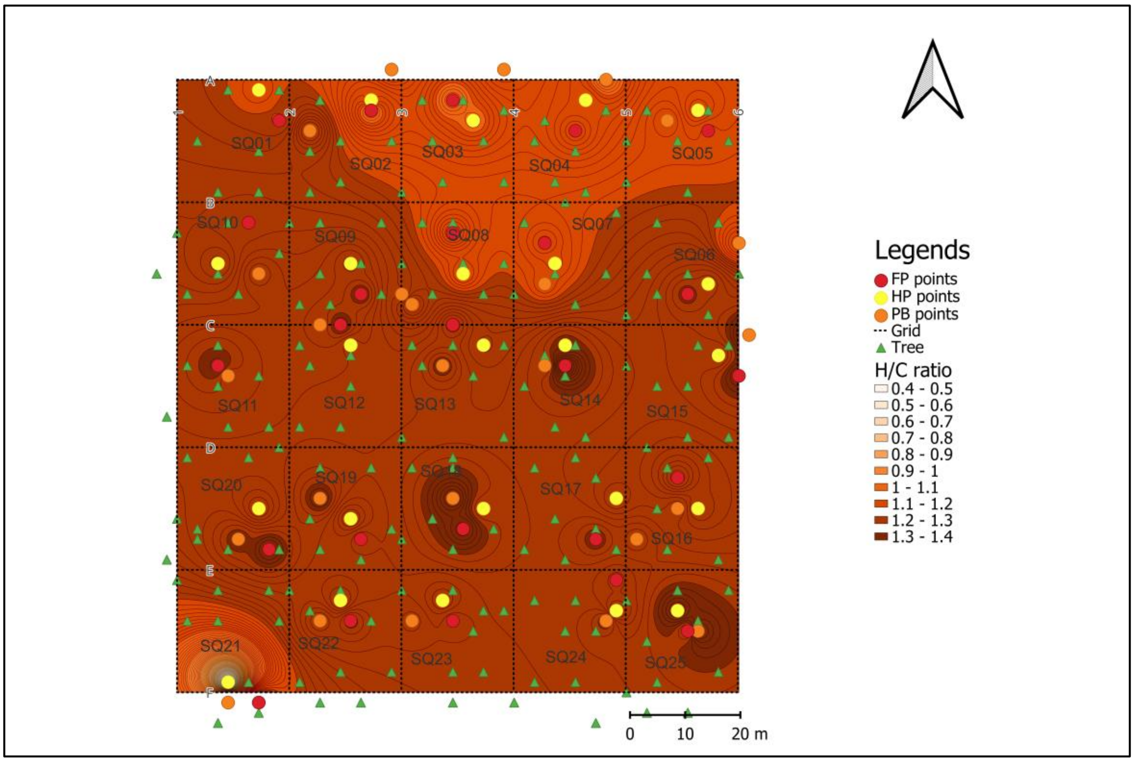
LASP plantation (50-100cm)



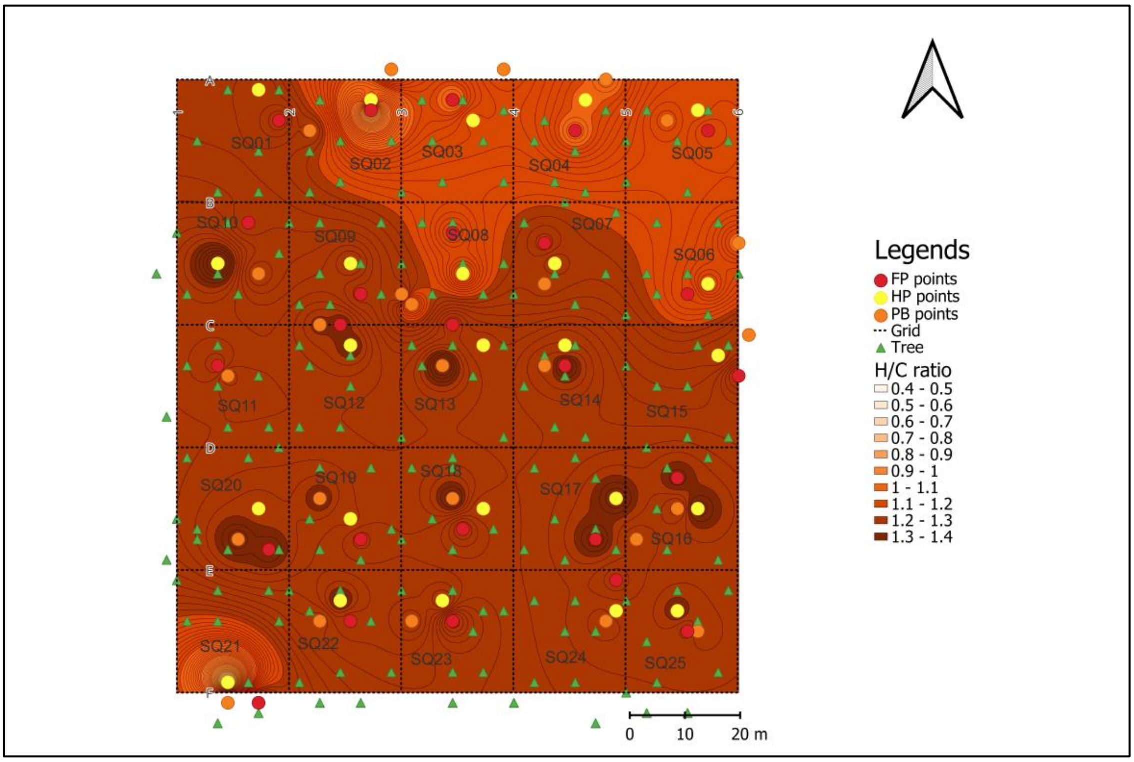
Pekan Forest Reserve

Figure 4.11: Spatial distribution map of CN ratio in LASP plantation and PFR

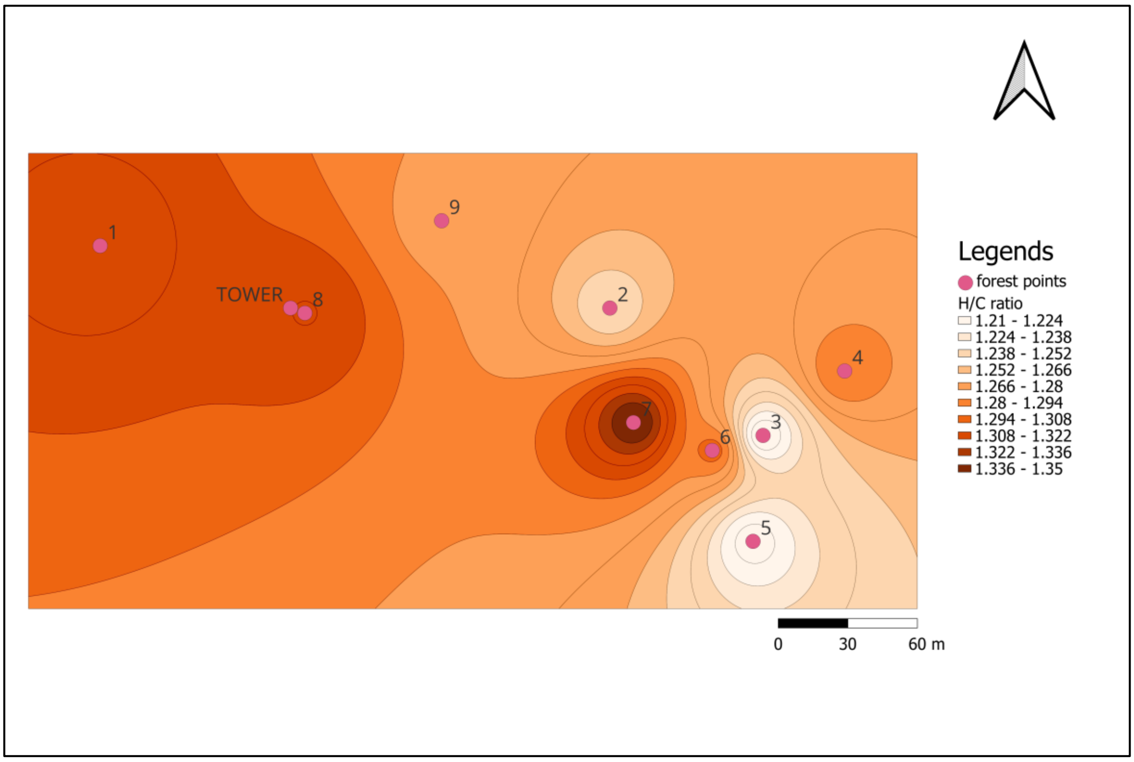
The elemental ratio can be used to describe the humification degree. The spatial map of CN ratio (Figure 4.11) shows that lower CN ratio mostly distributed on the Southern side of the plantation, with some scattering on SQ02, SQ05 and SQ09. The area of high CN ratio would require extra attention for fertiliser input as it was less fertile (Umaru and Samling, 2018). As for the forest, sampling points of no.6 to no.9 were shown to have high CN ratio, whereas no.1 -5 were of low CN ratio.



LASP plantation (0-50cm)



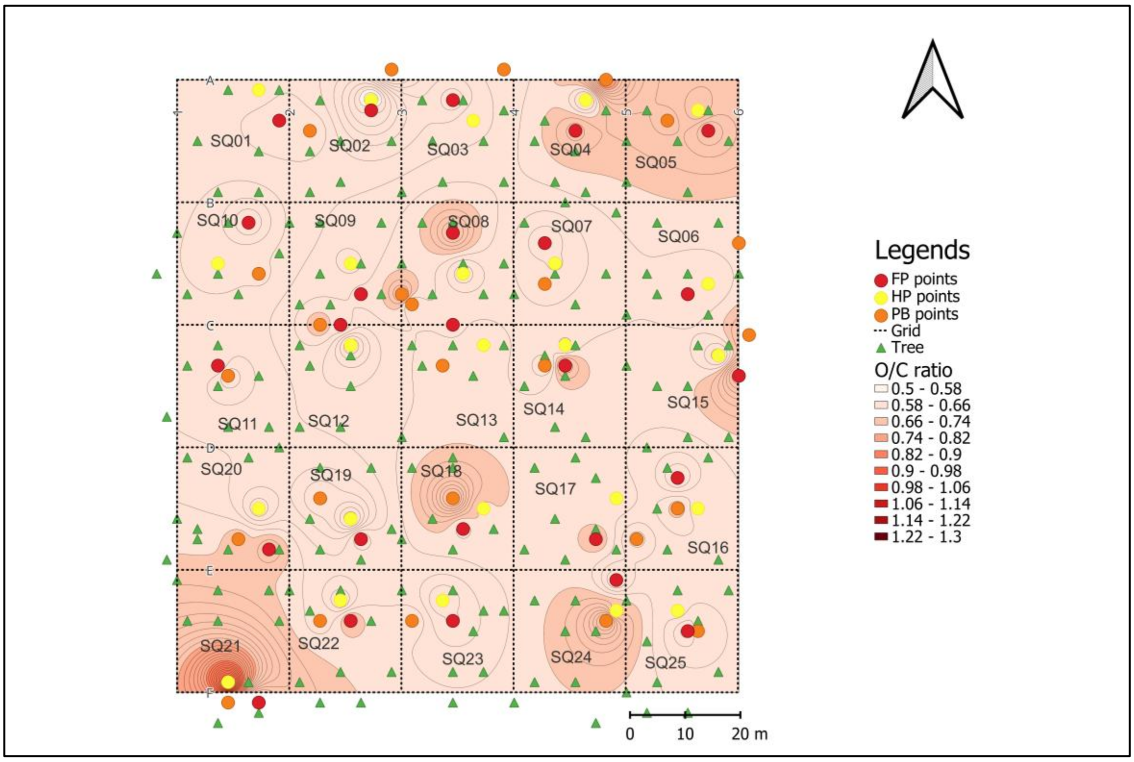
LASP plantation (50-100cm)



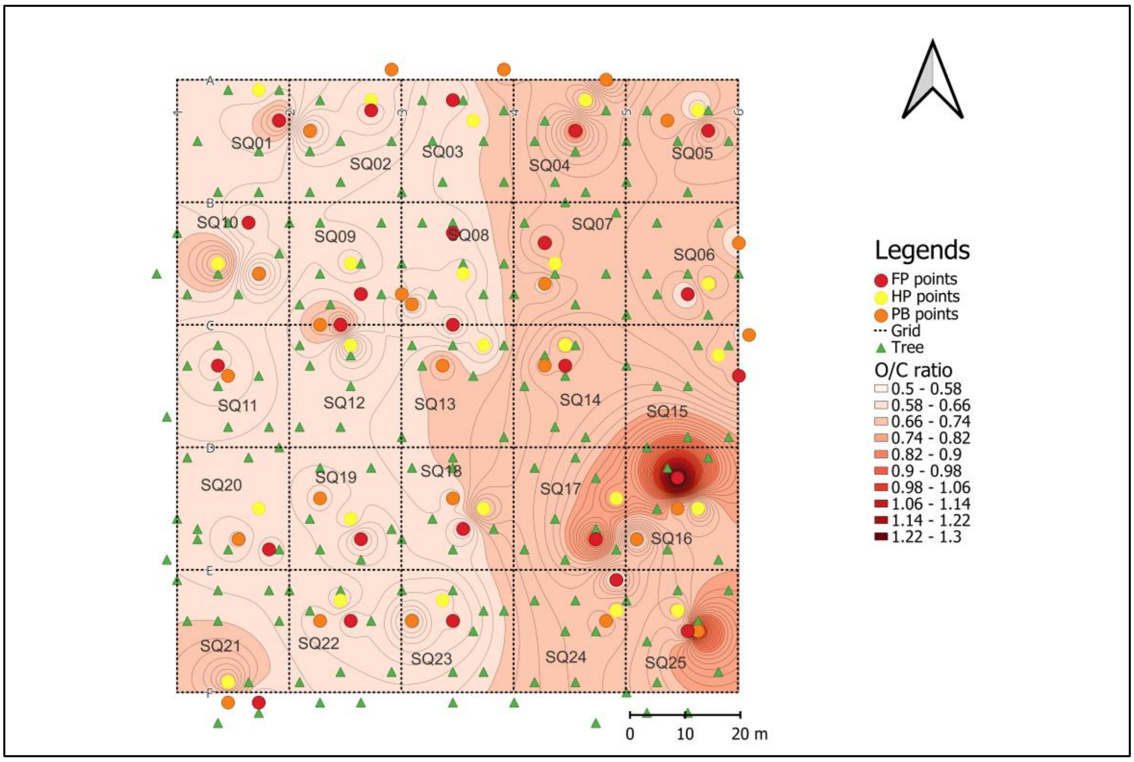
Pekan Forest Reserve

Figure 4.12: Spatial distribution map of HC ratio in LASP plantation and PFR

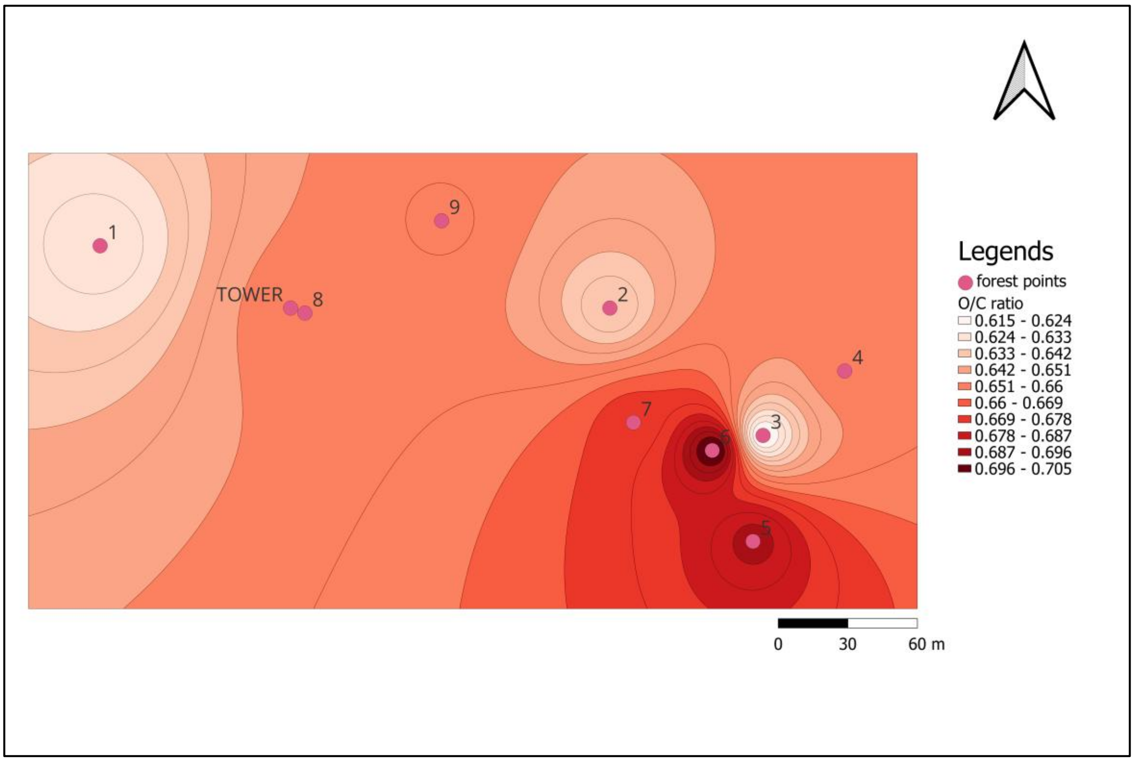
For HC, the surface layer shows that low values are found on SQ01-SQ05, SQ07-SQ08 and SQ21 (Figure 4.12). High HC ratio is scattered on SQ11-SQ14, SQ17-SQ20, SQ22 and SQ24-SQ25. The 50-100 cm shows similar trend as described in the surface layer with slight variation where low ratios are found on SQ01-SQ06, SQ08 and SQ21. High values of HC ratio covered almost all aforementioned square plots of high value in surface layer except SQ01, SQ07 and SQ23. From the forest map, highest value of HC ratio was observed on sampling point no.7 while sampling points of no.2, 3, and 5 had low HC ratio values.



LASP plantation (0-50cm)



LASP plantation (50-100cm)



Pekan Forest Reserve

Figure 4.13: Spatial distribution map of OC ratio in LASP plantation and PFR

The OC ratio in plantation at 0-50 cm (Figure 4.13) demonstrated low concentration with high values scattered on SQ04-SQ05, SQ08-SQ09. SQ14-SQ15, SQ18, SQ21 and SQ24. The map of 50-100 cm also shows low value range, with the high values dominated almost half of the right side of the plantation, with SQ16 having a high OC ratio. In the forest map, sampling points of no. 1-3 are of low HC ratio while no.5 and no.6 are found to be high OC ratio.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

Soil moisture, pH and electrical conductivity had shown significant differences in between different land use of oil palm plantation and primary forest. While within the plantation, soil moisture, pH and electrical conductivity had shown to have significant differences for different depth. Soil moisture and temperature has shown to have significant differences among collar zones for depth 0-50cm while only soil moisture had shown significant differences among collar zones for depth 50-100cm.

Nitrogen and CN ratio had shown significant differences in between different land use of oil palm plantation and primary forest. While within the plantation, Nitrogen and CN ratio had shown to have significant differences for different depth. Nitrogen and CN has shown to have significant differences among collar zones for depth 0-50cm.

The humification degree was found to be the highest in forest with low CN ratio of 20.1 along with high moisture (88.6%). On the other hand, within the plantation FP demonstrated low CN ratio (32.4) with high humification degree and high moisture (82.2) among the collar zones. FP data aligned with forest data for also having high humification along with high moisture.

From the results, agricultural land use does impact on soil quality of peat, even miniature variation of different working area within the plantation reflected back onto the data collected. This showed that peat is fragile and requires careful consideration, proper planning and decision making in handling peatlands.

The spatial mapping using GIS revealed distinct pattern of soil characteristics across the plantation. The information is crucial for managing soil changes that may affect nutrient availability or water shortage in which greatly impacts on the yield.

5.2 Recommendations

According to the soil data map of nutrient content, the plantation area within high CN ratio would require extra attention for nutrient supply. Although high humification is beneficial for nutrient supply and yield improvement, it is not great for peat preservation. Many studies suggested that high water table could help in preserving peat (Ismail et al., 2007; Wösten et al., 2008; Mishra et al., 2021) but for oil palm plantation it is impossible to submerge peat in water due to the nature of oil palm tree and its rooting issue. However, according to the results obtained from plantation and forest, along with supporting evidences of other studies (Anuar et al., 2008; Yule et al., 2016; Swails et al., 2018; Dhandapani et al., 2019; Manning et al., 2019) where fresh litter input at the forest could replenish peat and maintain peat loss. Therefore, along this idea, providing continuous fresh litter input at the plantation could be the mitigating effort in maintaining peat for its structure stability and moisture retention while ensuring nutrient supply to increase yield aside from the nitrogen fertiliser application to boost harvest. Results from FP has demonstrated high moisture content and low CN ratio, showing similar conditions as the forest, which is ideal for peat preservation while having adequate nutrient supply for oil palm trees.

The limitations of this study are that the data obtained for forest site is not as complete as the plantation due to the lack of a study plot establishment within the forest. Other limitations including the timeframe and manpower issues to obtain more crucial data such as the water table and organic matter compositions. Future studies should include long term monitoring and collection of baseline data in peatlands of different scenarios, especially on oil palm plantations and neighbouring peat swamp forests for quality control and peat maintenance.

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APPENDICES

Table 5.1: ANOVA summary for soil moisture

	Df	Sum Square	Mean Square	F value	Pr(>F)
Depth (0-50cm)					
Collar zone	2	189.6	94.82	5.56	0.00569
Residuals	72	1228.0	17.06		
Depth (50-100cm)					
Collar zone	2	81.4	40.71	5.457	0.00621
Residuals	72	5.7.1	7.46		

Table 5.2: ANOVA summary for pH

	Df	Sum Square	Mean Square	F value	Pr(>F)
Depth (0-50cm)					
Collar zone	2	0.006	0.00323	0.045	0.956
Residuals	72	5.164	0.07172		
Depth (50-100cm)					
Collar zone	2	0.045	0.02249	0.247	0.782
Residuals	72	6.553	0.09101		

Table 5.3: ANOVA summary for EC

	Df	Sum Square	Mean Square	F value	Pr(>F)
Depth (0-50cm)					
Collar zone	2	6015	3008	1.165	0.318
Residuals	72	185808	2581		
Depth (50-100cm)					
Collar zone	2	10272	5136	2.773	0.0691
Residuals	72	133344	1852		

Table 5.4: ANOVA summary for momentarily carbon dioxide flux and temperature

	Df	Sum Square	Mean Square	F value	Pr(>F)
Momentary Carbon dioxide flux					
Collar zone	2	0.437	0.21835	2.529	0.0905
Residuals	47	4.058	0.08633		
Temperature					
Collar zone	2	15.59	73.794	22.14	3.21×10^{-8}
Residuals	72	0.352			

Table 5.5: ANOVA summary for carbon

	Df	Sum Square	Mean Square	F value	Pr(>F)
Depth (0-50cm)					
Collar zone	2	3.91	1.955	0.588	0.558
Residuals	72	239.35	3.324		
Depth (50-100cm)					
Collar zone	2	81.4	40.71	5.457	0.00621
Residuals	72	537.1	7.46		

Table 5.6: ANOVA summary for nitrogen

	Df	Sum Square	Mean Square	F value	Pr(>F)
Depth (0-50cm)					
Collar zone	2	1.308	0.6539	13.34	1.18×10^{-5}
Residuals	72	3.530	0.0490		
Depth (50-100cm)					
Collar zone	2	0.0079	0.00395	0.097	0.907
Residuals	72	2.9225	0.04059		

Table 5.7: ANOVA summary for hydrogen

	Df	Sum Square	Mean Square	F value	Pr(>F)
Depth (0-50cm)					
Collar zone	2	0.393	0.1967	0.978	0.391
Residuals	72	14.483	0.2012		
Depth (50-100cm)					
Collar zone	2	0.342	0.1709	0.483	0.619
Residuals	72	25.453	0.3535		

Table 5.8: ANOVA summary for oxygen

	Df	Sum Square	Mean Square	F value	Pr(>F)
Depth (0-50cm)					
Collar zone	2	6.64	3.320	0.848	0.432
Residuals	72	281.85	3.915		
Depth (50-100cm)					
Collar zone	2	19.0	9.509	1.041	0.358
Residuals	72	657.7	9.135		

Table 5.9: ANOVA summary for CN ratio

	Df	Sum Square	Mean Square	F value	Pr(>F)
Depth (0-50cm)					
Collar zone	2	578.7	289.36	13.16	1.34×10^{-5}
Residuals	72	1582.9	21.98		
Depth (50-100cm)					
Collar zone	2	23.9	11.96	0.5	0.608
Residuals	72	1720.5	23.9		

Table 5.10: ANOVA summary for HC ratio

	Df	Sum Square	Mean Square	F value	Pr(>F)
Depth (0-50cm)					
Collar zone	2	0.0108	0.005391	0.479	0.621
Residuals	72	0.8106	0.011259		
Depth (50-100cm)					
Collar zone	2	0.0356	0.01781	1.04	0.359
Residuals	72	1.2328	0.01712		

Table 5.11: ANOVA summary for OC ratio

	Df	Sum Square	Mean Square	F value	Pr(>F)
Depth (0-50cm)					
Collar zone	2	0.00445	0.002225	0.653	0.523
Residuals	72	0.24522	0.003406		
Depth (50-100cm)					
Collar zone	2	00.0214	0.01072	1.122	0.331
Residuals	72	0.6876	0.00955		

Table 5.12: Summary of Tukey's HSD for soil moisture (0-50cm)

Groups	diff	lower	upper	p adj
HP-FP	-0.6992407	-3.494604	2.0961230	0.8212916
PB-FP	-3.6679808	-6.463345	-0.8726172	0.0068383
PB-HP	-2.9687402	-5.764104	-0.1733765	0.0348111

Table 5.13: Summary of Tukey's HSD for soil moisture (50-100cm)

Groups	diff	lower	upper	p adj
HP-FP	0.870788	-0.977943	2.7195189	0.5005947
PB-FP	-1.642208	-3.490939	0.2065229	0.0917385
PB-HP	-2.512996	-4.361727	-0.6642651	0.0048946

Table 5.14: Summary of Tukey's HSD for temperature (0-50cm)

Groups	diff	lower	upper	p adj
HP-FP	-0.003866667	-0.1851342	0.1774009	0.9985643
PB-FP	0.017466667	-0.1638009	0.1987342	0.9711233
PB-HP	0.021333333	-0.1599342	0.2026009	0.9572412

Table 5.15: Summary of Tukey's HSD for nitrogen

Groups	diff	lower	upper	p adj
HP-FP	-0.01211467	-0.1620001	0.1377707	0.9795912
PB-FP	-0.28598671	-0.4358721	-0.1361013	0.0000590
PB-HP	-0.27387203	-0.4237574	-0.1239867	0.000193

Table 5.16: Summary of Tukey's HSD for CN ratio

Groups	diff	lower	upper	p adj
HP-FP	-0.1413469	-3.315048	3.032354	0.9937573
PB-FP	5.8206529	2.646952	8.994354	0.0001125
PB-HP	5.9619998	2.788298	9.135701	0.0000764