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Doctor's Thesis

Studies on subsidence-related issues under paddy land use in boreal peatlands

（水田利用のなされた泥炭地の地盤沈下に伴う諸課題に関する研究）

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Chapter 1 Introduction

Land plays one of the most essential roles in all human activity, especially for agriculture. Land suitability for agriculture is constrained by natural conditions such as climate, topography and nutrient availability (Zabel et al., 2014), and currently, 4.9 billion ha which is equivalent to 37 % of the total land of the earth is utilized for agriculture in 2014 according to FAOSTAT. Due to these constraints, it is difficult to expand cropland area as actual data shows that cultivated area increased by only 12% from 1961 to 2008 (FAO, 2011). The growth of food production in the 20th century was mostly achieved by yield increase through intensification of agricultural practices such as large machinery introduction, chemical fertilizer, and breeding. By 2050, the world population is projected to reach 9 billion and food production must increase by 70% between 2007 and 2050 to support the population (FAO, 2012). Land resources must be one of the most important factors in a sustainable food production system struck by the growing demand for food. However, land use for agriculture has caused problems. Inappropriate cultivation practices through intensive agriculture have caused severe land degradation related to, for example, soil erosion, soil salinization, land subsidence and desertification, which resulted in diminishing agricultural productivities. Combined with the impacts of climate change, it is projected that substantial arable land will be adversely affected by aridity and soil erosion (Prăvălie et al., 2021). Also, the environment has been affected by land use and land cover change. The contribution of land use and land-cover change to anthropogenic carbon emissions, for example, was about 33 % of total emissions over the last 150 years (Houghton et al., 1999), 20 % of total emissions in the 1980s and 1990s (Denman et al., 2007), and 12.5 % of total emissions over 2000 to 2009 (Friedlingstein et al., 2010). Appropriate land use and management practices will be required to prevent further environmental degradation and to maximize productivity to feed the growing population.

Amongst various types of lands on the earth, peatlands are wetland areas with naturally accumulated layers of plant dead bodies (peat) at the surface under a saturated or water-rich environment. Generally, the accumulation of peat occurs under the condition where the rate of plant production exceeds its decomposition by bacteria or fungi. In terms of soil science, soil in peatlands is classified as "Histosols" in Soil Taxonomy (Soil Survey Staffs, 2014). In the peatland in a cold climate, peat material generally consists of herbaceous plants body such as *Sphagnum*

moss and sedge (*Carex* sp.). These plant materials deposit on the surface of wetlands at the rate of 1-2 mm yr^{-1}, and thus current peatlands with several meters thickness of peat are considered to form through thousands of years. Waterlogging and its unique composition create special and extreme site conditions. These conditions typically include a scarcity of oxygen and an anaerobic environment due to rich water content, spongy-like soft soil that even trees fall over easily under their own weight (Joosten & Clarke, 2002), a scarcity of nutrients which is the result of peat accumulation (by which nutrients are fixed in the peat), a limited nutrient inflow and chemical precipitation (Boyer & Wheeler, 1989). Overall, peatlands have unique characteristics according to their composition, hydrology, and formation process.

Reclamation and drainage for agricultural use of peatlands inevitably cause land surface subsidence. Many examples of subsidence thorough agricultural use of peatlands have been reported all over the world (Drexler et al., 2009; Leifeld et al., 2011; Pronger et al., 2014a; Schipper & McLeod, 2006; van Asselen et al., 2018; Zanello et al., 2011), and subsidence in these cases is usually caused by the combination of peat oxidation, peat compaction and/or peat shrinkage. Subsidence in reclaimed farmlands often leads to social, economic, and environmental troubles. These troubles include reduction of agricultural productivity due to relative groundwater level rise, increased risks of inundation combined with sea-level rise (Zanello et al., 2011), and increased cost to maintain farmland productivity (Gambolati et al., 2006; Wösten et al., 1997). Drain deepening and soil adding to recover farmlands' function may result in further subsidence, and it may lapse into vicious drainage intensification – subsidence cycle. In addition to the problems of agricultural productivity, peat subsidence has significant impacts on the global environment. Drained boreal peatlands are estimated to be causing more than 0.0085 Pg yr^{-1} of carbon emission through the oxidation process of peat substrate (Gorham, 1991), with ensuing indispensable consequences to global climate stability (Parish et al., 2008). Without appropriate management, the economic value of cultivated peatlands may be lost, and external costs may occur due to the above-mentioned subsidence issues.

Several agricultural management methods to mitigate subsidence has been proposed. Submerged drainage pipes that have introduced water from canals to the subsurface of cultivated peatland in the summer season to raise up the groundwater level has effectively reduced subsidence and emission of carbon dioxide (Hoogland et al., 2012). Rewetting of cultivated peatlands such as paludicultrue is also effective to reduce greenhouse gas emissions (Wilson et

al., 2016). Mainly in European contourites, new technologies to mitigate subsidence and carbon emission has developed. Quantitative evaluation of subsidence on peatlands is necessary for proper management of agricultural peatlands, but peat subsidence has large temporal and spatial variability depending on various factors such as depth of the groundwater table, peat type and thickness (Wösten et al., 1997), land use, and time since the reclamation and drainage (Pronger et al., 2014a). Because of various factors involving subsidence processes, generalized projection of peat subsidence is difficult, and therefore measurements in several fields which have been under different conditions (land use, peat type, time since reclamation, agricultural practice, climate etc.) will be required. Analysis and evaluation of various examples of peat subsidence will help the decision-making process in peatland use management.

Numerous studies related to peat subsidence have been conducted to clarify the relationship between environmental factors and subsidence as described in the following Chapter 2. (e.g., Asselen et al., 2018; Erkens et al., 2016; Miyaji et al., 1995; Pronger et al., 2014b; Schipper and McLeod, 2006). Most previous studies on peat subsidence have been focused on time since the installation of the drainage and relation with groundwater table(Hooijer et al., 2006), and few studies have evaluated impacts of land use or land use management on peat subsidence. Especially, subsidence in paddy-use peatlands has been barely reported so far as the majority of the previous studies were conducted in Europe and North America, where peatlands have been utilized for upland fields or grasslands.

In Hokkaido, northern Japan, peatlands cover approximately up to 270,000 ha, accounting for 27 % of total lowland area in Hokkaido. Nearly 70 % of the peatland area has been drained during the past century and converted to agricultural farmlands. The most remarkable point in the agricultural use of peatlands in Hokkaido is that peatlands have been used as paddy fields for rice production, which is a rare case if compared to other countries in the world. Generally, higher groundwater table restrains subsidence, and therefore knowledge of subsidence in paddy peatlands may be important to consider sustainable land use management. To understand dynamics of peat subsidence through paddy use can be helpful for discussion on future agricultural use of peatland including paludiculture. In addition to paddy use, mineral soil dressing for soil physical and chemical improvement has been done in paddy peatlands in Hokkaido, which is also unique if compared to other countries. Impacts of the soil dressing on the peat subsidence have been seldom studied and are still controversial. Furthermore, irrigation

systems such as pipelines and canals to provide water to paddies must be installed to grow rice; however, the effects of peat subsidence on those facilities have been not well documented. To investigate peat subsidence related issues in paddy use peatlands in Hokkaido will provide important insights for future land use in peatlands not only in Hokkaido but also in countries with peatlands around the world.

In this study, we investigated issues related to peat subsidence in Hokkaido, northern Japan, where peatlands have been uniquely cultivated as paddies for rice production to get knowledge about how paddy use affects peat subsidence and what is needed for sustainable paddy agriculture in peatlands. Following the circumstances mentioned above, the objectives of this study are to clarify the effect of paddy use of peatland on subsidence, to understand the impacts of mineral soil dressing in a paddy on peat subsidence, and to grasp the actual situation of subsidence of irrigation faculties on peatland, which have been poorly understood.

In this thesis, a brief review of previous studies related to peat subsidence thorough agricultural land use will be mentioned in Chapter 2 and describe the methodology of this study in following Chapter 3. In Chapter 4, we assess the current agricultural use of peatland in Hokkaido and its impacts on greenhouse gas emissions. In Chapter 5, we discuss the effect of paddy use of peatlands on land subsidence. In Chapter 6, the effect of mineral soil dressing on peat subsidence is evaluated. Subsidence of irrigation pipelines in peatlands is assessed in Chapter 7. Finally, conclusions and discussion toward sustainable use of peatland based on individual studies are provided in Chapter 8.

Chapter 2 Literature Review

2.1 Distribution and Exploitation of Peatlands

The total area of global peatlands is estimated to be 400 million ha which is equivalent to 3 % of the total land area (Charman, 2002). Because it is required for the peat formation process to restrain the activity of decomposition by microbes, peatlands generally occur under cool and humid climates (Joosten & Clarke, 2002), in spite of the exception in some tropical regions (Page et al., 2011). Indeed, at least 80 % of the peatlands are in area with northern temperate or cold climate, 15-20 % are tropical and subtropical and only a few are in a southern temperate or cold climate region (Rydin & Jeglum, 2006). More than 80 % of the boreal peatlands are in Russia and Canada, whereas nearly 80 % of tropical peatlands are in Indonesia and Malaysia (Page et al., 2011; Rydin & Jeglum, 2006). Japan has only a tiny fraction of global peatlands (200 thousand ha, 0.05 % of global peatland) and more than 80 % of them are in Hokkaido. Table 2.1 indicates countries that have a high proportion of peatland with a value of area and coverage.

Due to the above-mentioned extreme environment, peatland had been regarded as barren soil for a long time. Peatlands were utilized for agriculture, forestry and peat harvesting withh the development of agricultural engineering. The earliest uses of peatlands were as hayfields in which people just harvest natural vegetation on peatlands which was used as hay crops. (Rydin & Jeglum, 2006). In the eighteenth century, there was an increase in the rate of land drainage to convert peatlands into grain-growing areas. This happened first in Europe but soon after in North America around the Great Lakes (Rydin & Jeglum, 2006). In the nineteenth century, larger undertakings for drainage and reclamation of cultivated lands such as river regulation, canal construction and large-scale drainage project were conducted. Nowadays, the main kinds of agricultural crops are grasses for haying, silage and pasture, and grains (rye and oat) (Heathwaite & Goettlich, 1993). Vegetables such as carrots, onions, celery lettuce, potatoes and turnip can also be grown with good quality (Ilnicki, 2003; Kreshtapova et al., 2003). In east Asian countries including Japan, rice paddies often occur. In addition to agriculture, forestry has occurred since the 1900s in Baltic states, Russia, the UK, Canada, and Southeast Asia (Paavilainen & Päivänen, 1995). Peat also has been extracted for fuel, materials for horticulture and flavoring for whisky. Peatlands once had been regarded as not suitable land for humans to use, but the huge agricultural effort and technical development turned peatland into economically important lands.

Associated with exploitation by human activities, the area of pristine peatlands (mires) dramatically decreases. It was estimated that Europe has lost over 300 thousand ha of its original mire area which is equivalent to 50 % of peatlands area (Joosten & Clarke, 2002). According to available inventory information, 14 % of the total peatland area in Europe is used for agriculture with the largest area being in Russia, Germany, Belarus, Poland, and Ukraine (Ilnicki, 2003). In the rest of the world, approximately 5 % of peatlands are utilized for agriculture with the largest area being in Indonesia, the USA, and West Malaysia and China (Okruezko, 1996). The greatest areas of peatlands for forestry have been in Finland, Russia, and Sweden (Paavilainen & Päivänen, 1995). Most recently, extensive drainage has occurred in the tropical forest peatlands in Southeast Asia such as Indonesia and Malaysia (Page et al., 2011). Overall, in the non-tropical region, the total area converted from mire have been 25 million ha for agriculture, 15 million ha for forestry and 5 million ha for peat extraction (Joosten & Clarke, 2002). In Hokkaido, Japan, 70.2 % of peatland has been converted mainly into cultivated land between 1928 and 1996 (Fujita et al., 2009). Especially in the central part of Hokkaido, 97.8 % has been reclaimed for agricultural fields (Fujita et al., 2009). Table 2.2. shows the area of peatland drained or converted for agricultural use in the world.

Table 2.1 Countries with a high proportion of peatland and Japan's peatland area. The estimations are cited from the Global Peatland Database of International Mire Conservation Group (IMCG)

Country	Peatland area ($10^3 \, km^2$)	Total area ($10^3 \, km^2$)	Peatland cover (%)
Russia	1,390	17,075	8
Canada	1,235	9,971	12
USA	625	9,629	6
Indonesia	270	1,904	14
Finland	85	338	25
Sweden	66	450	15
Belarus	24	208	11
Ireland	12	70	16
Estonia	10	45	22
Japan	2	378	1

Table 2.2 Peatland areas that are drained or converted for agriculture in the world. These data are not fully compatible with **Table 2.1** due to differences in peatland definition

European Country [a]	Peatlands used for agriculture (km^2)	% of country's peatland	Rest of the world [b]	Peatlands used for agriculture (km^2)	% of country's peatland
Russia	70,400	12	Indonesia	37,200	18
Germany	12,000	85	USA	17,100	16
Belarus	9,631	40	Malaysia	5,769	61
Poland	7,620	70	China	1,930	13
Ukraine	5,000	50	Canada	1,410	1
Sweden	3,000	5	Sarawak	1,370	
Finland	2,000	2			
Netherlands	2,000	85	Hokkaido [c]	1,401	70
Norway	1,905	8			
Lithuania	1,900	8			
Iceland	1,300	13			
Estonia	1,300	12			

[a] The data are cited from Ilnicki (2003)
[b] The data are cited from Okruezko (1996)
[c] The data is cited from Fujita et al. (2009)

2.2 Function and values of peatlands

As mentioned in 2.1, peatlands now have high economic value on agriculture, forestry, and the extraction of peat. The exploitation of peatlands for agriculture or forestry is important to produce food or wood material and to support rural communities in the perspective of socio-economic. However, recently, the value of peatlands as public good has been increasingly focused. Indeed, many studies have reported its function and values as public goods, the wise use of peatlands has been suggested (Joosten & Clarke, 2002). These are public good values that tend to be largely unrecognized by current policy, but which are founded on a variety of ecosystem services which have been classified by the Millennium Ecosystem Assessment in terms of provisioning, regulating, supporting and cultural services (Millennium Ecosystem Assessment, 2005). In this section, we will briefly review these ecosystem services of peatlands, and activities for their conservation.

Table 2.3. shows an overview of the ecosystem services of peatlands and their examples. The provision services include food production by cultivation in peatland and supply of peat

substrate for fuel or horticulture. However, the provision aspects currently are considered not sustainable with current rates and methods of exploitation and extraction (Bullock et al., 2012). Recently, regulating the service of peatlands have attracted huge attention worldwide. A regulating service that is increasing contemporary significance is carbon sequestration. The pristine peatlands are one of net removal of carbon from the atmosphere as the plant material which is constructed by photosynthesis continue to accumulate without decomposition (Botch et al., 1995; Clymo et al., 1998; Gorham, 1991). Though peatlands cover only 3 % of the total global land surface, they store 469.2–486.4 Pg C, which is equivalent to one-fourth of global terrestrial carbon (Fig. 2.1) (Page et al., 2011). A further ecosystem service is moderating the rate of run-off during periods of high rainfall and reducing downstream vulnerability to potentially catastrophic flood events (Holden et al., 2011). Thus, peatlands largely contribute to global climate stability. In addition, peatlands also have supporting services such as maintenance of genetic diversity and wintering habitat for birds (Gibbs, 1993), and also cultural services such as beautiful landscape and tradition related to peatlands (Bullock & Collier, 2011). Several studies have calculated these values as an economic term. For example, from Ireland, a pristine peatland in Ireland had a value of € 101 million per year which was a little smaller value than industrially exploited peatlands, which had a value of € 154 million per year with considering external costs such as carbon emission (Bullock et al., 2012). So, now the non-private value of peatlands has been increasing.

As the high value of peatlands as public goods has been recognized, conservation, restoration and rehabilitation began to be undertaken, but there are, of course, conflicts between conservation and industrial exploitation (Chapman et al., 2006). Several methods have been suggested to restore or conserve peatland, and also agricultural means for low impact on peatland ecosystem services have been proposed (Hendriks & Akker, 2017; J. Price, 1997; Schouwenaars, 1993). Not only technical and scientific points of view but some political and institutional implementations have been conducted. Under the 1992 European Habitat Directive, in Ireland, the government is required to protect various species and natural habitats, including active raised bog, which are of international importance by designating areas as Special Areas of Conservation (SACs) (Bullock et al., 2012). In Japan, restoration and conservation projects have been conducted in some parts of peatlands that have been utilized for agriculture. In Sarobetsu Peatland located in the northern-most part of Japan, all stakeholders including farmers, national and local government, national park rangers, and local NPO discuss for future development of this area and

cooperate to achieve co-existence (Inoue et al., 2017). Since the begging of the 21st century, discussion to maximize the value of peatlands has occurred and is still argued.

Table 2.3 Peatland ecosystem services and their examples

Ecosystem services	Examples
Provision	Provide good quality water, food, industrial and domestic fuel, material for horticulture, and raw materials
	Preserve important archeological evidence under its anaerobic condition
Regulating	Moderate run-off during the period of heavy rainfall
	Regulate local climate condition by its high-water content
	Regulate global climate by its function of carbon sequestration
Supporting	Important habitat for birds and plant
	Support rich biodiversity and genetic diversity
Cultural	Success tradition related to peat such as turf-cutting
	Great landscape

2.3 Peat subsidence

Subsidence is a phenomenon that the level of the land surface gets lowered mainly due to consolidation and tectonics. It has been widely known that peatlands cause subsidence associated with reclamation and drainage for agricultural land use (Miyaji et al., 1995; Pronger et al., 2014a; Schipper & McLeod, 2006; Wösten et al., 1997). Although the magnitude of subsidence varies depending on various factors such as depth of drainage, peat types, and time since initial drainage, the initial subsidence is usually 50 - 100 mm yr^{-1} in temporal and subarctic peatlands, and its rate decreases thorough time since initial drainage. Schipper and MacLeod (2006) reported that subsidence was 137 cm for the 40 years or an annual average rate of 34 mm yr^{-1} since reclamation of the farm in New Zealand. Miyaji et al. (1995) also reported that the total subsidence was about 3 m for the past 40 years which is equivalent to the annual average of 75 mm yr^{-1}, and it continued at the annual rate of 33 mm yr^{-1}. For tropical peatlands, Wösten et al. (1997) reported that nearly 3 m for the past 40 years. Overall, subsidence is one of the most critical side-effects of agricultural use of peatlands globally.

Subsidence in those agriculturally developed areas is mainly caused by the combination

of physical processes and biochemical processes (Schothorst, 1977). The physical processes (densification) include shrinkage due to drying of spongy-like peat substrate and consolidation that compaction of peat substrate related to loss of buoyancy owing to lowering the groundwater table. On the other hand, the biochemical process is a process of peat organic matter decomposition by microorganisms (oxidative decomposition)(Schothorst, 1977). It also causes volume reduction of peat soil, resulting in subsidence. The ratio of contribution of densification and oxidative decomposition to peat subsidence has been discussed in several previous studies. Erkens et al. (2016) estimated the relative contribution of densification, decomposition, and extraction in the Netherlands during the last millennium, and reported that the relative contributions were 19 %, 48 % and 34 % respectively. van Asselen et al. (2018) also reported a wider range of the contributions of densification as 17-65 %, and that of decomposition as 25-71 % respectively, based on their investigation in the Netherlands. They suggested that the contribution of densification increased where the large load such as artificial embankment overlain above peat layers.

It is also well known that the surface of peatland fluctuated seasonally and in shorter time intervals without peat subsidence (J. S. Price & Schlotzhauer, 1999; Roulet, 1991). This reversible oscillation of peat surface ("bog breathing") is caused by shrinkage and expansion of spongy-like peat substrate according to the fluctuations of the groundwater table (Fritz et al., 2008). The reported values by previous studies are around 10 cm of oscillation in natural peatlands (Fritz et al., 2008; J. S. Price & Schlotzhauer, 1999; Roulet, 1991). The oscillation may be smaller in agriculturally managed peatlands because the peat substrate gets dense and solid due to consolidation and shrinkage in cultivated peatlands. Long measurement interval that makes the short-term oscillation of the surface negligible is better to detect actual subsidence.

The dynamics of peat subsidence is determined by several factors. The rate of peat subsidence is generally higher at right after the installation of drainage and land reclamation, and gradually slowing down through time passing since the reclamation (Hooijer et al., 2012; Ilnicki, 2003; Pronger et al., 2014a; Wösten et al., 1997). Pronger et al. (2014) reported that the subsidence rate in 37 years after the reclamation was 26 mm yr^{-1}, and it slowed to 19 mm yr^{-1} in 80 years after the reclamation in Waikato, New Zealand. Grønlund et al. (2008) reported that the subsidence rate has slowed to 9.5 mm yr^{-1} after 50 years since reclamation whereas the initial subsidence rate in the first 25 years was 28 mm yr^{-1} in Norwegian peatland. They also suggested

changes in the process of subsidence from rapid initial consolidation to slower, ongoing, oxidative-dominated subsidence processes (Grønlund et al., 2008; Pronger et al., 2014a).

The groundwater level is also one of the most important factors to determine the biochemical oxidation process of peat subsidence. Generally, a lower groundwater table accelerates the rate of peat oxidation (Hooijer et al., 2012; Schothorst, 1977). Hooijer et al. (2006) proposed the linear relationship between the subsidence rate and the groundwater depth using several peat subsidence data from published works from tropical, temporal, and boreal peatlands. They suggested that deeper groundwater depth induced a higher rate of subsidence though the amplitude of this effect varied according to climatic region. In terms of decomposition of peat substrate, Hirano et al. (2014) reported that the emission of carbon dioxide owing to peat decomposition linearly increased as groundwater level lowered in tropical peatland, employing micro climatic methods. Overall, shallower groundwater level generally reduces subsidence as it inhibits decomposition of peat organic materials, and as they maintain buoyancy to prevent consolidation or compaction of peat by reducing effective stress.

Temperature is another controlling factor. Despite the same groundwater table and time since reclamation, the subsidence rate tends to be lower in the peatlands belonging to cooler climates (Hooijer et al., 2012; Pronger et al., 2014a; Wösten et al., 1997). Pronger et al. (2014) conducted a literature synthesis with globally published work on peat subsidence and suggested that cooler climate may reduce oxidation of peat substrate.

Although land use and land use management may also have an impact on the rate of subsidence, studies that focused on them have rarely been reported. The studies of peat subsidence in the non-tropical region have been conducted mainly in European and North American countries in which peatlands have been utilized as upland fields for grain and hay, and therefore especially knowledge of peat subsidence in paddy land use is lacking. Miyaji et al. (1995) reported that paddy use of peatland has a lower value of subsidence rate than an upland field in Hokkaido, Japan. However, they employed just one field in each land use and only surveyed change of elevation through one year. Kasubuchi et al. (1998) also reported the rate of subsidence in paddy managed peatlands in Yamagata, the north-eastern part of Honshu, Japan was very small, though the survey was qualitative. Knox et al. (2015) suggested that carbon emission from rice paddy was lower than cornfields and pasture in the United States of America, but they did not mention subsidence. It seems to be insufficient to conclude the effect of paddy land use on peat subsidence,

and further long-term quantitative measurement is required.

2.4 Techniques for peat subsidence assessment

The simplest and well-employed method for peat subsidence was just surveying surface elevation change through certain intervals of time at the same point. Measurement of peat depth was also used as it also can be easily assessed. In these methods, relocating the surveying site is one of the constraints (Pronger et al., 2014a) because it is difficult to find exactly the same point after a long time since the first survey. Some studies have measured using a pole that is anchored to deep stable ground, assessed the length from the top of the pole to the ground surface, and compared the temporal change to calculate subsidence (Hutchinson, 1980). The way with pole seemed not to be affected by relocating problems. However, those point-scale measurement is difficult to cover a broad area, though spatial variability of peat subsidence is usually large depending on various factors such as distance from ditches (Gambolati et al., 2006).

Recently, spatial elevation models have been employed for the calculation of peat subsidence to measure spatial subsidence. Gambolati et al. (2006) assessed peat subsidence with the combination of ground-based elevation survey and digital elevation model (DEM) which was established by aerial photographic survey in Venice Lagoon, Italy. Hoogland et al. (2012) calculated the subsidence using point ground survey and DEM constructed by aerial laser survey. Aerial laser survey is currently often employed in tropical peatlands in Southeast Asia for the topological survey (Simpson et al., 2016). Though these spatial elevation surveys by aerial laser have been developed, few studies employed two DEMs for different times established by aerial laser survey. Another tool for spatial elevation surveys is a satellite-based survey. Pronger et al. (2014) suggested interferometry synthetic aperture radar may be useful and not labour-intensive to detect surface elevation change.

2.5 Irrigation pipelines buried in peatlands

As far as the range of our review, reports regarding irrigation facilities in peatlands were found only in Hokkaido. Here, we briefly review the current situation regarding irrigation

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pipelines in Hokkaido. Irrigation systems have been transferred from open channel systems to pipeline in peatlands in Hokkaido to improve the efficiency of water management for agriculture. Pipelines have been often installed in the Ishikari River basin and Furano basin where peatlands are used for paddy rice production. Transformation to the pipeline irrigation system has been still ongoing in the land improvement projects.

Leakage from pipelines buried in peatlands has been reported associated with the subsidence of pipelines due to the poor physical structure of peat. In Shinotsu Peatland located in the lower reach of the Ishikari River basin, the leakage associated with the subsidence has been reported for recent years (Personal communication with Shinotsu Chuo Land Improvement District). Similar cases have been reported also in Furano Peatland located in the middle reach of the Sorachi River basin (Personal communication with the town office of Furano City). Since peat subsidence proceeds thorough time, cases of leakage due to subsidence will increase in future. However, it is difficult to precisely predict the behaviour of the pipes. In Hokkaido, various studies have been conducted to prevent leakage from pipelines on peatlands.

Civil Engineering Research Institute for Cold Region (2016) collected case examples of pipeline failures in peatlands from Land Improvement Districts (farmers' association for water use) that manage the pipelines and reported that the leakage was often found where a longitudinal structure of the pipelines varies such as the intersections with roads and the connection points with other facilities. Sakamoto and Ueya (2021) examined the effect of land use (ie. paddy or upland) of surrounding farmlands on the misalignment of pipelines and suggested that upland land use possibly encouraged the subsidence of the pipelines. Not only observations but also technologies to prevent leakage have been developed by several researchers and institutes. Hideshima et al. (1995) achieved to reduce pipe subsidence by employing cement material as the basement of the pipes instead of rather large load gravels. Suya et al. (1995) reported that wrapping soil surrounding pipelines together with pipes by geotextiles could reduce uneven subsidence of the pipelines. Although knowledge about long-term behavior is needed to consider the design, construction, and maintenance of the pipeline buried in peat soils, most previous studies only collected the leakage cases or observed short-term movement of pipelines. Long-term displacement of pipelines constructed in peatland has scarcely been observed up to this point. In addition, assessment of longitudinal displacement along pipelines' course for the certain section is needed to grasp the non-uniform subsidence of pipelines which should be the

predominant cause of the leakage, but it has not been well studied.

Chapter 3 Study Site Description

3.1 Study Region

Field-based observations for the analysis of peat subsidence related issues were conducted in Shinotsu region, central Hokkaido. Shinotsu Peatland (Fig. 3.1) is in the lower reach of Ishikari River basin. This peatland lays on Tobetsu Town, Shin-Shinotsu Village, Tsukigata Town, and Ebetsu City. Its total area is about 12,000 ha, and currently almost all area has been converted into cultivated land. The mean annual temperature is 7.0 ℃, and the mean annual precipitation is 1,105 mm with 816 cm of snowfall at Shinshinotsu Weather Station. The peat started to accumulate in the middle Holocene, about 6,000 cal BP after the cessation of transgression (Ishii et al., 2017) as same as other peatlands in Hokkaido. Currently, peat deposited 6-7 m thick. The both of bog-type peat and fen-type peat are distributed all over the area, and generally the fen-type peat is surrounding bog-type peat.

We briefly review the history of agricultural development in Shinotsu Peatland. Following description is based onJapan's Society of Irrigation and Drainage (1995). This area had been highly affected by flooding induced by snowmelt and heavy precipitation, and it had been difficult to reclaim to cultivated land for long time. The first attempt of reclamation was in 1882 by people in 91 households coming from Miyagi Prefecture. However, they straggled bad condition of the peatland, and full-scale reclamation had not been conducted until the middle 1920s. By 1935, systematic large-scale drainage for 5,048 ha of peat area was conducted, but still large area remained barren wild peatland. After the second world war, 11,700 ha of land were converted into paddy fields in 1960s funded by World Bank. Spending 21 billion yen which is equivalent to 83 billion yen in the current value, the area was successfully developed into paddy, and it has contributed to Hokkaido agriculture so far.

The main crops in this area are currently paddy rice, wheat, soybean and vegetables. Originally, the area converted to paddy, but the area producing upland crop such as wheat have been increasing under rice acreage reduction policy by the national government since 1971. Table 3.1. shows the cultivated area for each crop in the 4 municipalities in Shinotsu Peatland in 2015. As it shows, more than 50 % of the total cultivated area is used for upland crops. In terms of value of agricultural production, the rice contributes large proportion (Table 3.2.).
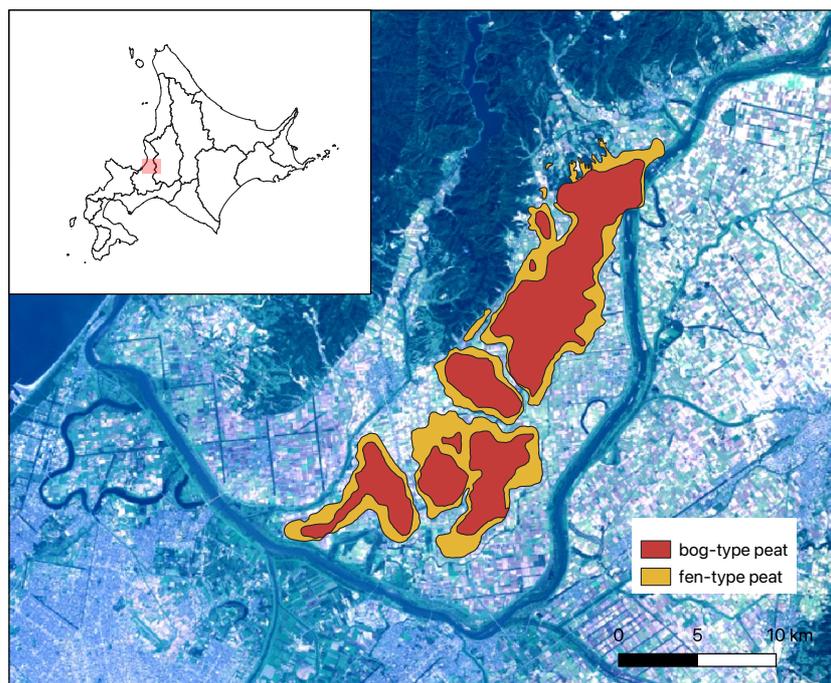
Fig. 3.1 The location of Shinotsu Peatland and peat distribution. The background aerial image is cited from Geospatial Information Authority of Japan.

Table 3.1 Cultivated area for rice, wheat and soybean in 4 municipalities in Shinotsu Region. The data are cited form Census of Agriculture and Forestry by Ministry of Agriculture, Forestry and Fishery Japan. Each crop percentage indicates ratio of area for the crop to the total cultivated area.

Municipality	Rice (ha) % Rice	Wheat (ha) %Wheat	Soybean (ha) % Soybean
Ebestu	1,137	1,733	420
	16 %	25 %	6 %
Tobetsu	1,675	3,327	444
	23 %	46 %	6 %
Shin-shinotsu	2,347	1,394	507
	50 %	30 %	11 %
Tsukigata	1,129	334	292
	43 %	13 %	11 %

Table 3.2 Total agricultural production and the contribution of each crop (million yen / yr) in 4 municipalities in Shinotsu Region. The data are cited form Census of Agriculture and Forestry in 2015 by Ministry of Agriculture, Forestry and Fishery Japan.

Municipality	Total (mi. ¥)	Rice (mi. ¥)	Wheat (mi. ¥)	Soybean (mi. ¥)
Ebestu	6,930	1,030	190	190
Tobetsu	4,910	1,800	470	200
Shin-shinotsu	4,070	2,260	210	210
Tsukigata	3,060	1,310	40	110

3.2 Study field plots

We used 50 field plots located in Kamishinotsu and Takakura Distirict in northern part of Shinotsu Peatland for the investigation on subsidence dealt in chapter 5 and chapter 6 (Fig. 3.2). This area had been developed to paddy field until early 20th century. The field plots have been cultivated as multipurpose paddy where both rice and upland crops are grown. So, the farmlands have been used for the mixed production of paddy, wheat, soybean, and vegetables. Most of the field plots are on the fen-type peat soil, with small exception on bog-type soils and peaty silt soils according to the soil map.
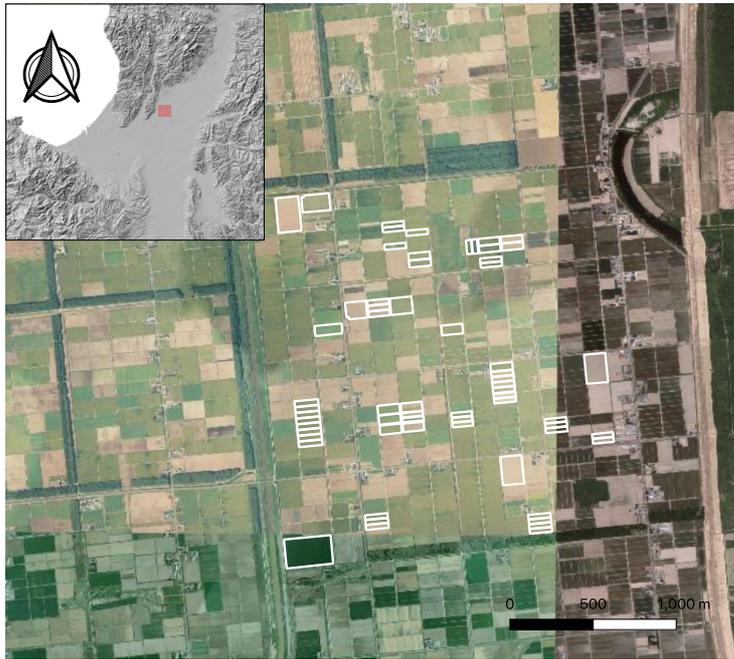
Fig. 3.2 The 50 field plots for subsidence investigation. The background aerial image is cited from Geospatial Information Authority of Japan.

Chapter 4 Assessment of the current agricultural use of peatlands in Hokkaido and its impacts on greenhouse gas emission

4.1 Introduction

Peatlands on the earth play an important role in terrestrial carbon storage. Though peatlands cover only 3 % of the total global land surface, they store 469.2–486.4 Pg C, which is equivalent to 15-20% of organic carbon in soils worldwide (Page et al., 2011; Parish et al., 2008) and is almost equal amount to the atmospheric carbon pool. This carbon deposited in peat is a result of unbalance of input primary production of plant and loss by decomposition due to water-saturated anoxic condition. Although natural peatlands act as sources of methane which has large global warming potential, they are regarded to have a net cooling impact on the atmosphere over longer periods (Frolking et al., 2006).

Peatlands have been reclaimed and developed for various human activities such as crop production, dairy farming and forestry, and peat itself was exploited for fuels and horticultural materials. It was estimated that Europe has lost over 300 thousand ha of its original mire area which is equivalent to 50 % of the peatlands area (Joosten & Clarke, 2002). In the rest of the world, approximately 5 % of peatlands are utilized for agriculture with the largest area being in Indonesia, the USA, and West Malaysia and China (Okruezko, 1996). In Hokkaido, northern Japan, peatlands have been also reclaimed for agriculture, and more than 70 % of the originally natural peatland area has been lost (Fujita et al., 2009). To use peatland for agriculture, drainage must be involved to withdraw excess water from fields. The drainage exposes organic materials which have accumulated under an anoxic environment to oxygen. It allows accelerating oxidative decomposition of peat resulting in large and continuous loss of carbon. The contribution of drained peatlands to anthropogenic greenhouse gas emissions is substantial. Globally total emissions from drained peatlands were $1.1 – 1.5$ Gt CO_2 yr^{-1}, which represent approximately 30 % of greenhouse gas emission from whole the forestry and land use sector, and 6 % of total anthropogenic greenhouse gas emissions (Smith et al., 2014). To reduce the emission from peatlands is one of the major challenges for land use and land use change sector.

United Nations Framework Convention on Climate Change (UNFCCC) requires the state parties to the convention to submit a greenhouse gas inventory that describes annual

anthropogenic greenhouse gas emissions in the nations. The inventory must follow the UNFCCC reporting guidelines. Generally, the emissions from drained peatlands are reported in land use, land-use change and forestry (CRF sector 4).

In Japan, the Ministry of Environment documents the inventory every year. In the inventory, the emission from organic soils (peatlands) is reported following the guidelines. In the process of the calculation of the emission from organic soils, they classified the cropland on peat soils to paddy and upland cropland based on land registration, and estimated greenhouse gas emission by multiplying the area by the emission factor for each land use which is given in the guidelines. However, the registered land use and actual land use are not consistent because lands originally registered as paddy have been transformed to upland cropland due to the set-aside policy for the overproduction of rice. The reported greenhouse gas emission in Japan's greenhouse gas inventory may have errors caused by the inconsistency between the registered land use and the actual land use.

In addition to the problems on the classification of land types, Japan's greenhouse gas inventory seems to have a critical misunderstanding on emission from grasslands on organic soils. In the section of grassland on organic soils in the inventory, it regards only grassland with renewal practices such as ploughing and seeding as the source of greenhouse gas emission. Therefore, the inventory ignored drained grassland without renewal practice at all. This treatment is totally unreasonable because only drainage of peat soil emits a significant amount of carbon dioxide regardless of the renewal activities. To account all emission from the grassland on peat soil, indeed, the IPCC current guidelines obligate the party nations to calculate the emissions from all peatlands under agricultural drainage activities (Verchot et al., 2006). In terms of this point, Japan's greenhouse gas seems to be against the IPCC guidelines resulting in the lack of accuracy.

In this study, we assess the land use of peatlands in Hokkaido with satellite image remote sensing and estimate CO_2 emission from them more accurately than Japan's greenhouse gas inventory. We also discuss the contribution of the emissions from the peatlands based on our estimates to the total anthropogenic emission from Hokkaido. In addition, we indicate the impropriety of Japan's greenhouse gas inventory.

4.2 Materials and Methods

4.2.1 Dataset

4.2.1.1 Distribution of peatlands

We used the series of 1:200,000 maps of the basic soil type classification survey conducted by the national government of Japan in 1967 to 1978 (Ministry of Land, Infrastructure, Transport and Tourism of Japan) to grasp the distribution of peat soils. Soils classified to peat soils were targeted by land use classification in this study. Though the peat soils are distributed across the entire region of Japan, we focused on the peatlands in the main island of Hokkaido (Fig. 4.1).
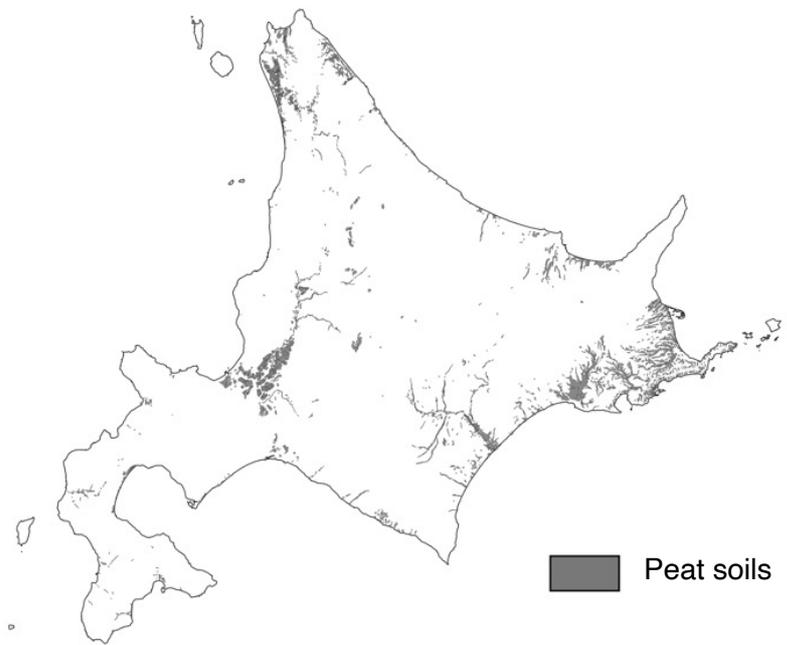
Fig. 4.1 Distribution of peat soil in the main island of Hokkaido. The data source is the series of 1:200,000 maps of the basic soil type classification survey conducted by the national government of Japan from 1967 to 1978.

4.2.1.2 Distribution of agricultural lands

We used field plots polygon data for investigation of areas of farmland by the Ministry of Agriculture, Fishery and Forestry (MAFF) as farmland area data. Combined with data of peat soil distribution, we extracted field plots on peat soils employing GIS application (QGIS). The example of field plots polygon data in the Ishikari River basin is shown in Fig. 4.2. All the field

plots on peat soils in Hokkaido were used for the land use classification and the estimation of greenhouse gas emissions.
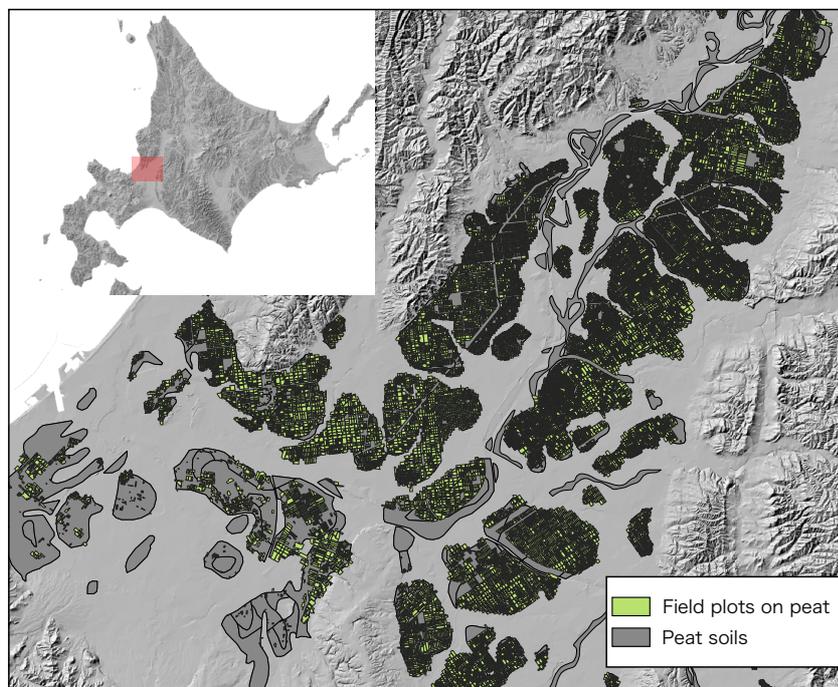
Fig. 4.2 The example of field plots polygon data in the Ishikari River basin.

4.2.2 Land use classification

The extracted field plots were classified into three land use categories: rice paddy, upland cropland, and grassland. The upland cropland included the plots which were transformed from the rice paddies. The process of the classification was divided into two parts. In the first step, we detect rice paddy using satellite images. In the second step, the rest plots are divided into the upland cropland and grassland using area statistics by MAFF. In this study, we classified the plots based on their land use in 2020.

In the first step to detect rice paddies, we used satellite images captured by optical sensors. The inundation since onset of rice transplantation is the key feature to identify the paddy rice fields, as paddy is the only crop that requires to be transplanted in a flooded soil environment in this region. Previous studies have suggested that the relationship between land surface water index (LSWI) and vegetation indexes such as normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI) can efficiently discriminate inundated paddy. (Boschetti et al., 2014; Dong et al., 2016; Xiao et al., 2002). As Dong et al. (2016) suggested, we applied the simple

criteria that are LSWI > NDVI or LSWI > EVI to detect flooded paddy field plots. The spectral indices were calculated using the following equations:

$$NDVI = \frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + \rho_{RED}}$$

$$EVI = 2.5 \times \frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + 6 \times \rho_{RED} - 7.5 \times \rho_{blue} + 1}$$

$$LSWI = \frac{\rho_{NIR} - \rho_{SWIR}}{\rho_{NIR} + \rho_{SWIR}}$$

where ρ_{blue}, ρ_{red}, ρ_{NIR}, and ρ_{SWIR} are the surface reflectance values of the blue band (Band 2; 0.493 μm), red band (Band 5; 0.705 μm), the near-infrared band (Band 7; 0.775 μm), and shortwave-infrared (Band 11; 1.610 μm) in Sentinel-2A sensors. For the determination of those indices, we used satellite images taken at the end of May to early June by Sentinel-2A. The spatial resolution of Sentinel-2A images was 10 to 20 m depending on the spectral bands, and the field plots generally covers several tens of pixels of the images. We averaged each surface reflectance value within the plots, and the indices were calculated with the average values for every single plot for the analysis. Finally, the criteria of LSWI > NDVI or LSWI > EVI was applied for each field plots to detected flooded paddy plots for rice transplantation. Validation of this method was not conducted because Dong et al. (2016) reported that the overall accuracy of this method was 97 %, which is precise enough to apply to this study.

In the second step for classification of upland cropland and grassland, we use statistics of cropland area in the Census of Agriculture and Forestry by MAFF of Japan because it is difficult to distinguish these two types of land use with satellite images due to the lack of key state in land cover like paddy. The rest of the field plots after the detection of rice paddies are divided into the upland cropland or the grassland according to the ratio reported in the census. The process of the division was done for each municipality because the ratio of the upland cropland or the grassland could be calculated for each municipality in the census.

The area of the three types of land uses was calculated in the GIS application. QGIS was employed in this study.

4.2.3 Estimation of greenhouse gas emission from agricultural peatlands

The area of the three types of land use was multiplied by each emission factor which represents the CO_2 emission per unit area to estimate CO_2 emission from agricultural peatlands in Hokkaido. We used the same emission factor as those in the greenhouse gas inventory of Japan. The factors are 1.6 t C ha^{-1} yr^{-1} for rice paddy, 4.2 t C ha^{-1} yr^{-1} for upland cropland, and 6.1 t C ha^{-1} yr^{-1} for grassland. The emission factors for the paddy and upland cropland are based on the studies in peatlands in Japan (Greenhouse Gas Inventory Office of Japan & Ministry of the Environment of Japan, 2021), whereas the factor for grassland is default value in the IPCC guidelines (temperate grassland, deep drained, nutrient-rich) (IPCC, 2014).

4.3 Results

4.3.1 Land use of peatland in Hokkaido

According to the series of 1:200,000 maps of basic soil classification survey, peat soil covered 274,000 ha, which was equivalent to 3 % of the total area of Hokkaido. Amongst 14 subprefecture in Hokkaido, Kushiro subprefecture had the largest area of peatlands in Hokkaido. 75 % of peatlands was distributed concentratedly in 5 subprefectures, which were Ishikari, Sorachi, Soya, Kushiro, and Nemuro.

In total, 114,000 ha out of 274,000 ha was used for agriculture. The value only included cultivated area and excluded the farm roads, irrigation facilities, and windbreak forest. Sorachi subprefecture had the largest area (22,700 ha) of the agricultural peatlands, followed by Soya subprefecture (15,400 ha) and Ishikari subprefecture (14,900 ha). In Sorachi, more than 75 % of peatlands have been used for cultivation, whereas only 14 % has been used in Kushiro. The agricultural usage rate of peatlands varied widely depending on the region. Based on the results from classification by satellite images, the use as rice paddy contributed 18,000 ha accounting for 16 % of agricultural use of peatland in Hokkaido. An example of the field scale classification by satellite images is shown in Fig. 4.3. The rest of the agricultural peatlands were divided into 46,000 ha of the upland cropland accounting for 40 % and 49,000 ha of the grassland accounting for 44 %. The land use as rice paddy often occurred in central Hokkaido such as Sorachi, Ishikari, and Kamikawa subprefectures. On the other hand, grassland use was predominant in the eastern and northern parts of Hokkaido, such as Soya, Kushiro and Nemuro subprefectures. Fig. 4.4 and

Table 4.1 represent the area and land use of peatlands in agricultural use for each subprefecture.
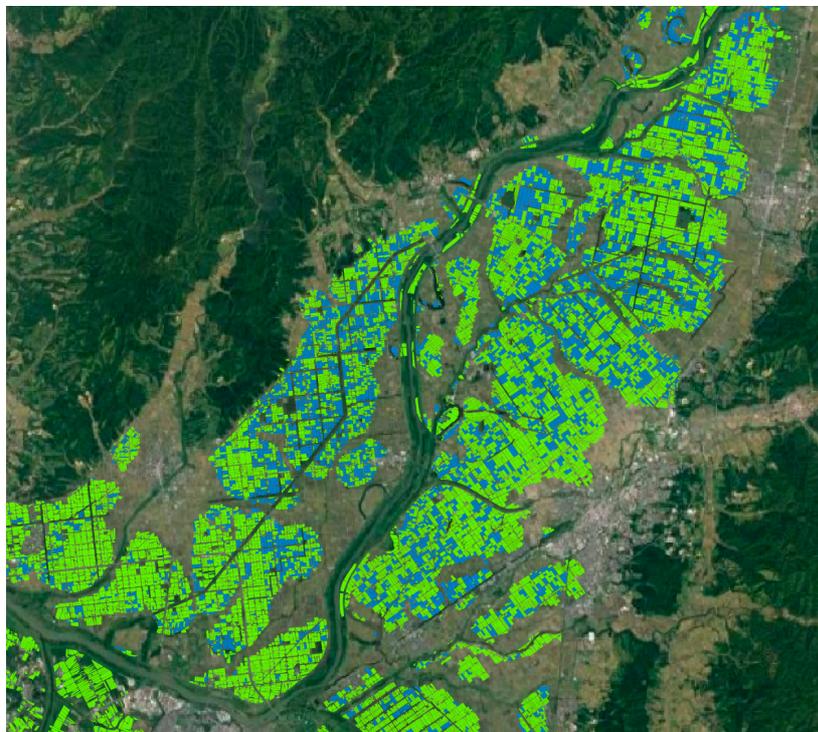
Fig. 4.3 Field polygon-based classification of agricultural use peatlands in part of Ishikari and Sorachi subprefecture. The polygons with blue colour and green colour represent rice paddy and non-paddy (upland cropland or grassland), respectively.
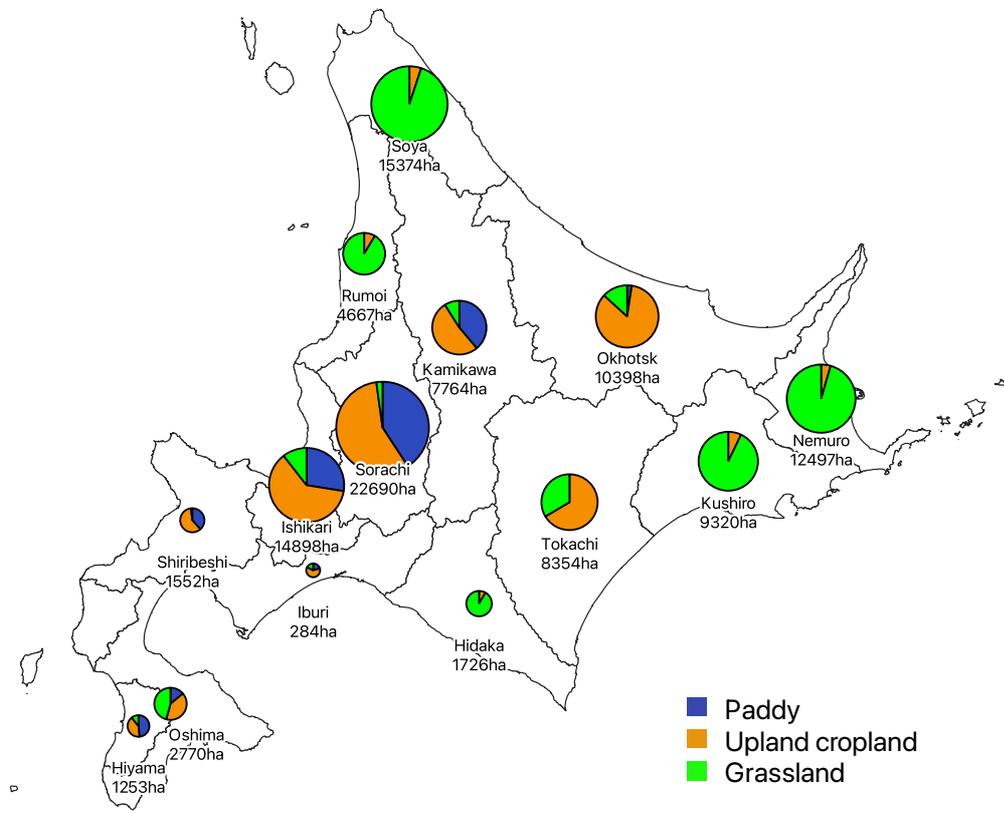
Fig. 4.4 Distribution and land use of agriculturally used peatlands in Hokkaido sorted by the subprefectures. The size of pies represents the total area of agricultural peatlands for each subprefecture. The division of the pies represents the ratio of each land use. The area shown below the pies represents the total area of agricultural peatlands.

Table 4.1 Distribution and land use of peatlands in agricultural use in Hokkaido sorted by the subprefectures.

Subprefecture	Total (ha)	Rice Paddy (ha)	Rice Paddy (%)	Upland Cropland (ha)	Upland Cropland (%)	Grassland (ha)	Grassland (%)
Tokachi	8,354	0	0	5,551	66	2,802	34
Kushiro	9,320	0	0	662	7	8,658	93
Nemuro	12,497	0	0	556	4	11,941	96
Hidaka	1,726	0	0	144	8	1,582	92
Iburi	284	59	21	176	62	49	17
Ishikari	14,898	4,107	28	9,230	62	1,560	10
Sorachi	22,690	9,264	41	12,944	57	482	2
Kamikawa	7,764	3,023	39	4,052	52	690	9
Rumoi	4,667	4	0	398	9	4,265	91
Soya	15,374	0	0	774	5	14,600	95
Oshima	2,770	389	14	1,115	40	1,266	46
Hiyama	1,253	610	49	508	41	136	11
Shiribeshi	1,552	596	38	929	60	27	2
Okhotsk	10,398	249	2	8,780	84	1,369	13
Total	113,547	18,300		45,820		49,427	

4.3.2 Estimation of CO_2 Emission from Peatland of Hokkaido in Agricultural Use

The peatland area for each land use, which is determined in 4.3.1, was multiplied by the emission factors for individual land covers to estimate CO_2 emission. The total emission from the entire agricultural peatlands in Hokkaido was estimated to be 1,919,000 t CO_2 yr^{-1}. 107,000 t CO_2 yr^{-1} was from the rice paddy, 706,000 t CO_2 yr^{-1} was from the upland cropland, and 1,106,000 t CO_2 yr^{-1} was from the grassland

.

Table 4.2 Estimation of CO2 emission from peatland of Hokkaido in agricultural use.

Land use	Area (ha)	Percentage (%)	CO_2 emission (t CO_2 yr^{-1})
Rice paddy	18,300	16	107,000
Upland cropland	45,820	40	706,000
Grassland	49,427	44	1,106,000
Total	113,547	100	1,919,000

4.4. Discussions

4.4.1 Comparison with the greenhouse gas inventory of Japan

The greenhouse gas inventory of Japan deals with the entire country whereas this study treated only Hokkaido. Although it may be inadequate to compare our results with the inventory due to the difference in the focused range, we will discuss the inconsistency between our findings and the inventory within the possible range of the comparison.

The greenhouse gas inventory of Japan indicated that the total area of cropland and grassland on organic soils under anthropogenic activities in "the entire region of Japan" was 213,800 ha (175,700 ha of cropland and 38,100 ha of grassland) (Greenhouse Gas Inventory Office of Japan & Ministry of the Environment of Japan, 2021). Our results indicated that the total area of agricultural peatlands in "Hokkaido" was 114,000 ha which is not immediately inconsistent with the inventory. However, the inventory suggested that there is only 16,100 ha of upland cropland on organic soils in "the entire region of Japan" though our results implied that there is 46,000 ha of upland cropland in "Hokkaido" alone. This large inconsistency could be attributed to the transformation of paddies to upland croplands due to the set-aside policy and encouragement of multipurpose use of paddies. The substantial underestimate of the area of upland cropland and overestimation of rice paddies on organic soils can cause a significant misunderstanding of greenhouse gas emission because the emission factors of rice paddy and upland cropland are far different. In the case of the inventory of Japan, the inconsistency of land use possibly resulted in the underestimation of the greenhouse gas emission.

Another inconsistency between this study and the inventory was related to the treatment of the grassland. In the inventory, the grasslands which were renewed with ploughing and seeding in the reported year were regarded as the source of greenhouse gas. So, they calculated active area by multiplying the renewal ratio of grassland by the area of organic soils in the grassland. According to the inventory, the renewal ratio of the grassland is 3% in Hokkaido based on Hatano (2017), and therefore they regraded only 3% of grassland emitted anthropogenic greenhouse gas. However, the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Chapter6, Volume 4) describes that drainage stimulates oxidation of organic matter at about the same rate after exposure to aerobic conditions, regardless of the management system (Verchot et al., 2006). According to the guidance, the grassland on drained organic soil must be included in the active area regardless of the renewal activities. This misunderstanding caused the significant

underestimation of greenhouse gas emissions because the emission factor of grassland was quite large.

As a result, the inventory reported that the CO_2 emission from agricultural organic soils was 1,193,000 t CO_2 yr^{-1} in "the entire region of Japan" (Greenhouse Gas Inventory Office of Japan & Ministry of the Environment of Japan, 2021). In contrast, our analysis which had been consistently calculated by the IPCC guidelines suggested that the CO_2 emission from agricultural organic soils was 1,919,000 t CO_2 yr^{-1} in "Hokkaido" alone. This gap which reaches almost double was attributed to the ignorance of the set-aside of rice paddy and misunderstanding of the active area of grassland. Although we did not compare the emission in the whole country, the inventory certainly underestimated the emission from organic soils.

4.4.2 Contribution of emission from peat soil to the total emission in Hokkaido

According to the report by Hokkaido government, the total annual emission from Hokkaido was 72,890,000 t CO_2(Hokkaido Government, 2021). The contribution of the emission from peatlands based on this study was estimated to be 2.6 %. Although it was not substantial, it contributed largely to the scope of agricultural sector. The emission from agricultural sector in Hokkaido was estimated to be 640,000 t CO_2 yr^{-1} excluding the emission from agricultural peatlands(Hokkaido Government, 2021). The emission from peat soil revealed by out study was much larger than that value. Therefore, the peatlands could be the largest component of the emission from agricultural sector in Hokkaido. To prevent further emission, practical interpretation is strongly required.

4.5 Conclusion

In this study, we assess the actual land use of peatlands in Hokkaido with satellite image remote sensing and then estimated CO_2 emission from them more accurately than Japan's greenhouse gas inventory. The results showed that the emission from organic soils reported in Japan's greenhouse gas inventory was obviously underestimated. The contribution of the emission from peatlands based on this study was estimated to be 2.6 % of the total anthropogenic CO_2 emission from Hokkaido, and it could be the largest component to the emission from the agricultural sector in Hokkaido. Preventing emissions from peatlands is one of the critical

challenges to agriculture in Hokkaido to achieve sustainable agriculture. Practical interpretation to reduce the emission is strongly required with consideration of the situation of all stakeholders. This assessment will be helpful to consider the future use of peatland in Hokkaido.

Chapter 5 Effect of Paddy Land Use on Peat Subsidence

5.1 Introduction

Peatlands, in the past, were originally considered to have low economic value for agriculture as they were too humid to grow up crops, and therefore intensive drainage has been installed to peatlands to make it possible to produce agricultural products. Drainage and land reclamation for agricultural use of peatlands, however, inevitably causes ongoing land surface subsidence. Many examples of subsidence thorough agricultural use of peatlands have been reported from all over the world (Leifeld et al., 2011; Pronger et al., 2014b; Schipper & McLeod, 2006; Zanello et al., 2011). Subsidence in reclaimed farmlands often lead to social, economic, and environmental troubles including reduction of agricultural productivity due to relative groundwater level rise, increased risks of inundation combined with sea-level rise (Zanello et al., 2011), and increased cost to maintain farmland productivity(Gambolati et al., 2006; Wösten et al., 1997). Additionally, drained boreal peatlands are estimated to be causing more than 0.0085 Pg yr^{-1} of carbon emission through the oxidation process of peat substrate (Gorham, 1991), with ensuing indispensable consequences to global climate stability (Parish et al., 2008). Without appropriate management, not only will the agricultural economic value of cultivated peatlands be lost, but also the whole society will be adversely affected by the subsidence related problems. Hence, appropriate land use management on agricultural peatlands is strongly required.

Recently, several techniques of land use management on cultivated peatlands have been proposed to mitigate further subsidence and greenhouse gas emission. Although numerous processes contribute to peatland surface subsidence, the major causes of agricultural peat subsidence are oxidative decomposition of peat substrates and physical densification (compaction and consolidation) of peat. Higher groundwater level generally reduces decomposition of peat substrate and effective stress on peat by increased buoyancy, and therefore, maintaining the water table high with rewetting and submerged infiltration of water has been regarded as a promising option (Hendriks & Akker, 2017). Paludiculture, the agricultural use of wet or rewetted peatlands mainly for biomass production, has been discussed as a solution to the subsidence related problems in peatlands. It may effectively reduce the decomposition of organic material and, is acknowledged as a possible land use option on organic soils as it combines the production of bioenergy and simultaneously retains the peat substrate. As a result, the IPCC Wetland supplement

acknowledges paludiculture as a possible land use option for the mitigation of GHG emissions from organic soils. However, paludiculture in the EU has conflict with conventional agriculture because the products from paludiculture are mainly for bioenergy and fibre materials not for food. To avoid the conflict with food security is one of the major challenges to realizing paludiculture.

Several studies have reported the effects of paludiculture on carbon balance with economic evaluation. Günther et al. (2015) suggested that *Phragmites* and *Typha* paludiculture successfully reduced net GHG emissions and achieved net climate neutrality. In addition to the assessment of environmental impacts, an economic analysis of paludiculture has been conducted because the practice must be feasible and economically competitive with conventional practices for land users, who are mostly farmers. de Jong et al. (2021) implied that the paludicultural practice with cattail cultivation for insulation materials is not yet competitive with dairy production in Netherland due to high cultivation costs and low revenues of cattail. They suggested that improvement in business such as the application of carbon credits is needed. Although knowledge about paludiculture has been reported from various perspectives, few studies have documented long-term records of peat subsidence through agriculture in wet peatlands because the implementation of paludiculture has evolved only in recent years.

In Hokkaido, northern Japan, peatlands cover approximately up to 270,000 ha. Nearly 70 % of the peatland area has been drained during the past century and converted to agricultural farmlands mainly for pasture, upland crop production and rice paddy. Some of those peatlands have been cultivated as multi-use paddy fields (rotational cultivation of paddy rice and upland crop), one form of paludiculture, for more than a half-century. It is a very unique way to use peatland when compared with other countries. Paldiculture with rice cultivation does not conflict with food production, unlike bioenergy and insulation material production. Also, paludiculture with rice paddy is economically competitive as rice is stapled crop for Japanese people. Therefore, it could be a feasible option for peatland use in Hokkaido.

In paddy fields, the groundwater table maintains near the ground surface or above during the summer irrigation period, so the subsidence in paddy is expected to slow due to the reduction of decomposition of peat substrate. Some studies, indeed, suggested the possibility of a lower rate of peat subsidence in paddy fields compared to upland fields in Hokkaido (Kasubuchi et al., 1998; Miyaji et al., 1995), yet the number of observations in those studies quite small. Knox et al., (2015) and Knox et al. (2016) reported in terms of carbon balance that the net annual GHG

emissions from rice paddy were smaller the that from pasture and corn cultivation, which implied the decomposition of peat might be small in paddy. Although a small number of subsidence observations and the short-term assessment of GHG flux suggested that paddy might reduce subsidence rate with a low rate of decomposition of peat, quantitative evaluation of the effect of paddy use on peat subsidence with long-term numerous observations has not been done yet.

Here, we present the first quantitative comparison of the long-term peat subsidence rates between paddy and upland fields in Hokkaido to assess the potential of agricultural use of wet peatlands as a solution of peat subsidence-related problems. This study will provide an essential suggestion for future land use in Hokkaido and also key knowledge for the attempt of the paludicultural use of peatlands worldwide as well.

5.2 Materials and methods

5.2.1 Study site

The investigation of peat subsidence was conducted in Shinotsu Peatland (Fig. 5.1; 43°13′ N, 141°36′ E), central Hokkaido, Japan. Its total area is about 12,000 ha, and currently, almost all area has been converted into cultivated land. The mean annual temperature is 7.0 °C, and the mean annual precipitation is 1,105 mm with 816 cm of snowfall at Shin-Shinotsu Weather Station of Japan Meteorological Agency. Currently, peat deposited 6 to7 m thick. Both bog-type peat and fen-type peat are distributed all over the area, and generally, the fen-type peat is surrounding the bog-type peat.

The peatland has been cultivated as multi-use paddy fields (rotational cultivation of paddy rice and upland crop) (Fig. 5.2), and the main crops in this area are currently paddy rice, wheat, soybean, and vegetables. Initially, the area converted to paddy, but the area that is producing upland crop such as wheat have been increasing under the situation of overproduction of rice and the implementation of the set-aside policy by the national government since 1971. In the paddy fields, the ground surface is always saturated with irrigation water between middle May and middle August. Both the paddy and the upland fields have drainage ditches and subsurface drainage systems to maintain a suitable groundwater table for the crops, so either paddy rice or upland crops can be grown by the combination of irrigation and drainage systems.

We used randomly selected 50 field plots for the analysis to assess the effect of the land

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use form (paddy or upland) on peat subsidence. The 50 filed plots belonged to the same township, and the conditions such as the time since reclamation and the peat type were not different except the land use form.

Fig. 5.1 The study area. The red boundary line in the right figure represents the range of the DEM. The orange square in the left figure indicates the location of the study site in Shinotsu Peatland. Red rectangles indicate the targeted field of this study. The background aerial photo is from the Geospatial Information Authority of Japan.

5.2.2 Subsidence measurement

Digital elevation models (DEMs) acquired by airborne laser surveys were employed for the measurement of subsidence. Those DEMs were provided by Hokkaido Reginal Development Bureau. The spatial resolution of the DEMs was 1 m × 1 m. The spatial subsidence model which represents subsidence of this region between 2006 and 2017 was established by subtracting the DEM of 2017 from the DEM of 2006 using GIS software (QGIS). The subsidence rates of each targeted field were calculated based on the regional subsidence model by averaging subsidence in each mesh within the fields. The DEM of 2006 which was based on the airborne laser survey in July has an error due to vegetation height in some field plots, so those plots were excluded from the analysis. This was the reason why we chose only 50 field plots for the investigation not all the plots in the DEMs.

5.2.3 Reconstruction of the history of land use form

 We used satellite images that were taken by the optical sensors. The satellite included Land Sat 5 TM, Land Sat 8 TM and Sentinel-2. We employed the bands of visible red (R), near-infrared (NIR) and short-wave infrared (SWIR). The reflection of bands of electric waves on the ground surface varies depending on the land cover because each land cover has a different spectral reflection characteristic (Fig.5.2). Water can absorb all bands, so reflectance of R, NIR and SWIR are usually low. The green vegetation highly reflects NIR, but less for R and SWIR. Soil can highly reflect SWIR, but less for R and NIR. Utilizing these characteristics, we can distinguish land cover.

 Here we briefly describe detail about the method. Firstly, we collected satellite images of the R, NIR and SWIR bands between the end of May and early June. In this period in Shinotsu Peatland, the status of land can be divided into three types: bare land, wheat-growing land, and inundated paddy field before or right after the transplanting. Thus, we can easily classify these three land covers using the above method. The next was to composite these three bands' images into one coloured (Red, Green, Blue) image using GIS software. We assigned R, NIR and SWIR into Blue, Green, and Red respectively. Then, paddy was coloured dark black because it seldom reflected these bands. The wheat-growing land was coloured light green because it reflected NIR highly. The bare land was coloured pink as it highly reflected SWIR and intermediately reflected NIR. Finally, we classified each field plot into the above three categories according to the colour of the image for each year. We regarded the bare land and the wheat-growing land as upland fields.

 Band 5 (1.55 - 1.75 µm; SWIR), Band 4 (0.76 - 0.90 µm; NIR) and Band 3 (0.63 - 0.69 µm; R) of Land Sat 5 TM were used. Also, Band 6 (1.560 – 1,660 µm; SWIR), Band 5 (0.845 – 0.885 µm; NIR) and Band 4 (0.630 – 0.680 µm; R) of Land Sat 8 TM, as well as Band 11 (1.610 µm; SWIR), Band 7 (0.775 µm; NIR), and Band 5 (0.705 µm; R) of Sentinel 2 were used. Detailed information about employed satellites for each year is in Table 5.1. We reconstructed land cover between 2006 and 2017, excluding 2012 and 2017 due to lack of satellite image.

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Table 5.1 Data set of satellite images for land cover classification

Year	Date of satellite image	Satellite
2006	25 May	Landsat-5 TM
2007	28 May	Landsat-5 TM
2008	1 July	Landsat-5 TM
2009	25 June	Landsat-5 TM
2010	12 June	Landsat-5 TM
2011	30 May	Landsat-5 TM
2013	4 June	Sentinel-2A
2014	31 May	Sentinel-2A
2015	25 May	Sentinel-2A
2016	23 May	Sentinel-2A
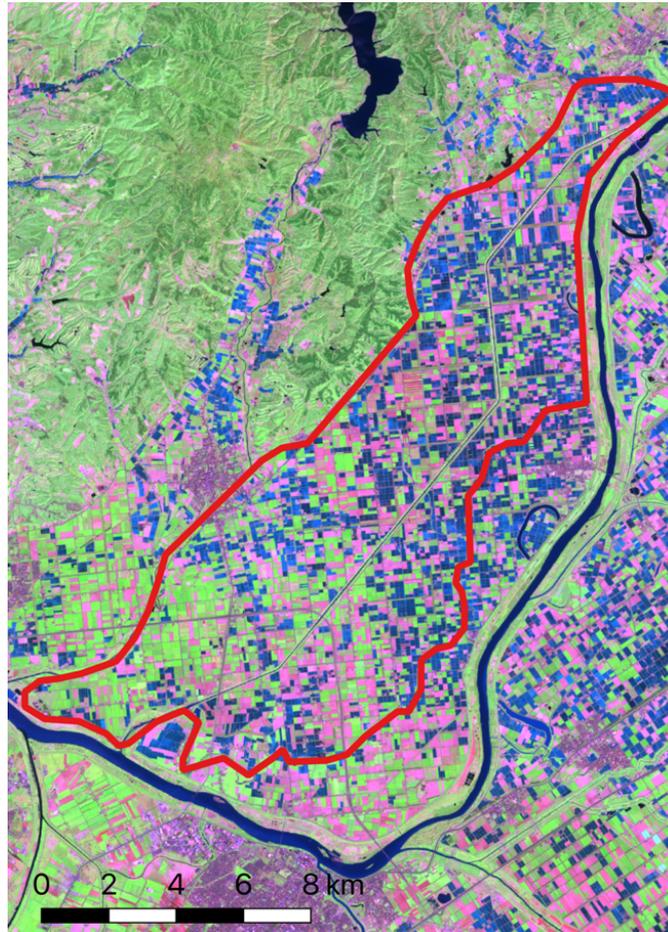
Fig. 5.2 Satellite image covering Shinotsu, composed of bands of red (R), near-infrared (NIR) and short-wave infrared (SWIR) of Sentinel-2 taken on 23rd May 2016. RGB = (SWIR, NIR, R) Green, pink, and blue areas represent wheat lands, bare lands and rice paddies respectively. The red polygon shows the range of study area.

Fig. 5.3 Satellite image covering the targeted area, composed of bands of red (R), near-infrared (NIR) and short-wave infrared (SWIR) of Sentinel-2 taken on 23rd May 2016. RGB = (SWIR, NIR, R) Green, pink, and blue areas represent wheat lands, bare lands and rice paddies respectively.

5.3 Results

5.3.1 History of land use between 2006 and 2017

　　　As a result of the reconstruction of the history of the land use form, 8 field plots out of the 53 plots were used as rice paddy for 9 years or more between 2006 and 2016 (referred to herein as the "paddy plots"), and 12 plots were used as upland fields for 9 years or more ("upland plots"). The rest 30 plots were for rotational use of paddy and upland ("rotation plots"). In the rotation plots, rotation of paddy rice and upland crops were generally conducted every 3 or 4 years. The composited satellite image for land use classification in 2016 was shown in Fig. 5.2 and Fig. 5.3 for the whole region and targeted area respectively for example.

5.3.2 Relationship between subsidence and land use

　　　The relationship of the peat subsidence to the crop rotation was examined in 53 fields.

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The overall mean of the subsidence from 2006 to 2017 in the 50 fields was 13.8 cm, which equals 12.5 mm yr^{-1}. The total subsidence from 2006 to 2017 was plotted against the year in which each field was used for rice paddy in the same period (excluding 2012, in which satellite images were not available) (Fig. 5.4). The mean subsidence was 0.5 ± 1.9 cm ($\pm$SE; n = 8) for 11 years in the paddy plots, and significantly less than the subsidence of 24.3 ± 1.7 cm (n = 12) in upland plots ($p < 0.001$). So, the subsidence rate in the paddy plots was significantly smaller than that in upland plots. In the rotation plots with 1 to 8-year cultivation of paddy, the subsidence was intermediated value between the paddy and the upland plots as the difference was statistically significant level ($p < 0.05$) in the Tukey-Kramer multiple comparisons. The subsidence reduced linearly as the period of paddy increased.
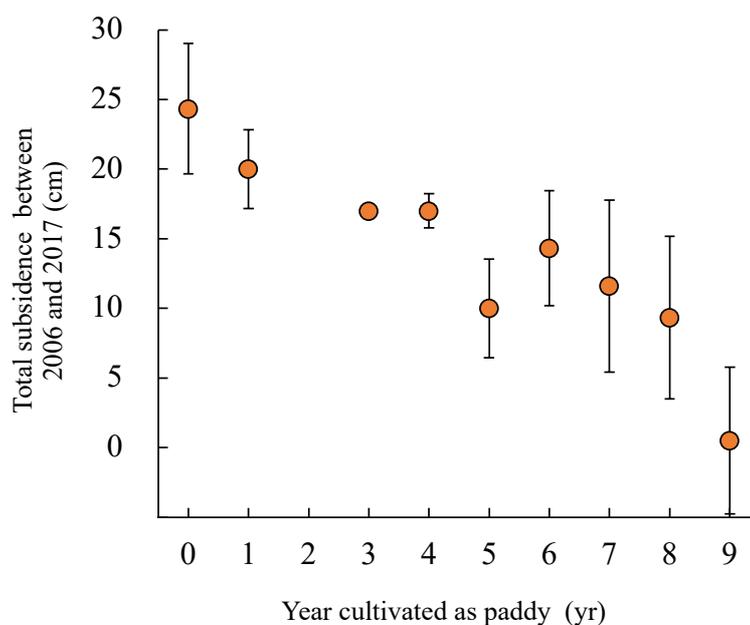
Fig. 5.4 Relationship between the total subsidence in 2006 – 2017 and year in which each filed was used as paddy field out of satellite image available 10 years. The error bars represent the standard deviation of the samples.

Table 5.2 Subsidence between 2006 and 2017 in different land uses

Land use	Total subsidence ± SE (cm)	Subsidence rate ± SE (mm yr^{-1})	Number of plots
Paddy	0.5 ± 1.9 a	0.5 ± 1.7	8
Upland	24.3 ± 1.7 b	22.1 ± 1.2	12
Rotation	13.1 ± 1.0 c	11.9 ± 1.0	30

* The values with the same letter are not significantly different in the Tukey test ($p < 0.05$)

5.4 Discussions

5.4.1 Effect of paddy cultivation on peat subsidence

The total subsidence in the permanent paddies was significantly smaller than that of the permanent upland fields. The result was expected by previous studies which reported high groundwater table reduced oxidative decomposition (Hirano et al., 2014; Kim & Verma, 1992), and well exhibited reported phenomena as subsidence. The average subsidence rate of 0.5 mm yr^{-1} in paddy use peatland was an extremely low value compared with other reported values. Compared with the permanent upland fields, the value in the paddy was nearly 8 times lower. Peat subsidence generally decrease as time passed since the first drainage. Thus, the elapsed time since reclamation of peatland must be considered in the comparison of subsidence rate. In the same time scale with our study site, Leifeld et al. (2011) reported 13 mm yr^{-1} of subsidence in peatland drained 70 years ago in Switzerland. Hutchinson (1980) also reported 31 mm yr^{-1} in peatland drained 64 years ago in the UK. The subsidence rate in the paddy plots in our study site was substantially less than the globally reported values whereas the subsidence rate in the upland plots was well consistent with the global values. The value in the paddy plots was less than the rate of 5 mm yr^{-1} observed in Dutch peatland after 550 years since initial drainage (Hoogland et al., 2012). Our result suggested obviously that the paddy land use reduced subsidence.

The possible reason for this may have been the high groundwater table which inhibits oxidation of peat substrate. Peat subsidence is generally caused by two processes which are peat densification and peat oxidation. An increasing relative contribution of the oxidation of peat through time was reported in many previous studies (Grønlund et al., 2008; Pronger et al., 2014). Pronger et al. (2014) suggested that the contribution of the oxidation is about 50 % in peatland

with 100 years since drainage. Based on those studies, the contribution of peat oxidation to subsidence in our study site has been getting larger. Therefore, it is important to regulate the oxidative decomposition of peat to reduce subsidence. Previous studies have reported that high groundwater table reduced decomposition of peat substrate(Hendriks & Akker, 2017; Kim & Verma, 1992). Knox et al. (2015) reported a significantly low value of CO_2 emission in paddy caused by peat decomposition in the peatland in the USA. In our study site, the paddy plots have maintained the water table above the surface in the cultivated period in summer and kept the peat layer anaerobic, which reduce oxidation of peat substrate and following subsidence. After the irrigation period, the water table generally lowered from harvesting period in autumn to early spring in Hokkaido, but the temperature is usually quite low, and a lot of snowfall occurs. Our result implied that it is possibly important for the prevention of subsidence to maintain a high water table during the period with high temperature, which encourages decomposition peat. Kasubuchi et al. (1998) also stated that keeping groundwater table high with irrigation was important to reduce subsidence on peatland.

Compared to the subsidence value in permanent paddies (9-year cultivation of paddy) and rotation plots (1-8 year cultivation of paddy), the difference of the mean values of subsidence was relatively large, though it was not statistically significant level. Especially, the difference between the plots with 8-year paddy cultivation and the plots with 9-year paddy cultivation was quite large even though the period of paddy cultivation differed was only 1 year. This may be attributed to "the effect of soil drying". It is commonly known that the rewetting of dried soil encourages the decomposition of organic materials (Birch, 1958). This effect was also reported in boreal peatlands and repetition of drying and wetting increased the decomposition of peat (Fenner & Freeman, 2011; Goldhammer & Blodau, 2008). In our study site, this effect may have encouraged subsidence with upland cultivation after paddy cultivation. We have not conducted oxidation measurements, so it is difficult to conclude.

Overall, our results suggested that paddy use of peatland had a significantly lower impact on peat subsidence, compared with that in upland fields and also globally reported values of subsidence. The high groundwater table likely inhibited peat oxidation. However, we did not examine the actual rate of peat oxidation and survey only a tiny fraction of Shinotsu Peatland. In addition, few studies have reported subsidence on paddy peatland, so our conclusion here was more speculative. More studies involving plenty of samples are required to confirm the observed

trend in this study.

5.4.2 Other controlling factors

The variation of subsidence in the plots with the same duration of paddy cultivation was relatively large, suggesting that not only the duration of paddy cultivation but also other controlling factors are involved in controlling the rate of subsidence. For example, actual water table depth, total peat thickness, depth of drainage ditch, the thickness of surface mineral soil layer, and type of peat would be important. We did not have water table measurements on the individual plots. The variation can be associated with the difference in water table depth of individual sites which was according to the intensity of drainage. Peat thickness and peat type in our study site were relatively uniform because all the plots were located in the same block of the same township covering approximately 6.3 km^2 (2.5 × 2.5 km). The depth of peat was around 5 m and the predominant peat type was fen-type peat according to the soil map. Therefore the impact of those two factors can be small.

The thickness of the surface mineral soil layer can vary depending on the history of soil dressing in each experimental plot. This might affect the subsidence rate. However, the effect of the mineral layer overlying the peat layer has not been well studied. Yokochi et al. (2018) reported that the soil dressing accelerate the subsidence possibly due to increasing load on the peat layer. On the other hand, Brouns et al. (2015) suggested that the presence of a clay cover have slower subsidence as oxygen intrusion in the peat layer is limited due to the clay layer. It has been still controversial; however, the thickness of the mineral soil layer could be involved in the variation of subsidence. The effect of mineral soil dressing on the peat subsidence will be discussed in the following chapter of this thesis, but more studies regarding those factors are strongly required to more accurately explain and predict the difference in the subsidence rate. Though the other factor can affect the subsidence, the relationship between subsidence and land use was still obviously significant, and therefore land use is the dominant control on the surface subsidence rate.

5.4.3 Methodological consideration

The airborne laser survey technique detected averaged 0 to 30 cm of subsidence in each field plot for 11 years. The official precision of the airborne laser survey for one point in laser scanning is ± 15 cm which is substantially large compared to subsidence; however, we used the average value of the scanned points within each field plot, and therefore this random error on

individual scanned points might be cancelled. Each field plot had around 1,500 scanned points on average, which assured the precision of the mean values of subsidence within individual field plots with low standard errors. Overall, in terms of the precision in elevation of each scanned point, using the airborne laser survey data for measurement of peat subsidence for the decadal interval is adequate with averaging in the scale of field plots.

Another problem with the airborne laser survey is systematic errors. In the airborne laser survey, systematic errors can be caused by the error of ground reference point, error of GNSS and IMU on an airborne platform, and surface condition of the ground. Systematic errors occurring widely is not matter for the relative evaluation of peat subsidence in different land uses because the relative difference of subsidence is not affected by constant errors which are found in a broad area. Therefore, the impact of the error of ground reference point and the error of GNSS and IMU on the aircraft can be small. However, the absolute values of subsidence possibly were underestimated or overestimated.

Systematic error with the surface condition of the individual plots could affect the relative evaluation of subsidence. This sort of error possibly included vegetation cover and water cover in paddy. Those errors were actually found in the DEM of 2006 in this study since the DEM was based on the airborne laser survey conducted in the growing period in July. For the DEM of 2006, the plots with water or vegetation such as wheat and soybean were omitted from the evaluation to avoid and to minimize the systematic error due to surface conditions. It is better to conduct an airborne laser survey in autumn when the field plots are not covered with vegetation or water for the peat subsidence evaluation.

Another technical issue in this study is about land cover classification. In this study, we employed satellite images for land use classification. We used composited images of several spectral bands based on the theoretic difference of spectral reflection characteristics on each land cover. The problem was a lack of information on ground truth as we do not assess actual land use in the field. Although the accuracy of reconstruction of land use in this study was not validated, previous studies reported that the performance of classification with satellites' optical sensor images is sufficient with an accuracy of 98 % (Dong et al., 2016). To reduce the uncertainty of land use history, a combination of ground truth and satellite images are necessary. To get more adequate results on a larger scale, classification algorithms such as machine learning will be helpful, and many methods were suggested (Otukei & Blaschke, 2010; Verbeke et al., 2004).

5.5 Conclusion

We calculated the subsidence rates in different land uses, i.e., paddy or upland field. The subsidence rate in the field plots which was permanently used for rice paddy had a significantly lower value. This suggested that paddy land use had a lower impact on peat subsidence. Currently, re-wetting of cultivated peatland such as "paludiculture" has tried to be conducted to prevent further subsidence and carbon emission on peatlands in some European countries. The lower subsidence rate in paddy land use implied by this study may encourage these activities to maintain a high groundwater table. However, in Japan, the demand for rice has been continuously decreasing, and it is difficult to expand the paddy use of peatland. To reduce subsidence, not only technical implementations but also political intervention were required for the sustainable use of peatlands.

Chapter 6 Effect of Soil Dressing on Peat Subsidence

6.1 Introduction

Soil dressing is an implementation that brings soils from other places to agricultural fields to improve the physical and chemical nature of the surface soils and to increase the productivity of the land(The Japanese Society of Irrigation, Drainage and Rural Engineering, 2010). Soil dressing is often implemented in the field with a lack of surface soils, special soils such as heavy clay, volcanic ash, and peat, and paddies with high water conductivity. In those poor soils, the dressed soils play roles in improving permeability, nutrient condition, and soil texture to better conditions for crop production. The most adequate surface soil is generally loam soils with up to 30 % of the content of clay, and those are often dressed. Depending on the situation of the farmlands, appropriate soil types are applied with consideration of the soil texture, soil structure, pH, and heavy metal contents of the dressed soils. The thickness of dressed soil is generally 15 cm or more, which sufficiently compensates for the lack of surface soils (The Japanese Society of Irrigation, Drainage and Rural Engineering, 2010). Dressed soils are put into the field surface via several means such as carry-in by dumper trucks, digging up underlying mineral soil layers, and pumping with water by pipelines. Recently, the major way to input soil is the carrying by dumper trucks in Hokkaido though soil dressing with horse-drawn sleigh or railway occurred in the early stage of agricultural settlement. Soil dressing with digging up the underlying layer is often found in European countries. For poor soils, soil dressing is essential to improve agricultural productivity.

In order to use peatland as agricultural land, it is essential to lower the groundwater table by drainage. In addition to improving the drainage condition, soil improvement must be implemented because peat soil represents very low pH, poor nutrients, and low bearing capacity, which is not suitable for crop production (Khama et al., 1995). Since peat soil mainly consists of incompletely decomposed plant bodies, lack of mineral nutrients is a critical problem for agricultural use. Several methods have been employed for the soil improvement in cultivated peatlands. These include fen black cultivation, German raised bog cultivation, Dutch fen cultivation and sand cover cultivation (Heathwaite & Goettlich, 1993). For example, Dutch fen cultivation (so-called Fehn cultivation) was developed in the Netherlands in the 16th century. In this method, the peatlands are firstly drained by ditches and dried peat is extracted for fuel. Then,

sandy soils excavated from the bottom of the ditches are added to the surface to provide minerals to the surface soil with covering the underlying peat layer. In other methods, surface soil is to be covered with mineral soils through the specific way to bring the soil is different. Historically, covering the surface peat with soil dressing is one of the major ways to improve soil conditions in cultivated peatlands.

In Hokkaido, mineral soil dressing onto surface peat soils has been implemented in peatlands as same as other countries. The onset of the soil dressing in Hokkaido was around 1910 and the implementation in the early era was done by private investment (Kohyama et al., 1995). The central government of Japan began to subsidize soil dressing in the 1920s, then the soil dressing in peatland has been implemented several times with subsidies until now (Kohyama et al., 1992). Compared with European countries where peatlands have been cultivated as pasture, the thicker layer of dressed mineral soils with repeated implementations is present in peatlands in Hokkaido to grow the rice. This remarkably thick dressed mineral soil layer is unique to Hokkaido's peatlands under paddy land use (Inoue, 2012).

The effect of thick soil dressing on peat subsidence has not been well understood because such thick soil dressing is generally rare. However, several studies have reported how natural or artificial clay covers placed on the peat layer affect the subsidence and compaction of peat. In the Netherlands, it is suggested that thicker overburden increase the compaction of the peat layer due to enhancing the effective stress of the peat layer (Asselen et al., 2018). Yokochi et al. (2018) also reported in the case study in Hokkaido that the soil dressing accelerate the subsidence possibly due to increasing load on the peat layer. On the other hand, Brouns et al. (2015) suggested that the presence of a clay cover have slower subsidence as oxygen intrusion in the peat layer is limited due to the clay layer. Considering based on those previous studies, soil dressing may have both effects of accelerating and reducing the subsidence though it is not clear which effect is predominant. If the latter effect is larger, soil dressing will be one of the reasonable solutions for the subsidence in cultivated peatlands. Thus, the investigations on the peatlands with thick dressed soils will provide important implications for the future land use on peatland. However, those have barely been done because the thick soil dressing is rare.

To overcome this knowledge gap, we studied land subsidence caused by peat densification and oxidation in the certain numbers of field plots reclaimed on lowland peat soil in Shinotsu Peatland located in the lower reach of the Ishikari River basin, Hokkaido, Japan, where

the peatlands have been used for paddy rice production with a thick cover of dressed mineral soil layers. First, we observed the actual depth of the dressed mineral soil layer with simple hand-operated boring in the field plots. The relationship between the measured thickness of the dressed layer and the surface subsidence in the recent decade was examined to reveal the impact of dressed layer on the land subsidence. At selected sites, we assessed the current degree of peat compaction with a high-resolution vertical profile using continuously sampled peat cores. Based on the relationship between surface subsidence and the thickness of dressed soils, and vertical profiles of the degree of compaction, we discussed the contribution of the soil dressing on the dynamics of peat subsidence. The principal objective of this study is to understand how mineral soil dressing affects the surface subsidence of peatlands. This knowledge will provide insights into the future land use practices on cultivated peatlands.

6.2 Study Sites

The investigation of the dressed soils and peat subsidence was conducted in Shinotsu Peatland located in the Ishikari River basin, the central Hokkaido as described in Chapter 3. The same 50 field plots of description in 3.2 and also analyzed in Chapter 5 were investigated on the thickness of the dressed mineral soil layer and the surface subsidence. The area was mainly covered by fen-type peat according to the soil investigations (Seo et al., 1965). According to previous studies that have collected the history of soil dressing by national or local government projects, the onset of the soil dressing in the study area was in the 1970s and the 3 or 4 times of the soil dressing had been implemented by the 1990s (Kohyama et al., 1992). Based on the history of the project, the thickness of dressed soils was estimated to be around 15 cm in the study area (Kohyama et al., 1995), though they did not investigate the actural depth of the dressed layer. The last implementation of soil dressing has been done in the spring of 2006 according to the record of the projects, and there have been no soil dressing in the study plots since 2006 (personal communication with Shinotsu Chuo Land Improvement District).

6.3 Methods

6.3.1 Thickness of the dressed soil layer

The thickness of the dressed mineral soil layer in the 50 study plots was measured by simple boring using a boring stick. The measurement was conducted in several points randomly chosen within the single field plot to examine the variability of the thickness. The density of the measurement was around one point for 10 a of the field. On average, 3 to 5 points were investigated in each field plot. The soils with a depth of 1m were extracted by a boring stick to examine the depth of the dressed mineral soil layer at the measurement points. The boundary between the dressed soil layer and the underlying peat was determined based on whether fibric organic materials can be confirmed or not (Fig 6.1). The layer above the boundary was regarded as the dressed soil layer, and its thickness was recorded. The points of observation were referenced in coordinates and altitude by the GNSS survey. For the GNSS survey, ProMark 3 (Magellan Navigation, Inc.) was employed. The GNSS-based control station by the Geospatial Information Authority of Japan was used as a base control point in the GNSS baseline analysis.

Fig. 6.1 Example of excavated soil and peat by the boring stick.

6.3.2 Peat Compaction

Peat cores were sampled in 2 field plots (reffered herein as plot K and plot O) with the different thicknesses of the dressed mineral soil layer to examine the impacts of the mineral soil layer on peat compaction. Both of the field plots have been used as upland fields. These 2 cores were excavated from neighbouring two plots to avoid the effect of other factors rather than the thickness of the mineral layer. The core length was 2 m for both of the cores. A hand-operated Russian type peat sampler was used for core acquisition. In the lab, the cores were cut in the

interval of 5 cm, and entirely and continuously sampled for the measurement of the dry bulk density. Each sample was dried by oven at 105 °C for 24 h and weighed on an electronic scale (accuracy of 0.1 mg) to determine the dry bulk density. For the calculation for the dry bulk density, the dried weights of each sample were divided by the volume of the 5-cm length of the sampler. Subsequently, the samples were heated at 750 °C by an electric oven until reaching constant mass to determine loss on ignition, which is a measure for the organic-matter content.

The amount of compaction for each peat sample was estimated using an equation to calculate the uncompacted dry bulk density of the peat sample (van Asselen, 2011):

$$\rho_{uncomp} = a - c \cdot \exp\left(-\frac{b}{LOI}\right)$$

where ρ_{uncomp} is an estimate of uncompacted (before compaction by agricultural use) dry bulk density; LOI is loss on ignition determined in the lab; a, b, and c are constant parameters fitted for particular sites. In this study, we used the same value with van Asselen (2011) (a = 1.5, b =6, and c =1.53). This equation has originally been constructed and fitted based on organic-matter content and dry bulk density measurements of relatively uncompacted fen peat from the Rhine-Meuse Delta (van Asselen, 2011). The degree of peat compaction was determined by using current compacted dry bulk density (ρ_{comp}) measured in the lab and estimated natural uncompacted dry bulk density (ρ_{uncomp}) with the following equation:

$$Compaction\ (\%) = \frac{\rho_{comp} - \rho_{uncomp}}{\rho_{comp}} \times 100$$

For every 5 cm interval of the sample, the amount of compaction was calculated. The uncompacted dry bulk density estimated by this method have errors because the parameter in the equation can vary relying on the region. Therefore, in this study, we relatively compared the compaction between plot O and K rather than discussing the absolute values of compaction. Indeed, a previous study used this formula in peatlands in Hokkaido for the estimation of the natural dry bulk density for compacted dry bulk density (Ishii et al., 2016), suggesting that the method can be applied for peatlands in Hokkaido. Thus, the error caused by parameter can be regarded insignificant.

6.3.3 Classification of Land Use

The analysis of the relationship between the surface subsidence and the thickness of the dressed layer was conducted separately depending on the land use of each plot because the effect of the soil dressing is expected to vary among different land uses. As treated in Chapter 5, we classified the study plots into 3 types of land use, i.e., paddy, rotation, and upland. The results of the land use classification with satellite images in Chapter 5 were applied to this chapter. 8 field plots were the paddies, 12 plots were the upland, and 30 plots were the rotation.

6.3.4 Land Surface Subsidence

The surface subsidence between 2006 and 2017 was calculated in all the field plots using the digital elevation models constructed by airborne laser survey as same as Chapter 5.

6.4 Results

6.4.1 Thickness of Dressed Soil Layer and Surface Subsidence

As described in Chapter 5, the overall average of the surface subsidence in 50 plots was 13.8 cm, and the subsidence rate highly depended on land use. The overall average thickness of the dressed mineral soil layer was 40.7 cm with the standard variation of 8.9 cm. The variations of the thickness within the field plots were generally low, and the mean standard variation of the thickness within the field plot was 4.2 cm. There is no significant difference in the thickness of the dressed layer depending on the land use.

Fig. 6.2 represents the relationship between the thickness of the dressed soil layer and surface subsidence between 2006 and 2017 classified by land use. In the paddy plots, there is no significant correlation. For the paddy plots, the subsidence was quite small as described in Chapter 5, and the effect of the dressed soil was not observed. On the other hand, a significant correlation between the thickness and the subsidence in the upland plots is apparent. The subsidence was linearly reduced as the thickness of the dressed soil layer increased. In the rotation plots, the correlation was weaker than that of upland plots and not significant.
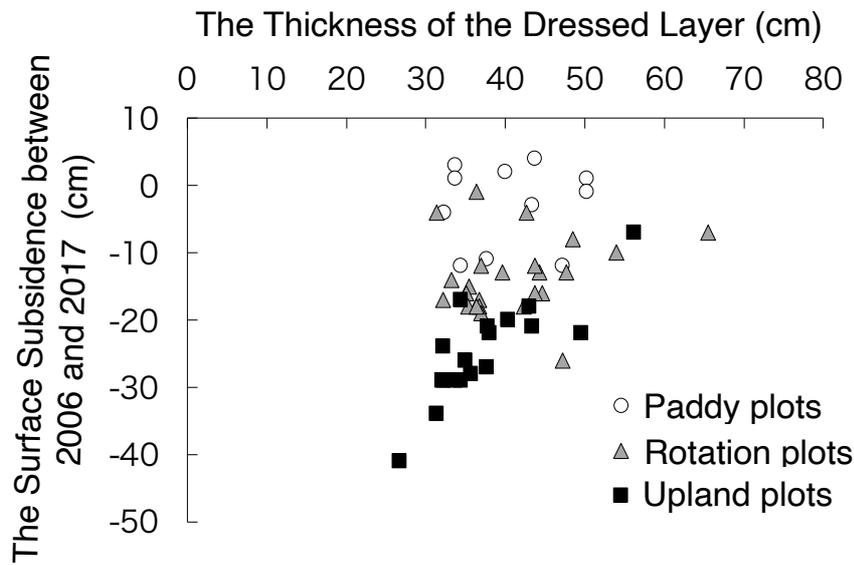
Fig. 6.2 The relationship between the thickness of the dressed mineral soil layer and the subsidence between 2006 and 2017.

6.4.1 Peat Compaction

The peat compaction was examined with the two peat cores excavated from upland field plots (plot K and plot O). The thickness of the dressed mineral soil layer was 56 cm and 32 cm in the plot K and plot O respectively, and plot K has a nearly double thickness of the dressed layer compared with plot O. The subsidence between 2006 and 2017 in both plots were 7 cm in plot K, and 29 cm in plot O. The subsidence in the plot O was larger than that of the plot K.

The estimated profiles of peat compaction with the depth of 2 m were shown in Fig. 6.3. The estimated compaction was calculated with the current dry bulk density and loss on ignition. For both of the plots, the underlying peats were estimated to be compacted to approximately 50 % of their original volume. The overall averages of the estimated compaction for the 2 m cores were 48 % and 43 % in plot K and plot O respectively, and plot K had a slightly higher magnitude of the compaction. Overall profiles in both sites well correspondant but the estimated compaction just beneath the dressed layer which is in the depth of 50-100 cm was significantly different. The plot K with thicker dressed soil had a higher degree of compaction in the shallow peat layer.
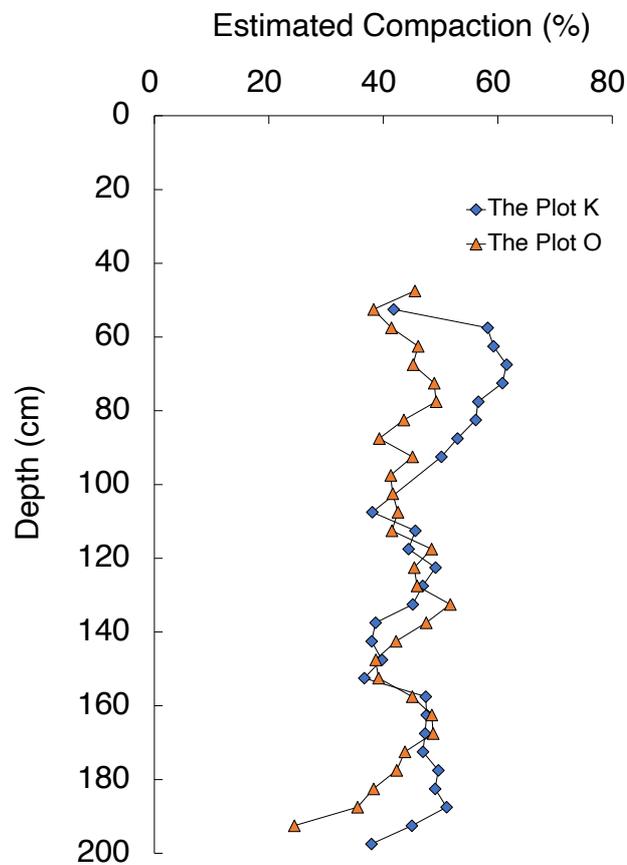
Fig. 6.3 The vertical profiles of the estimated compaction in the underlying peat layers in plot K and plot O.

6.5 Discussions

6.5.1 Effect of Soil Dressing on Peat Oxidation

The last soil dressing in our study sites had been done by the spring of 2006, and this is the same year with the initial time of the observation of the subsidence. Therefore, the observed elevation change in our study did not include the direct effect of the soil dressing; ie. the elevation rise by the dressed soil itself did not affect the observed subsidence. The observed elevation change possibly occurred in the underlying peat layer.

Peatland subsidence rates are usually large in the first few years after the onset of the drainage and then get slow as time passes since the first drainage (Armentano, 1980). The initial

period of rapid subsidence is largely caused by peat densification including shrinkage and consolidation. Long-term subsidence rates generally decline and get stabilized at a rate that reflects the oxidation rate (Stephens et al., 1984). The contribution of the oxidation of the peat substrate to the peat subsidence usually increases over time (Grønlund et al., 2008; Pronger et al., 2014b). Pronger et al. (2014) suggested that the contribution of the decomposition of peat to the subsidence reached 50 % in the peatlands with 100 years of cultivation. In our study site, the onset of drainage was nearly 100 years ago, and therefore the peat subsidence was considered to be controlled largely by oxidation of peat.

Our results implied that the thicker dressed mineral soil layer reduces the subsidence in upland plots. In the upland fields, the subsidence was significantly larger than that in paddy fields because groundwater depth is generally deep inducing the oxidation of peat as described in Chapter 5. Nevertheless, the subsidence in the upland fields with thick dressed soil was almost the same as that of paddy fields. This may be attributed to the reduction of peat decomposition due to thick mineral soil cover. Given that groundwater depth is the same condition, a thicker dressed soil layer can place more peat layers below the groundwater table, which reduces peat oxidation and subsidence. On the other hand, the more peat layer locates above the groundwater table with the thinner dressed layer, which accelerates the oxidation and subsidence. Fig. 6.4 provides the schematic view of the effect of soil dressing on peat subsidence by describing the relation to the groundwater table. The effect of the dressed layer was not observed in the paddy plots. In paddy plots, the groundwater table was high enough to prevent oxidation of peat regardless of the thickness of the dressed layer.
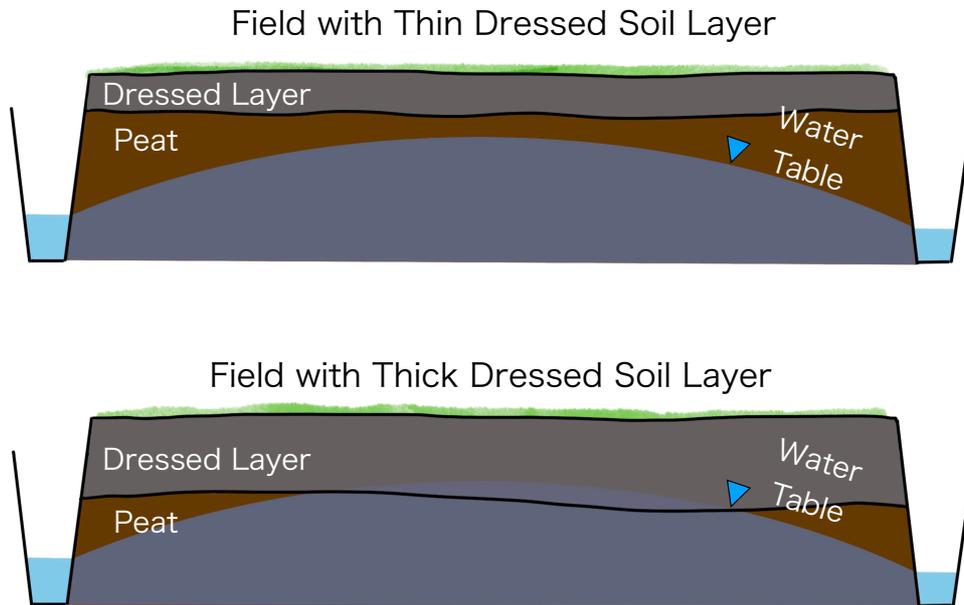
Fig. 6.4 Schematic view of the effect of soil dressing on peat subsidence with describing the relation to the groundwater table.

6.5.2 Effect of Soil Dressing on Peat Compaction

Although the peat subsidence decreased in the upland field with a thicker dressed mineral soil layer as described in 6.5.1, the comparison of the compaction in two upland plots suggests that thicker soil dressing may cause larger compaction. This was consistent with previous studies on the effect of overburden on peat compaction. The studies implied that a larger load on the peatlands induced a higher degree of compaction with the cases in the Netherlands (van Asselen et al., 2018). In Hokkaido, it is suggested that soil adding to the peatland pastures accelerated the subsidence after a few years since its implementation (Yokochi et al., 2018). However, compaction is a generally rapid process that occurs and is settled in the first few years after increasing the effective stress (Armentano, 1980). In our observation period of the peat subsidence (2006 – 2017), substantial time was already passed since the implementation of the soil dressing which had mainly been done in the 1970s. Thus, the compaction of peat induced by the increased load with soil dressing had already settled in our observation period. This may consistently explain our investigation result that peat compaction was large with thicker dressed soil but smaller subsidence in recent years.

6.6 Conclusion

In this chapter, the relationship between land surface subsidence and thickness of the dressed mineral soil layer was examined with field plots that have been used as multipurpose paddy for the production of wheat, soybean, and vegetables as well as rice. In the plots with paddy land use, the subsidence was very small and there was no significant correlation between the subsidence and the dressed layer thickness, whereas subsidence in upland plots had a significant negative correlation with the thickness. This suggested that thicker soil dressing can effectively reduce surface subsidence. The thick layer of dressed soil may reduce the oxidative decomposition of peat by relatively deepening the peat layers from the surface.

Chapter 7 Displacement of Irrigation Pipelines Associated with Peat Subsidence

7.1 Introduction

Recently, deterioration or malfunction of irrigation facilities for paddies that have been constructed after the World War 2 have been attracting increasing attention in Japan. Management of the facilities based on appropriate performance diagnostics is important to improve life expectancy and reduce life-cycle cost. Deterioration of the irrigation systems causes sudden accidents such as leakage. Irrigation pipelines, especially, are vulnerable to deterioration. More than 70 % of sudden failure of agricultural irrigation facilities in Japan occurs at pipelines and its ratio has been increasing (Muromoto, 2011). Given that, an urgent challenge is to understand the actual state of the deterioration and the cause and the tendency of the failure of pipelines to continue stable provision of irrigation water to the paddies.

In the context of civil engineering, peat soil is regarded as a problematic foundation that easily causes significant consolidation and subsidence. Land subsidence widely occurs in peatlands in Hokkaido, northern Japan (Miyaji et al., 1995; Yokochi et al., 2020), which has an adverse impact on farmlands and irrigation facilities. Associated with the land surface subsidence, the pipelines buried in peat soil also subsided and leaked. Recently, the incidents related to leakage got more frequent as time passed since the construction. For example, in Shinotsu Peatland, central Hokkaido, pipelines leakage induced by peat subsidence occurs several times every year (Personal communication with Shinotsu Chuo Land Improvement District). Also, the same problem was reported in peatland in Furano, northern Hokkaido (Personal communication with the town office of Furano City). Leakage caused by the subsidence will continue to increase on since peat subsidence continuously progresses for a long time. Therefore, it is strongly required to understand the actual situation of pipelines' subsidence and examine the relationship with leakage to manage irrigation facilities on peatland with appropriate maintenance and replacement. This should be one of the key issues to sustain paddy agriculture on peatlands in Japan.

Civil Engineering Research Institute for Cold Region (2016) collected case examples of pipeline failures in peatlands from the information provided from Land Improvement Districts (farmers' association for water use) that manage the pipelines and reported that the leakage was often found where a longitudinal structure of the pipelines varies such as the intersections with

roads and the connection with other facilities. Sakamoto and Ueya (2021) examined the effect of land use (i.e., paddy or upland) of surrounding farmlands on the misalignment of pipelines and suggested that upland land use possibly encouraged the subsidence of the pipelines. Besides those reports, individual inspections of the pipeline leakage on peatlands and observation of the behaviour of pipes after a few years since the construction were conducted (e.g., Akutsu et al., 2004; Hideshima et al., 1995; Ishioka et al., 1993; Tamai et al., 2004).

Although knowledge about long-term behaviour is needed to consider the design, construction, and maintenance of the pipeline buried in peat soils, most previous studies only collected the leakage cases or observed short-term movement of pipelines. Long-term displacement of pipelines constructed in peatland has scarcely been observed up to this point. In addition, assessment of longitudinal displacement along pipelines' course for a certain section is needed to grasp the non-uniform subsidence of pipelines which should be the predominant cause of the leakage, but it has not been well studied. Long-term latitudinal assessment of pipelines must be helpful for the design of irrigation pipelines expecting future uneven subsidence in peatlands.

In this study, we surveyed multiple irrigation pipelines constructed in peat soils more than ten years ago regarding their vertical displacement. Based on the survey, quantitative evaluations of the displacement for a decade were conducted, and the relationship between the displacement and the surrounding environment was discussed. Through the discussion, we will provide implications for future management strategies of irrigation pipelines constructed in peatlands.

In addition to 1) standard sections that were not under particular construction condition, we dealt with the following three construction conditions; 2) intersection with a road, 3) flexible rubber pipe connected to an aqueduct, and 4) section along with different land use that previous studies implied as vulnerable to the leakage risk. Section 5.2 describes an overview of study sites and the methodology of the survey, and Section 5.3 shows the result of the observation. Finally, Section 5.4 discuss the effect of the above-mentioned four construction condition on uneven subsidence of the pipelines.

7.2 Study sites and methods

7.2.1 Overview of study sites

Investigation of the irrigation pipelines was conducted in Shinotsu Peatland. As already described in previous studies as well as the preceding chapters in this thesis, land subsidence due to agricultural use of the peatland is one of the major concerns in this area. The maximum elevation loss in this area since the onset of the agricultural development was estimated to reach up to 2 m (Inoue & Obana, 2000; Yokochi et al., 2019). Peat subsidence in this area has been ongoing with its rate of 10 to 20 mm yr^{-1} even though it has been passed more than 100 years since the onset of the reclamation. The rate of peat subsidence highly depends on the time since the initiation of the land development and the land use (i.e., rice paddy and upland) (Yokochi et al., 2020).

In this study, we surveyed irrigation pipelines laid by the National Project of Irrigation and Drainage for Shinotsu Chuo District (1985 – 2007) and its related projects. They are currently managed by Shinotsu Chuo Land Improvement District (farmers organization for agricultural water use). It passed more than ten years since the surveyed pipelines were constructed. The pipelines are for branch lines and terminal lines that provide water from larger main lines with diameters between 300 to 1,650 mm.

7.2.2 Selection of pipelines for survey

Studies on the vulnerability of the irrigation pipelines in peatlands to non-uniform subsidence suggested the tendency of the displacement of pipelines (e.g., Civil Engineering Research Institute for Cold Region, 2016; Sakamoto and Ueya, 2021). Base on the tendency that they reported, we focused on standard sections with no special conditions and 3 other conditions. An overview of those construction conditions except the standard section is as follows.

7.2.2.1 Intersection with road

Civil Engineering Research Institute for Cold Region (2016) suggested that pipelines in peatlands tended to unevenly subside at intersections with roads and connection with other irrigation facilities (junctures and aqueducts etc.), where overburden and longitudinal structure change. Thus, the longitudinal sections of the pipelines that intersect with farm roads with embankments were examined in this study. Elevations of the pipelines at multiple points, including the intersections, were surveyed. Fig. 7.1 shows the conceptual diagram of the observed section. The sections targeted for the survey were chosen based on route maps of the irrigation

pipelines and aerial photos taken by the Geospatial Information Authority of Japan. We surveyed eight sections of the intersection of pipeline and road. The roads included small-scale ones with thin gravel layers and large-scale ones with embankments. The vertical loads of the roads are estimated from the shape of the road embankment and the density of the embankment material. The roads included ones existing before the construction of the pipelines and ones newly laid after the construction. With those eight sections of the pipeline, we examine the effect of concentrated overburden by farm roads on subsidence of the buried pipelines.
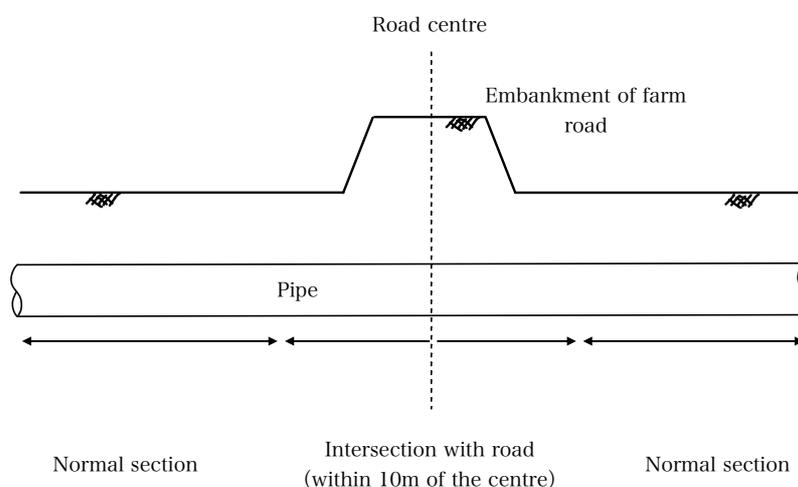
Fig. 7.1 Schematic cross-section of the pipeline and the farm road.

7.2.2.2 Flexible pipes connected to aqueducts

Kasubuchi et al. (1998) implied that peat subsidence near the drainage ditches was generally greater than other places, which often causes discordance between bridges across the ditch and surrounding land surface. Pipeline aqueducts crossing the drainage ditches have solid pile foundations like bridges across ditches, whereas ordinal sections of the pipelines are generally just buried in peat layer without such solid foundation (Fig. 7.2). This may cause non-uniform subsidence of both sides of the pipelines at the connection points of a standard section of the pipeline and an aqueduct section. Flexible pipes which allow some degree of displacement are usually adapted to the connection points. However, the actual behaviour of the flexible pipes has been seldom assessed. It might be possible that displacement beyond the design allowance causes

leakage passing more than ten years since the construction. Knowledge about non-uniform subsidence in an aqueduct and a pipeline based on actual observation could be helpful to future design. Therefore, we assessed the displacement of 11 aqueducts and connected pipelines.
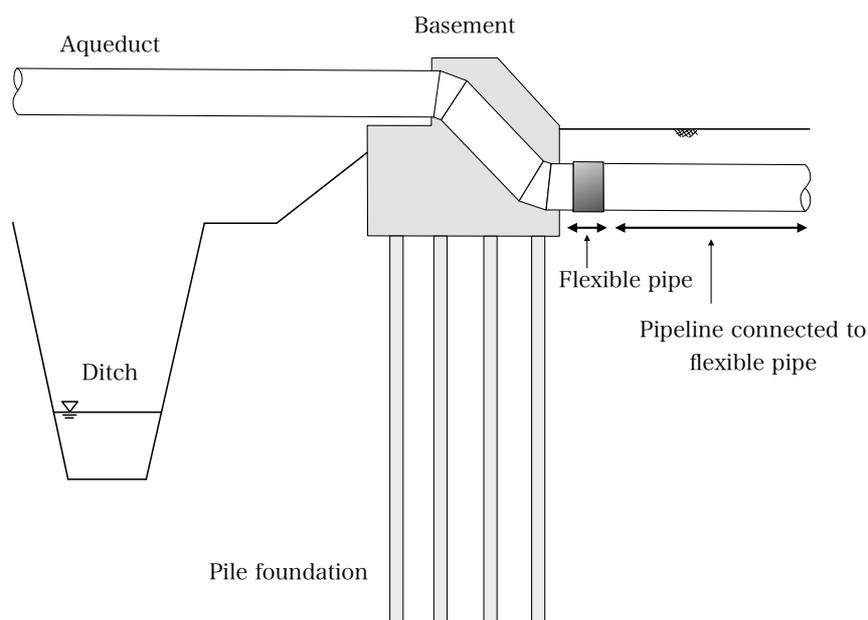
Fig. 7.2 Schematic cross-section of the pipeline connected to an aqueduct.

7.2.2.3 Pipelines passing different land use

Sakamoto and Ueya (2021) investigated the effect of land use (paddy or upland) of surrounding farmland on the subsidence of pipelines. They reported that subsidence of the pipelines with paddy land use was smaller than that with upland use due to high groundwater table in the paddy area. Based on this report, it is expected that subsidence rates of the pipelines in paddy and upland are different, which cause uneven subsidence in the section across different land use. Thus, we investigated the subsidence of pipelines that passes through farmlands for a certain length of time under different land uses to examine this hypothesis.

Land use history from 1993 to 2019 in the field in the study area was reconstructed by the same procedure mentioned in 5.3.2 of Chapter 5 in this thesis. Data for 1998 and 2012 were excluded because the satellite images were not available. The sections targeted for the survey were chosen based on route maps of the irrigation pipelines and the assessed land use history.

Finally, we investigated four sections to elucidate the effect of land use on the non-uniform subsidence of the pipelines.
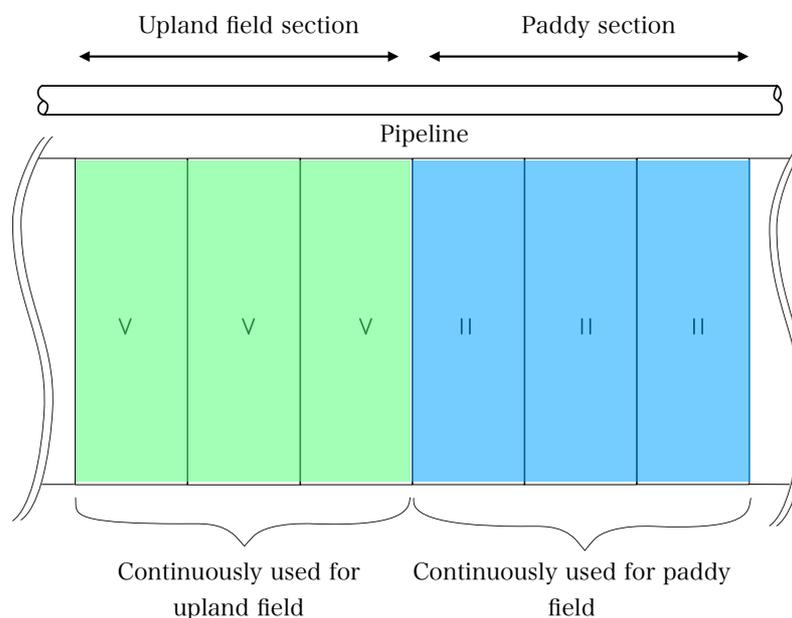
Fig. 7.3 An overview of the pipeline along with different land use.

7.2.3 Measurement of displacement of the pipelines

It is difficult to investigate the pipeline's condition and its alinement by completely digging up the pipelines in terms of budget, workability, and efficiency of data acquisition as the pipelines are generally buried in the ground with a depth of $1-2$ m. In order to easily and quickly get as much data as possible, an extensible metal rod was inserted from the ground surface to the top end of pipelines, and its elevation was measured by the level survey. The rod was carefully and slowly inserted not to damage the targeted pipelines. In advance to measure the elevation of pipelines, we determined the lateral position of the pipeline. Firstly, the position was roughly referenced with foreseeing the air valves connected to the center of the pipelines. Then, the cross-section of the pipeline was measured at several points with measuring elevation across the pipeline with an interval of 10 cm to reference the centerline further precisely. The highest point of the cross-section was regarded as the center. Once the points on the center were established with this method, the centerline was set by foreseeing the points on the center. Along the referenced centerline, the longitudinal elevations of the pipeline were measured with intervals of

10 to 20 m to clarify the vertical displacement of the pipe. Note that only the elevation of the top end of the pipelines was determined, and oblate deformation of pipes was ignored. Therefore, displacement showed in the result includes deformation of pipes by earth pressure though the deformation effect is not significant. Japan Industrial Standard (JIS) for Fiberglass reinforced plastic mortar pipes (A5350-1991), for example, regulates that the standard oblateness of the 1000 mm diameter pipes should be 51 mm under maximum allowable pressure of the pipes. Benchmarks for the level survey was referenced in 3D coordinate by the GNSS static survey. The field investigation was conducted in 2018 and 2019.

7.2.4 Evaluation of displacement of the pipelines

The amount of subsidence of the pipelines since their construction was calculated by subtracting the current elevation that was surveyed in this study from the designed elevation presented in the blueprints. Prior to the calculation, we have considered the accuracy of the elevation value presented in the blueprints as follows.

The designed elevation of the pipelines presented in the blueprints is generally determined based on the elevation of tentative benchmarks established for each reclamation project. Elevation values of the benchmarks are usually surveyed in accordance with the Grade 3 Level Survey in the standard for the land survey that the Geospatial Information Authority of Japan established. Although the GNSS survey referenced to the national GNSS base points has been allowed since 2013 in the Grade 3 Level Survey, previously, the survey needed to be by the direct level survey from the national benchmark. The nearest national benchmark is located ca. 10 km apart from our study area. Based on the Japanese regulation for the management of the survey accuracy, the precision of elevation values of the tentative benchmark for the design of the pipelines could be approximately 10 cm. However, this value of the error is not enough to calculate the subsidence of the pipelines because the error value is large compared to the generally observed rate of peat subsidence (10 cm for ten years). Thus, simple subtraction of the current and designed elevation of the pipelines is not an appropriate way to evaluate the subsidence.

The following method was applied to evaluate pipelines subsidence to overcome this problem. When the blueprints had the elevation values of the solid structures with pile foundation (e.g., the foundation of bridges or electric grids) that can be regarded as stable for a long time, their elevation is used as the benchmark. Then, we calculated the "absolute subsidence" in those cases.

On the other hand, when the blueprints had no mention of the benchmarks that can be regarded as stable for a long time, we did not calculate the "absolute subsidence". Instead of the absolute subsidence, the "relative subsidence" was calculated to compare the subsidence within the certain section of pipelines that can be referred to examine the non-uniform subsidence. Specifically, the point where the difference between the current elevation and designed elevation was the smallest supposed to be stable, and the relative subsidence for comparison of the subsidence within the section using that point as a basis.

7.3 Results and Discussions

7.3.1 Subsidence of the pipeline in standard sections

Before discussing the non-uniform subsidence in special conditions, we first present subsidence in the standard section of the pipelines. In the eight standard sections out of 17 sections, the absolute subsidence of the pipelines could be assessed with stable benchmarks. The sections with special conditions such as aqueducts and intersections with farm roads were not included in the following discussion. The subsidence of the ground surface on each pipeline as well as that of pipelines was calculated by comparing current elevation and the designed elevation.

The subsidence rates were calculated at several points in the certain section (20 - 500 m) in the targeted pipelines comparing the values in blueprints, and the values were averaged within each pipeline. In addition to the subsidence, we defined the uneven subsidence per length of the pipeline as the difference of subsidence in adjacent two measurement points divided by their distance. This value represents the magnitude of non-uniform subsidence within the section. The observed subsidence of the pipelines and their specification are shown in Table 7.1. The mean value of subsidence in the eight pipelines was 20.7 cm with a maximum value of 44.1 cm (2.5 cm yr^{-1}). Subsidence was observed in all the investigated pipelines, and no pipeline floated up. The variation of subsidence and the uneven subsidence per length of the pipeline was relatively small compared with a special condition such as the intersection with roads discussed later. Therefore, the subsidence occurs relatively uniformly within the whole section of the pipeline.

The Standard for Management of Civil Engineering presented by MAFF of Japan has regulated that the allowable error of the height of the pipeline for irrigation should be within ± 20 mm. Therefore, the pipelines regarded to be constructed within this precision because each

pipeline has passed its completion inspections after the construction work. However, the observed subsidence is much higher than the range of this standard, so it must be the subsidence that occurred after the construction and never be misconduct of the construction. Furthermore, the subsidence of pipe and subsidence of the ground surface were almost the same except for two pipelines. This suggested that the whole layer above the pipe, including refilled soil, subsided and consolidation of the peat layer below the pipe should be the major cause of subsidence of pipes.

The subsidence in the points within each pipeline did not vary, but the average values of subsidence highly varied depending on the pipelines, which suggested that a unique factor on the sites controls the rate of subsidence. The relations between subsidence of the pipeline and time since construction, the pipe diameter, and the pipe depth were examined, but no factor presents significant relations. The groundwater table that we did not investigate for this time is one of the important factors for peat subsidence (Schothorst, 1977; Yano et al., 1980), and other factors could possibly control the subsidence of the pipeline. Further investigation is required to clarify the factor that predominantly controls subsidence.

The standard section without special conditions tended to uniformly subside across the whole section, suggesting that the risk of uneven subsidence which causes leakage is not so high.

Table 7.1 The specifications of the irrigation pipelines without special installation condition and their subsidence since their construction.

No.	Time since construction (yr)	Diameter (mm)	Length of observation (m)	No. of observation points	Subsidence of pipe * (cm)	Maximum uneven subsidence per length of pipeline (mm m^{-1})	Annual rate of subsidence (cm yr^{-1})	Subsidence of ground surface (cm)
1-1	14	300	22	5	15.8 (2.0)	22.9	1.1	16.3
1-2	14	1,000	264	13	9.8 (5.2)	9.7	0.7	23.9
1-3	15	1,000	50	6	5.4 (4.0)	12.9	0.4	38.2
1-4	17	900	350	10	32.8 (8.6)	16.7	1.9	23.3
1-5	17	900	225	15	19.7 (11.7)	19.7	1.2	22.6
1-6	18	1,650	35	6	44.1 (5.7)	29.4	2.5	46.3
1-7	23	500	260	29	18.9 (6.7)	12.4	0.8	14.6
1-8	26	1,650	45	7	19.1 (4.4)	16.1	0.7	17.1

* ( ) represents standard deviation of subsidence

7.3.2 Uneven subsidence at intersections with farm roads

Eight sections on the intersection of the pipelines with farm roads of various sizes were investigated to evaluate uneven subsidence. For those sections, the absolute subsidence of the pipelines was not evaluated due to the technical problem mentioned in section 7.2.4. Instead of the evaluation of absolute subsidence, we compared "subsidence in 10 m section of pipeline in front and behind of the farm road" and "subsidence in the other standard sections" to evaluate the relative and local subsidence at the intersection, defining the "uneven subsidence at the intersection" as the difference of average subsidence between the 10 m in front and behind of the farm road and the other standard sections. As well as 7.3.1, the uneven subsidence per length of the pipeline defined as the difference of subsidence in adjacent two observation points divided by their distance was employed as the index of subsidence unevenness. In addition, the embankment load of the farm road was estimated based on the blueprints to parameterize the size of the road. One of eight pipelines was not on the peat soil, which was used for the reference to examine the effect of peat soil on the subsidence. The overview of the survey results is shown in Table 7.2, and Fig. 7.4 shows the example of a cross-section of pipelines.

The subsidence of the pipelines at the intersection with farm roads was larger than the other sections regardless of the size of the farm roads, as shown in Table 7.2. This was because the load of the embankment of the farm roads induced the consolidation. The uneven pipelines subsidence at the intersection with the farm road increased as the size of the road increased. The subsidence at the intersection was 35.8 cm larger than that of the standard section on average at the pipeline 2-7, where the maximum uneven subsidence of the eight intersections was observed. On the other hand, only slight uneven subsidence (a few cm) was found in the small roads with a thin layer of gravel. In pipeline 2-4, the subsidence at the intersection was instead 1.8 cm smaller than that of the other standard sections, suggesting that small-scale roads possibly do not cause uneven subsidence. At the reference pipeline of 2-1, which has no peat soil, the uneven subsidence was not found even though a load of the embankment was large.

The pipeline that we investigated generally consisted of a joint system of 6 m long pipes. The connecting joints usually have a certain flexibility that allows bending to a certain degree. The local and uneven subsidence found in the intersection with the roads might be absorbed by the increase in the angle of bend of the flexible joints. The intense subsidence occurred in the concentrated section around the roads, so the only limited number of the joints absorbed load

caused by subsidence. In pipeline 2-8 shown in Fig. 7.4, a pipe with 6 m length behind the farm road subsided 42 cm, originally designed to cross the road horizontally. In this section, the pipeline consisted of fibre-reinforced plastic mortal (FRPM) pipes with a diameter of 1,000 mm and a length of 6.01 m. Given that a single pipe in the pipeline system subsided 42 cm, the angle of bending at the joint was estimated to be up to 4.0 degrees that are exceeding the allowable value of 3.5 degrees presented in the Japanese standard for construction of irrigation pipelines with flexible joints (National Institute for Rural Engineering, 2007). The results suggested that the large-scale road embankment on the pipelines can increase the risk of falling off the joints and will cause leakage.

According to the personal communication with Shinotsu Chuo Land Improvement District, leakage with failure of the joints was found in 2 pipelines out of 8 dealt with in this section. The leakage was found in a juncture between the main pipelines (Steel Pipe) and the branch pipeline (FRPM pipe). In another example of the leakage, the connection between the FRPM pipe and the polyethylene pipe was leaked. The vulnerability of leakage is generally high in joints of different pipe types like the examples mentioned above because the joint is less flexible. Therefore, the localized subsidence of pipe under the road caused leakage in those examples.

To summarize the discussion, the investigation implied that the load of the farm road embankment possibly induced the subsidence at the section beneath the road, and the magnitude of subsidence depended on the size of the roads. The joint of pipes in some highly subsided pipelines might receive excess load beyond the allowable value. Further subsidence at the localized section beneath the roads could possibly cause leakage from the joints of pipes. Leakage has been already reported from the joints of the juncture of different pipe types where the joint could not absorb the uneven subsidence induced by the load of the farm roads. Therefore, it is necessary to continuously monitor the pipelines crossing the farm roads to prevent leakage and improve the longevity of the pipelines. In addition to the maintenance, it is required to avoid constructing the road to cross the pipelines in peatland in future design and construction. When it cannot help to construct roads on pipelines in peatlands, the design of the joint should be tolerant and flexible enough to absorb the localized subsidence that is expected to occur at the intersection.

Table 7.2 Subsidence of the irrigation pipelines crossing farm roads.

No.	Type of farm road	No. of observation		Uneven subsidence at intersection (cm)	Maximum uneven subsidence per length of the pipeline (mm m^{-1})	Estimated load of road (kN m^{-2})
		Intersection	Normal section			
2-1	Embankment (no peat)	3	11	0.3	9.2	46.2
2-2	Gravels	7	15	0.1	25.3	2.2
2-3	Gravels	2	8	0.8	3.1	2.8
2-4	Gravels	2	8	-1.8*	3.2	2.8
2-5	Embankment	3	4	7.8	20.9	14.6
2-6	Embankment	7	15	18.0	54.2	15.8
2-7	Embankment	6	15	35.8	44.5	16.1
2-8	Embankment	3	8	24.1	85.4	30.1

*The negative value represents the subsidence at the intersection was lower the that of the normal section.
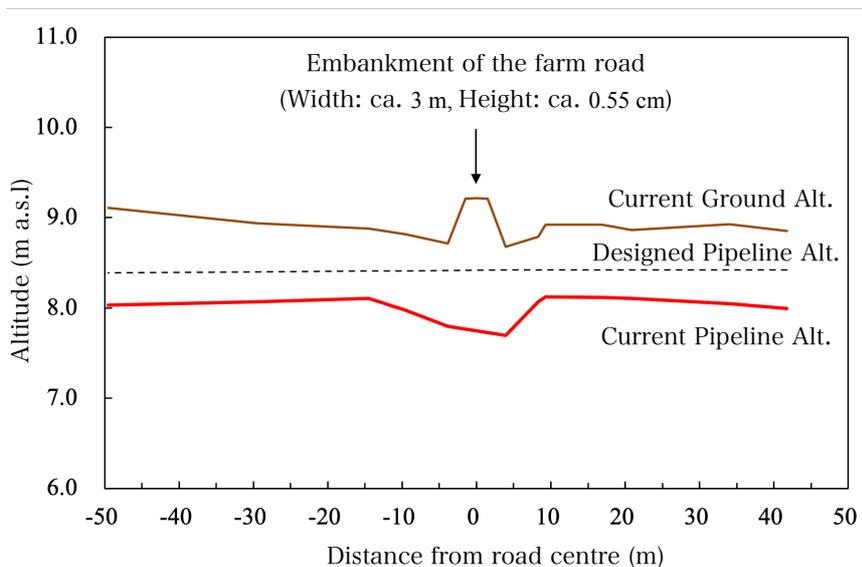
Fig. 7.4 Cross-section of the irrigation pipeline crossing a farm road at Survey Point 2-8.

7.3.3 Uneven subsidence at flexible pipes connected to aqueducts

Subsidence at the 11 flexible pipes that connect the pipe of a standard section of pipelines with no solid foundation to the aqueducts with solid pile foundation was investigated. We defined "flexible pipe displacement" as the displacement in the flexible pipes, i.e., the difference of elevation at both ends of the flexible pipe. We also defined "mean subsidence of the standard pipelines" as the subsidence of the pipeline jointed to the flexible pipe. The results are shown in Table 7.3, and an example of the cross-section of the pipeline is shown in Fig. 7.5.

Displacement of the flexible pipe was found in all the investigated pipelines due to uneven subsidence between the aqueduct with a solid foundation and the standard section of the pipeline. The displacement in the seven pipes out of 11 exceeded the designed allowable value (20 cm) of the flexible pipe. The subsidence of the pipes in the standard section got maximum at the point just behind the flexible pipes, as shown in Fig. 7.5. The unlevelled elevation between the standard pipeline and the aqueduct was compensated by the flexible pipe as expected in the original design. The most significant displacement between the aqueduct and the pipes in the standard section was found in pipeline 3-1, where the displacement was 37.1 cm in a 1.55 m-long flexible pipe with a diameter of 1,660 mm. The mean subsidence in pipes of the standard section is larger than the displacement of the flexible pipe in some investigated sections (pipeline 3-2, 3-

4, 3-7, 3-11), which suggested that the flexible pipe could not compensate fully to the unlevelled elevation between the pipeline and the aqueduct caused by subsidence.

It is well known that peat subsidence of ground surfaces around drainage ditches is generally intensified due to lower groundwater tables, which encourages peat degradation and consolidation (Miyaji et al., 1995). As shown in Fig. 7.5, the subsidence of the pipelines was also intensified around the drainage ditch. Consolidation of peat soil associated with increased effective stress due to low groundwater table might induce the pipe subsidence. On the other hand, the aqueduct crossing over the ditch is stable as it is on the solid pile foundation. As a result, the intensified subsidence of the pipes near the ditch made the large gap between the pipe in the standard section and the aqueduct. Sawada et al. (2021) reported a similar gap between fixed and unfixed parts in the pipelines under an embankment.

As the result of the investigation showed, the flexible pipe that jointed the pipelines to the aqueducts had large displacement due to the difference of the foundation, which sometimes exceeded the designed allowable value. Further subsidence will possibly cause accidents such as leakage. Although the flexible pipes were initially being expected to buffer the gap between the standard section of the pipelines and the aqueducts, the actual gap caused by peat subsidence was larger than the expectation in the design. It is necessary to continuously monitor the connection between aqueducts and pipelines because uneven subsidence easily occurs in the connection where the fixed section by the foundation locates often subsiding place around ditches.

Table 7.3 Subsidence of the flexible rubber pipes connected to aqueduct bridges.

No.	Displacement at flexible pipe （cm）	Mean subsidence of pipeline connected to the flexible pipe （cm）	No. of observation
3-1	37.1 *	19.1	7
3-2	17.8	20.4	13
3-3	28.8 *	17.0	15
3-4	31.1 *	35.9	16
3-5	13.4	12.5	2
3-6	22.3 *	15.8	5
3-7	26.0 *	44.1	5
3-8	16.9	6.3	6
3-9	26.8 *	12.9	7
3-10	22.4 *	13.9	7
3-11	12.8	24.5	9

* represents displacement excessing the designed allowable value.
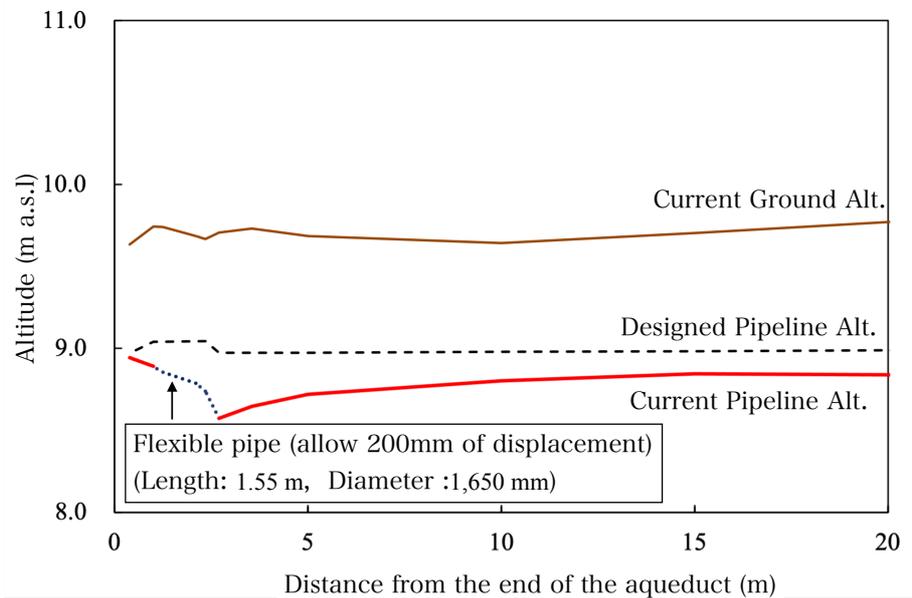
Fig. 7.5 Cross-section of flexible rubber pipeline connected to an aqueduct at Survey Point 3-1.

7.3.4 Subsidence of the pipelines passing different land use

We examined the effect of land use (paddy or upland) in the surrounding field on the subsidence of pipelines by investigating four sections. The results are shown in Table 7.4. The comparison of subsidence between the paddy section and the upland section suggested no significant effect of land use on the subsidence of the pipelines. Compared with the impacts of road embankment and aqueducts with a drainage ditch, the result suggested that the effect of land use was so small that there was no substantial uneven subsidence which possibly caused leakage.

Miyaji et al. (1995) and Yokochi et al. (2020) reported that paddy land use on peatland could effectively reduce the land surface subsidence based on comparing subsidence in the paddy and the upland fields. In addition to land surface subsidence, Sakamoto and Ueya (2021) showed that the subsidence of pipelines passing the paddy fields was significantly less than that in upland fields. The results in this study controversially implied that subsidence did not relate to land use despite the previous studies.

The pipelines we investigated in this study were constructed in the dedicated space for the irrigation pipelines apart from farm fields. The pipelines did not go through just beneath the

farm fields. Therefore, the difference of groundwater table in paddy and uplands fields in the irrigation period did not possibly reach the place where the pipelines were buried to modify the subsidence rate of the pipeline. Further investigation with groundwater table observation is needed to clarify the effects of land use on pipelines' subsidence.

To summarize this section, uneven subsidence of the pipelines passing through different land use was little compared with that in the intersection with road embankment or the aqueducts with a drainage ditch, suggesting that possibility of accidents regarding leakage is not high in the pipelines with the different land use. However, pipelines that are buried in the place where the groundwater table is more directly affected by the differences in land use will possibly cause uneven subsidence. Therefore, further investigation, including groundwater table observation, is required to examine the effect of land use on the subsidence of pipelines.

Table 7.4 Subsidence of the irrigation pipelines constructed in different land use.

No.	Length of observation (m)		No. of observation		Subsidence of pipeline in upland section (cm)	Subsidence of pipeline in paddy section (cm)	Difference (upland-paddy) (cm)
	Upland	Paddy	Upland	Paddy			
4-1	129	107	15	13	20.4	17.0	3.4
4-2	100	100	6	6	-	-	-1.9
4-3	189	46	7	3	36.6	29.3	7.3
4-4	215	91	14	4	21.3	21.1	0.2

* Only the difference is shown at 4-4 due to lack of absolute subsidence data.

7.4 Conclusion

In this study, we investigated the subsidence of irrigation pipelines constructed in peatlands with the number of examples of actual cross-sections. The quantitative observation and evaluation of subsidence of the pipelines are suggested as follows.

(1) Pipelines buried in peat soil with no special construction condition subsides 5 to 44 cm for the whole section for approximately 20 years since the construction.

(2) Subsidence of pipelines is locally intensified under the high load by farm road embankment which possibly causes leakage associated with failure of joint of the pipes.

(3) Connection of aqueducts with solid pile foundation and pipes in the standard section with no foundation has a large gap that exceeds the designed allowable value. As a result, the risk of leakage is very high in the connection.

(4) The difference in land use of surrounding fields of pipelines does not significantly affect the subsidence of the pipelines. However, this result is against the previous studies, so further and detailed investigation is required to conclude.

Accidents of irrigation pipelines on peatlands have been reported in many places. They will probably increase in the future as it has been passed more than 30 years since the construction of the pipelines in the 1990s. Appropriate management and maintenance of pipelines at the sections with risk of subsidence are the urgent challenges to reduce the pipelines' life cycle cost and sustain the irrigated paddy agriculture on peatlands. In this study, we quantitatively clarified the actual situation of pipelines' uneven subsidence in the sections that the previous studies suggested as a high risk of leakage. The findings in this study will be helpful to consider future design and maintenance of pipelines on peatlands with adopting the nature of peat.

Chapter 8 Overall Discussions and Conclusions

8.1 Interpretation for the Future Use of Peatlands

In this series of studies, subsidence-related problems were dealt with, particularly in the peatlands under paddy land use. Paddy use on peat is unique land use of peatland compared with other countries with peat soils. Focusing mainly on the paddy land use and associated mineral soil dressing, impacts of those implementations on peat subsidence was examined. Overall, the results of this study implied that the practices associated with rice paddy cultivation had positive effects on the prevention of peat subsidence. The paddy use itself could effectively reduce, with some examples of almost no subsidence for a decade. Soil dressing for paddy rice cultivation on peat soils also had a positive effect of reducing subsidence. Though irrigation facilities for paddy fields in peatlands were vulnerable to subsidence and possibly require more cost for their maintenance than those on the other soils do, paddy use and agricultural practices with paddy rice cultivation are certainly practical solutions in terms of avoidance of further subsidence. In addition to our studies, studies in other countries with peatlands have implied that wetted or rewetted use of peatlands such as paludiculture successfully reduced the emission of greenhouse gasses (de Jong et al., 2021; Knox et al., 2015; Schlattmann & Rode, 2019). From these perspectives, the paddy use of peatlands should be encouraged for sustainable use of them.

However, the socio-economic situations of paddy rice cultivation in Japan possibly conflict with the encouragement of paddy use of peatlands. Associated with the population decline and change of dietary habits, the demand for staple rice has been continuously decreasing for decades. The price of rice has also been depreciated by more than 30 % for 30 years. As a result, the economic situation for rice production got worse and worse. MAFF of the Japanese government has introduced several policies as countermeasures for the decreasing rice demand. Currently, the ministry encourages the use of paddy for upland crops such as wheat, soy, and forage crops with direct payment for those cultivations and agricultural engineering implementations such as the installation of subsurface drainage. However, considering the current socio-economic circumstances mentioned above, it is challenging to facilitate the paddy use of peatlands. For sustainable use of agricultural peatlands, technological means and a socio-economical approach is strongly required.

One of the most promising options to encourage rice cultivation in peatland is to take

advantage of the carbon credits. As reviewed in Chapter 4 of this study, peatlands have been substantially responsible for the emission of greenhouse gas in the agricultural sector in Hokkaido. So, a countermeasure for the greenhouse gas emission in the agricultural sector must focus on the emission from peatlands. Unfortunately, the government has not recognized the emission from agricultural peatlands in their policy for climate change so far. Besides, even the greenhouse gas inventory report misunderstood the emission from peatlands. Therefore, policymakers should recognize the agricultural peatland related external costs such as greenhouse gas emission and land surface subsidence and should optimize the external costs related to agricultural use of peatlands with appropriate intervention based on economic analysis. The implication of this study will hopefully provide important insight into subsidence-related issues on peatlands for future land use strategies.

Regarding the situation of other countries with peatlands, as reviewed in Chapter 2, many implementations to reduce greenhouse gas emissions and subsidence in peatlands have been attempted, particularly in European countries. In those attempts, they usually struggle against the profitability of the implementation (Buschmann et al., 2020). For example, the rewetting of agricultural peatlands to reconstruct natural wetlands will force farmers to lose entire agricultural profit from their lands. Paludiculture also substantially reduce agricultural profits (Schlattmann & Rode, 2019). In contrast to these circumstances, the paddy rice cultivation in Japan is still profitable though the situation gets severer. In this perspective, there is nothing better than using peatlands as paddy.

8.2 Conclusion

In this study, issues related to peat subsidence were investigated. In Hokkaido, peatlands have been uniquely cultivated as paddies for rice production, and to get knowledge about how paddy use affects peat subsidence and what is needed for sustainable paddy agriculture in peatlands had been studied. Despite more than 50 years since the reclamation, the subsidence continues. Subsidence is a crucial problem accompanying agricultural use of peatlands, and thus future decision-making on land use must consider this continuous subsidence and environmental consequences. The result of this study implied agricultural practice with paddy cultivation could possibly reduce subsidence. However, the socio-economic condition conflicts with this as the

demand and price of rice has been decreasing. Therefore, a combination of technical and socio-economic implementation is necessary to make the best future land use and management on peatlands to mitigate further subsidence, additional cost to maintain agronomic production, and related environmental problems.

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