Master's Thesis of Geography

Holocene Climate Change and Human Impact around Lake Pomeho on the East Coast of Korea

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Abstract

Climate change continues to be at the forefront of scientific research and global political debate. The ability to understand and predict future climate patterns is an important concern. Reconstruction of the paleoclimate is a vital step in modeling future climate change. The Holocene epoch(11700cal yr BP-present) contains periods that were warmer and cooler than present conditions. Careful examination of past climate events can provide researchers with greater predictive accuracy for modelling future climate change.

Until now, there have not been many paleolimnological studies carried out in Korea due a lack of natural lakes and undisturbed sediments. However, lakes on the east coast of Korea have remained relatively undisturbed and are providing a wealth of climate data for Korean researchers.

The purpose of this study is to reconstruct mid- and late Holocene climate and environmental changes around Lake Pomeho on the east coast of Korea. Pollen analysis, grain-size analysis, organic content analysis, magnetic susceptibility analysis and radiocarbon dating were performed on an approximately seven meter long section of a core taken from the northern edge of Lake Pomeho.
The sediment core was radiocarbon dated to approximately 6700 cal yr BP. Based on statistical analysis(CONISS) of the pollen data, five zones were created.

The climate in Zone PM 1(??-6700 cal yr BP) had a high percentage of *Quercus* and other mesic hardwoods, likely representing the Holocene Climate Optimum(HCO) in Korea.
In zone PM 2(6700-4000 cal yr BP), the percentage of *Quercus* pollen decreased while *Pinus* increased at around 5800-5500 cal yr BP. This likely represents the end of HCO in Korea. Magnetic susceptibility data and grain-size analysis indicate that erosion levels remained heavy until around 5600 cal yr BP, when both decrease, suggesting the stabilization of sea level rise. At around 4300-4000 cal yr BP, there was a sudden decrease in arboreal species and an increase in cold tolerant plants, indicating climate conditions deteriorated, corresponding to the 4.2 kiloyear cold event found in other parts of the northern hemisphere. This study presents the first evidence for it in Korea.

Zone PM 3 (4000-2500 cal yr BP) is characterized by either a deterioration of the climate after 4000 cal yr BP due to decreased EASM activity or a localized amelioration of the climate possibly due to the Tsushima Warm Current(TWC). In the first scenario, *Pinus*, thought to be of the relatively warm weather species *Pinus thunbergii*, decreases while *Quercus* increases, indicating cooler conditions. The percentages of *Artemisia* and Poaceae both decrease, possibly due to shifting soil conditions. In the second scenario, a warm phase could be indicated by the return of several hardwood species after the 4.2 kiloyear event. *Quercus* showed a significant increase from the previous zone, possibly indicating warmer and wetter conditions.

Zone PM 4 (2500-850 cal yr BP) represents the beginning of agriculture in the area around Lake Pomeho. Disturbance indicator species *Artemisia*, Poaceae and Amaranthaceae increase in this zone, as does *Oryza* type pollen. Pollen concentrations in PM 4 are very low, while mean grain size is relatively high. This data suggests agriculture began in the region around 2500-2100 cal yr BP.

Zone PM 5 (850-350 cal yr BP) is characterized by the intensification of agricultural activity around Lake Pomeho. Wild and domesticated Poaceae both continue to increase, as does *Artemisia*. *Quercus* continued to decline while *Pinus* and *Betula*, both sunlight loving trees, increased. High mean grain size indicates increased erosion, probably due to land clearance resulting from intensified agriculture.

This study attempts to reconstruct the mid- to late-Holocene environment around Lake Pomeho on the east coast of Korea. Because there are few areas in Korea with undisturbed sediments, this study can be a meaningful contribution to paleoclimate research in Korea and East Asia. The end of the HCO, stabilization of sea level rise and the intensification of agricultural activities around Lake Pomeho correspond with data from other nearby study sites, indicating continuity in the area. Furthermore, this study is the first in Korea to find evidence of the 4.2 ky event, making it a meaningful contribution to the study of paleoclimate reconstruction.

Keyword: multi-proxy analysis, east coast of Korea, coastal lagoon, paleoenvironmental reconstruction, paleoclimate, mid- and late-Holocene

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Chapter 1. Introduction

1.1 Background

Climate change is the largest threat facing the biosphere today. Problems ranging from sea level inundation to deforestation and desertification are already impacting vulnerable regions. Further increases in temperature and a growing human population will only exacerbate this issue. Human induced environmental degradation and production of greenhouse gases continues to accelerate this process, putting humanity's most vulnerable groups in imminent danger. Moreover, natural hazards such as floods, typhoons and blizzards have a major impact on societies; phenomena often attributed to climate change. Understanding not only how climate change occurs, but also how its strength and frequency vary over time is important to modeling future climate change.

Computer modeling is an important step in determining how climate change will impact the Earth. Scientists are working on creating increasingly accurate mathmatical models that can predict short and long term changes to the climate. However, the models are only as good as their predictive power. Climate model researchers utilize past climate data to test the predictive accuracy of models. Even allowing for uncertainties in reconstructing past climates, data from paleoclimate research provides a useful tool in constructing climate models for future conditions. Future research in paleoclimatology will continue to provide valuable information for climate modeling and help improve our understanding of long and short term fluctuations in the Earth's climate(IPCC, 2007).

As of yet, it is not well known how rapidly climate change will occur, nor what effects it will have on the natural environment and humans. The Holocene epoch, representing approximately the last 11,700 years, including the rise of human domination of the earth and the rise of agriculture, is a useful analogue for studying future change. The natural vegetation history of the Holocene includes climate optima, when temperatures were warmer and wetter than present and cold events, when temperatures dropped below those of modern values. Moreover, human impact on the environment is also recorded in Holocene paleo-records. Such periods can be carefully studied to increase the accuracy and resolution of climate models (Yum et al., 2003; Yang et al., 2007; Lim et al., 2012; Park et al., 2012a; Nahm et al., 2013).

Many types of analysis are useful for reconstructing paleoclimate and paleoenvironment**.** In areas where human disturbance on lake environments have been minimal, sediments cores can be analyzed to offer a window into proximal environmental and climate changes of the past. Though paleoclimatology is a well-researched field, relatively few studies have been carried out in Korea due to a lack of natural lakes with undisturbed sediments. Many areas of the country, especially lowland areas and lakes, have been drained to make way for agriculture activity. However, the east coast of Korea contains several coastal lagoons that with deep, undisturbed sediments dating to the early Holocene and beyond. Researchers have been examining cores from this area since the 1970s (Y. Yasuda, 1977; Chang and Kim, 1982; M. Tsukuda, 1978; Fujiki and Yasuda, 2004). Many of these initial studies focused only on pollen analysis and radiocarbon dating, providing limited resolution for reconstructing the environment around the study areas and the local climate. Recent studies have used a broader array of analytical techniques including physical and chemical analysis of sediments to increase the amount and type of data and to help better understand the nature of climate change during the Holocene(Park et al., 2012a; Park et al., 2012b; Park and Constantine, 2015).

1.2 Regional Setting: Lake Pomeho, Yang Yang County, Gangwon Province, South Korea

Lake Pomeho (37°57’ N 128°46’ E) is located in Yang Yang County, Gangwon Province, on the central east coast of the Korean Peninsula. It is one of several coastal lagoons located on the east coast of the peninsula. Due to the relative scarcity of natural lakes in Korea, especially those not disturbed by human development, Lake Pomeho is an important resource for paleoenvironement and paleoclimate reconstruction research on the Korean peninsula. This site has not yet been investigated for environmental and climate reconstruction analysis.

Lake Pomeho covers an area of 0.14 km^2 with a shoreline circumference of 2.16 km. Its average annual depth is between 1-2 meters. The study area lies on the western edge of the Sea of Japan(East Sea), a semi –enclosed marginal sea. The only oceanic water flowing into the Sea of Japan today is a the Tsushima Warm Current(TWC), a branch of the Kuroshio Current that originates in the subtropical north Pacific waters(Gallagher et al., 2015). On the landward side, Lake Pomeho sits on the edge of the Yeongdong area of Korea, a thin coastal plain that is bordered by the East Sea on the east and the Taebaksan mountain range on the west.

The Lake Pomeho core was taken on the northern edge of the lake in the middle of a farm access road. Due to marshy conditions, the coring equipment was not able to approack closer to the edge of the lake. Due to the coring location, approximately the top four meters of sediment core were not used for this analysis because it consisted of sand and other clastics used to build the farm access road. The remaining bottom approximately 8 meters were used for analysis.

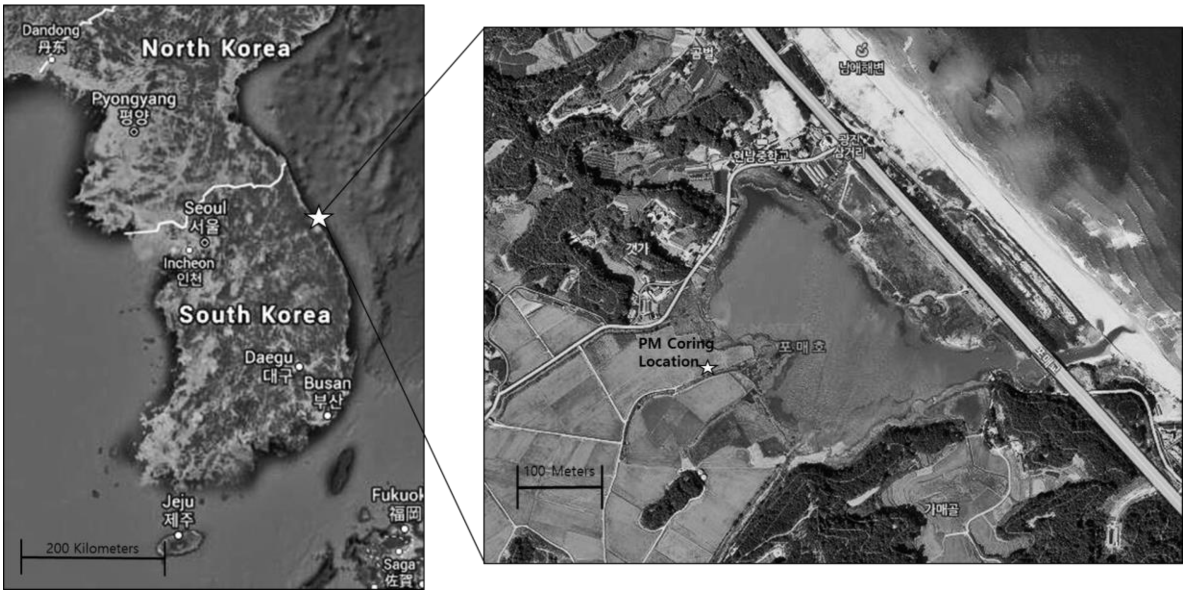

Figure 1.1. Regional setting and drilling site for Lake Pomeho (37°57' N 128°46' E) core (Google Maps, 2015; Naver Maps, 2015) Lake Pomeho is located on the central east coast region of the Korean peninsula. The coring location(indicated by the star) was located on the northern shore of the lake in the middle of a farm access road.

Figure 1.2. Lake Pomeho coring site and coring process. One meter long core sections were taken in the middle of a farm access road on the north side of Lake Pomeho using a hydraulic piston corer.

1.3 Climate

Korea has four distinct seasons, with a large difference between the coldest and warmest months. Lake Pomeho lies in the East Asian Monsoon belt, and the EAM is the dominant factor influencing climate in the region(Yihui and Chan, 2005). Lake Pomeho has a continental climate with hot summers and dry winters. The coastal regions have relatively warmer temperatures in winter and cooler temperatures in summer than the central region of Korea. The cold season has an average temperature of ∽7℃ between December and March. The warm season has an average temperature of around 23℃ with highs that can exceed 30℃. Average precipitation in the area is approximately 1593 mm, with the heaviest rainfall occurring during the months of July and August. During the summer rainy season, precipitation averages 849.5 mm, accounting for 53.3% of annual precipitation in the area. The distinct seasonal changes are controlled by the East Asian Monsoon (EAM) in both summer and winter (Yang and Kira, 1975; Korea Meteorological Association, 2009; Park et al., 2012b).

Table 1.1. Average temperature and precipitation data of Yang Yang area 2000-2012. (Worldwide Weather Online. http://www.worldweatheronline.com/yangyang-weather-averages/kr.aspx

	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Ave. High Temp. C°	2	6	11	19	24	28	29	30	26	20	11	4
Ave. Low Temp C°	-10	-7	-2	4	10	16	21	20	14	6	-1	-7
Precipitation (mm)	21.2	28.4	47	77.6	117.2	142.3	476.9	372.6	172.7	58	51.3	26.7

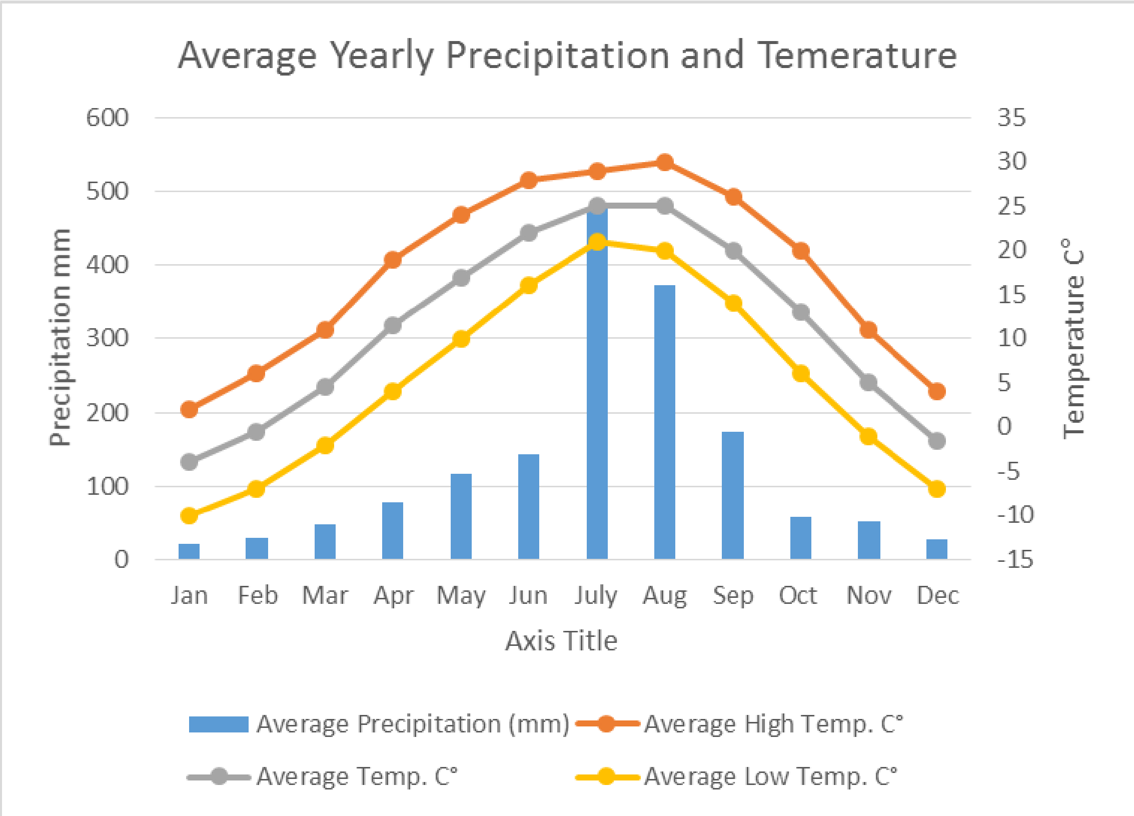

Figure 1.3. Graph of average precipitation and temperature for Yang Yang County, Gangwon Province. (Worldwide Weather Online. http://www.worldweatheronline.com/yangyang-weather-averages/kr.aspx)

1.4 Vegetation

Lake Pomeho is classified under the cool temperate forest, central zone region of the Korean peninsula. The main tree species in the central zone region consist of *Quercus mongolica*, *Quercus serrata*, *Abies holophylla*, *Carpinus laxiflora*, and *Styrax* spp. Anthropological disturbance in the area has led to *Pinus densiflora* dominating in areas that are not under cultivation (Yim and Kiram, 1975; Park et al., 2012a). Plant and tree species found around the lake include Pinaceae, *Abies holophylla,* Cupressaceae, *Thuja orientalis,* Betulaceae, *Alnus hirsute,* Fagaceae, *Quercus variabilis,* Polygonaceae, *Persicaria amphibian,* Theaceae, *Camellia japonica,* Rosaceae,*Kerria japonica, Potentilla egedei var. groenlandica, Prunus yedoensis,* Leguminosae, *Lathyrus quinquenervius,* Aceraceae, *Acer palmatum, Acer triflorum,* Celastracea, *Euonymus japonica, Tiliacea, Tilia amurensis*

Oleaceae, *Chionanthus retusa,* Convolvulaceae, *Calystegia soldanella, Labiatae, Scutellaria dependens, Scutellaria strigillosa,* Scrophulariaceae, *Euphrasia maximowiczii, Linaria japonica,* Plantaginaceae, *Plantago camtschatica Chamisso,* Compositae, *Achillea alpia, Ixeris repens,* Alismataceae, *Alisma plantago-aquatica var. orientale, Sagittaria aginashi,* Potamogetonaceae, *Ruppia maritime,* LiLiaceae, *Allium tuberosum,* Pontederaceae, *Monochoria korsakowi,* Iridaceae, *Iris ensata var. spontanea,* Gramineae, *Elymus mollis,* Cyperaceae, *and Carex kobomugi*(Water Quality and Management, 2011).

1.5 Research Purpose

The purpose of this study is to reconstruct the middle and late Holocene climate and environmental changes around Lake Pomeho, a lagoon on the central east coast of the Korean Peninsula, using a multi-proxy approach. The sediment was sampled at depths of between 1-12 centimeters to discern changes in the past environment and climate change in the region around Lake Pomeho. The research aims to:

1. Reconstruct the environment around Lake Pomeho using pollen analysis.

2. Reconstruct the past climate by using a variety of proxy data.

3. Determine when agricultural disturbance began in the area and when agricultural activities intensified around the lagoon.

This thesis is divided into six chapters. Chapter One discusses the background for the study, along with the regional setting, climate and vegetation characteristics of the site. In Chapter Two, the literature reviewed for this study is discussed. In Chapter Three the methodology used in this study is explained in detail. In Chapter Four, the results are presented and in Chapter Five the results are discussed in terms of how the environment and climate changed around Lake Pomeho and how this data relates to other studies in East Asia.

Chapter 2: Literature Review

The Holocene epoch, part of the Quaternary Period, began at the end of the Pleistocene epoch. The Holocene spans roughly the last 11,700 years and encompasses the growth and development of human society, including writing systems and agriculture. The Holocene is generally divided into five categories; Pre-Boreal(10-9 ky cal yr BP), Boreal(9-8 ky cal yr BP), Atlantic(8-5 ky cal yr BP), Subboreal(5-2.5 ky cal yr BP), and Subatlantic2.5 ky cal yr BP-Present)(Anderson et al., 2007). The Holocene's climate can be broken roughly into three periods for ease of discussion; early-Holocene, mid-Holocene, and late-Holocene. In East Asia, the early-Holocene can be characterized by the warming of the climate after deglaciation, starting around the end of the Younger Dryas at 11,700 cal yr BP. During this time the climate warmed up, and contains the Holocene Climate Optimum(9000-5000 cal yr BP), on average the warmest period of the Holocene epoch. The Mid-Holocene in East Asia is characterized by a drying out of the climate as the East Asian Summer Monsoon(EASM) decreased in strength after around 4000 cal yr BP(Stebich et al., 2015; Lim et al., 2012; Hong et al., 2001). The late Holocene is characterized by slightly lower temperatures than those of the middle Holocene. Fluctuations in the climate during this period had a large impact on flora and fauna and thus an indirect impact on human settlements. In Korea, human impact on the environment in the form of agricultural began in the late-Holocene. The environments around many of the study sites reviewed below were changed markedly by manmade land clearance and agriculture from their original environments, making climate reconstruction based on the natural environment difficult after around 3000 cal yr BP.

Therefore, this literature review is broken down into two parts; the pre-rice cultivation period and post-rice cultivation period.

2.1 Pre-rice Cultivation Period Environmental and Climate Change in East Asia

Korea

On the East Sea(Sea of Japan) side of Korea, an early study at Lake Youngrango (Chang and Kim, 1982) found that the climate began warming at the end of the late-glacial, with *Pinus*, *Quercus* and *Carpinus* increasing steadily. Increased arboreal pollen and decreased herbaceous pollen indicate expansion of secondary forest. This zone (II) is estimated to cover the time period from ∽9500-4500 cal yr BP, encompassing the Holocene Climate Optimum in Korea. A more detailed study 40 kilometers south at Lake Hyangho(Fujiki and Yasuda, 2004), suggests a similar timing for the end of the HCO in Korea. It found that Korea was drier during the middle Holocene compared to the Japan side of the East Sea(Sea of Japan). The authors suggest dominance of *Pinus* along the east coast at 6500 cal yr BP may be a result of increased rainfall and rocky conditions which were not conducive to soil formation, limiting the growth of *Quercus* forests. The period between ca. 5000-2000 cal yr BP showed a decrease in *Pinus* and an increase in *Quercus*, signifying a cooling off of the climate and the end of the HCO.

Research on Lake Soonpogae(Park et al., 2012a), south of Hyangho, further supports Fujiki and Yasuda's study. Their results indicate dense stable forest dominated by *Quercus* from about 8200-7700 cal yr BP. Between approximately 7700-5900 cal yr BP, there were exceptionally high sedimentation rates and high percentages of *Quercus* and Cyperaceae. This period is presumed to represent the HCO. Sedimentation rates were high until ∽5800 cal yr BP, indicating the stabilization of sea-level rise around this period. Jo(1980) suggests a similar time frame for east coast sea level stabilization. At around 5900 cal yr BP, sedimentation rates decreased, as did forest density, indicative of the weakening of the East Asian Monsoon(EAM).

On the Yellow Sea(west) side of Korea, Yi et al (Yi et al., 2012) suggest the HCO occurred at around 7000-4800 cal yr BP around Paju, Cheonggye(Gwantong Trench A), and Hannam, and between 8420-4700 BP at Paju Unjeong (Yi and Kim, 2011), near the lower reaches of the Han river. Evidence from the Cheollipo area around Pyeongtaek (Nahm et al., 2013) also support this time frame. Their results suggest the HCO occurred almost simultaneously at the three sites, between 7300 and 5000 cal yr BP. This is further supported by a study done in the Cheollipo wetlands (Yang et al., 2007), which indicates that the period between 7400-4500 cal yr BP is the warmest and wettest period on the Korean west coast after 10,000 cal yr BP. Between about 4500-1300 cal yr BP, the Cheollipo area became drier and turned into marshland. This period coincides with climate records in other parts of Korea that show a cooling and drying trend in the climate as the HCO ended and the East Asian Monsoon weakened.

China

Studies carried out in Northeast China also display similar climate trends related to the timing of the HCO and the weakening of the EASM in the mid- to late-Holocene. At Lake Jingpo in northeast China (Chen et al., 2014) a study found that from ~5100-3600 cal yr BP, the EASM was relatively strong but from ~3600-2100 cal yr BP the climate dried and the EASM weakened. From approximately 2100-100 cal yr BP, they suggest that the EASM again strengthened. A sediment core from Huangqihai Lake(Hao et al., 2014), located between semi-arid and semi-humid regions, further indicated an overall strengthening of the EASM until around 4700 cal yr BP, after which a drying and cooling trend occurred between ~4700-3500 cal yr BP. Pollen concentration reached a maximum at around 3600 to 3000 cal yr BP and then shrubland expanded again as the EAM began to weaken at 3000 cal ka BP. A study from Daihai Lake, suggests the HCO occurred between 8500 and 3000 cal yr BP. Similar to Huangqihai Lake, a drying and cooling of the climate occurred from ~4450-2900 cal yr BP, indicated by a large scale retreat of forest and an expansion of grassland vegetation. The authors argue that fluctuations in the Daihai Lake region are linked to changes in summer solar radiation in the ocean current of the western North Pacific and temperature variations in the lake are related to changes in the position and strength of polar high-pressure systems. (Xiao et al., 2004).

Further inland, a study of aeolian deposits in the Hulun Buir Desert indicate that the Holocene Climate Optimum occurred from 11 ka to around 4.4 ka ago due to enhanced monsoonal response to orbital forcing, which caused heavier precipitation in the study area(Li and Sun, 2006). Zhang et al.(2014) also suggest that in the interval before 4370 cal yr BP, soil sections in the Hulun Buir Desert indicate a wetter environment corresponding to the Holocene monsoon maximum. At around 3900 cal yr BP, wetland initiation at the site corresponds to the monsoon weakening event. Evidence from Hulun Lake(Wen et al., 2009) however, suggests that a general cooling trend occurring in the middle Holocene starting around 8000 BP, with two relatively cold intervals occurring around 4400-3350 and 2050-1000 cal BP. The authors suggest precipitation levels were extremely low between 4400 and 3350 BP, occurring at nearly the same time as a sharp decline in water temperature in the western tropical Pacific and the eastward shift and reduction of the Kuroshio Current.

A study from Lake Xiaolongwon (Xu et al., 2014), identified ∽500 year cyclical cold phases at 4650, 4150, 3550, 2850, 2550, 1750, 1250, 750, and 150 cal yr BP, closely matching variations in total solar irradiance (TSI). Oxygen isotope records from Dongge Cave in southern China (Wang et al., 2005) support this, indicating weakening monsoon events taking place at 8300, 7200, and 6300 cal ky BP, with a temporal spacing average of 1200 years, suggesting a possible linkage to northern Atlantic ice-rafting events or discharge from the Laurentide ice sheet. The authors contend it is possible that oceanic circulation changes in the North Atlantic triggered changes in the Asian Monsoon and that changes in the Holocene

Asian Monsoon are the result of a number of factors, including orbitally induced insolation changes, changes in solar output and changes in oceanic and atmospheric circulation.

In mud belts along the inner shelf of the East China Sea, K. Wang et al. found evidence for decreases in the intensity of monsoonal precipitation at 6000, 5300, 4500, and 3700-3300 cal yr BP. Decreases in sediment intensity during these periods indicate low discharge drought events on the Yangtze River. These findings correlate with those in Chinese cave stalagmites(K. Wang et al., 2014). Further inland, a study on the Chinese Loess Plateau(Xia et al., 2014) suggest that the HCO was interrupted by a drying period between 6300 and 5300 cal yr BP.

Japan

T. Sagawa et al. (Sagawa et al., 2014) used planktonic foraminiferal $\delta^{18}O$ records to reconstruct late Holocene sea surface temperatures(SST) off the eastern coast of Hokkaido. They suggest changes in SST could be the result of perturbations in solar activity. Their study identified eight colder periods punctuated by seven warmer periods at intervals of around 500 years each during the past 6000 years, corresponding to Chinese cave stalagmite records and Xu et al.'s study of Lake Xiaolongwon. Further south in the Tokyo Bay region, a study by B.R. Shonea et al.(2004) suggest the HCO occurred around 6500 to 5500 cal yr BP. Average temperatures were around 3 degrees warmer than modern values until around 5500 cal yr BP when the climate became drier. A core from Lake Biwa(K. Yamada, 2004) in Honshu, central Japan also suggests millennial scale variation in both the EAWM and EASM, with increases in precipitation occurring at 7000, 6000-4500, 4000-2500, and at 2000 cal yr BP, and a particularly dry phase around 4000 cal yr BP.

On the Japan Sea side, several studies suggest the mid- and late-Holocene climate was affected by the Tsushima Warm Current (TWC), ameliorating the climate in the Sea of Japan region. The TWC is the dominant current flowing into the Sea of Japan(East Sea). The intensity of the flow into the East Sea has fluctuated over the past 9000 years due to changes in sea level and has been associated with climate changes in the Alps in Europe(Khim et al., 2005; Gallagher et al., 2015). A study of diatom derived sea surface temperatures around the Sea of Japan suggests the Holocene was warmer by 1-2 C° between 8200-3300 cal yr BP, with fluctuations of 1000 and 400-500 years. The authors suggest that annual SSTs in the southern warm water region of the Sea of Japan oscillate strongly due to fluctuations in the location of the TWC(Koizumi, 2008). Y. Igarashi(2013) found evidence for fluctuations in Quercus percentages on the west coast of Hokkaido that also seem to correspond with TWC diatom temperature(Td) values. Similarly, a study done by Leipe et al.(2013) on a core sample taken off the western coast of Hokkaido suggests the climate in the study region may be influenced by another factor not directly related to large scale changes in East Asian Monsoon variations and solar insulation. After around 6900 cal yr BP, sea level rose and allowed the TWC to strengthen in the Sea of Japan, reducing the influence of cold water masses. Their evidence suggests a slightly cooler and drier climate than present between 5500 and 3600 cal yr BP, and warmer and wetter conditions similar to present after 3600 cal yr BP.

The literature reviewed above suggests that climate variability during the mid- and late-Holocene is broadly similar throughout East Asia. It suggests that the HCO occurred between roughly 8500-5000 cal yr BP, and afterwards there was a general drying trend as the EASM weakened. Some evidence from the East Sea(Sea of Japan) area indicate that a local warming trend may have been caused by changes in the influx of the Tsushima Warm Current. Though much research has been done, more studies are needed to broaden our understanding of both overall climate variability and shorter term climate events in East Asia. Korea's east coast lagoons provide an opportunity to expand climate knowledge in the region, making Lake Pomeho an important site worthy of investigation.

2.2 Environmental Change after the Beginning of Rice Cultivation in Korea

Archaeological Evidence for Rice Cultivation in Korea

Rice has been a staple of the Korean people for thousands of years. It is the mainstay of the Korean diet and one of the world's 'great grains' that sustain massive population densities. Its origin in China is well researched(Khush, G., 1997; Crawford and Chen, 1998; Fuller and Harvey, 2007; Molina et al., 2011; Gross and Zhao, 2014) in many fields including genetics, archeology, biology, geography, history and others. Though there is still lively debate about the origins of rice agriculture, its home in Southern China seems fairly certain. The diffusion of rice to other areas of the world is still debated however, and its dispersal out of

China and into the Korean peninsula and Japan is still contested. Three plausible diffusion routes have been suggested; a northern route through China that moved south into the Korean peninsula, a southern route by sea, and a direct route by sea across the Yellow Sea. The theory commonly supported by researchers suggests the northern route is the most likely one. However, no reliable information regarding the diffusion routes of rice agriculture within Korea is yet available(Park, J., 2007). Current research in South Korea has provided some evidence for how rice agriculture dispersed around the Korean peninsula. However, the current political state of affairs has made it difficult to examine information collected in North Korea. Furthermore, a lack of natural lakes with undisturbed sediments makes it difficult to examine ecological changes through pollen analysis(Park, J., 2012a).

Several archeological studies have been done in Korea that shed light on the dispersal of rice agriculture around the peninsula. Choe(1982) argues that, although it is well established that rice agriculture was present in Korea by the early Mumun period (3500-3000 cal yr BP), it is difficult to trace the diffusion route from China onto the peninsula due to a lack of direct evidence in the form of rice grains being found in Liaoning and Manchuria. The author suggests that the introduction of stone tools into the peninsula would have accompanied rice agriculture, as the knives are manufactured to harvest rice plants and therefore make a useful proxy for the presence of rice cultivation. Semi-lunar shaped knives have been found along with large quantities of rice grains in prehistoric sites, suggesting that this type of knife was used for harvesting rice. Four types of stone knives; rectangular polished; straight edged with convex back; convex edge with convex back; and convex edge with straight back have been found. Rectangular polished blades are thought to have originated in Northern China and spread to areas of Manchuria and North Hamgyong Province in North Korea. Blades with a straight edge and convex back were widely distributed in China, and in North Pyongan Provence in North Korea. Convex edged knives with convex backs have been found in Liaoning and southwestern Manchuria, along with a few in northern North Korea. Convex edged knives with straight backs have been found in the Yangtze River area, North Korea, South Korea and Kyushu. The development and expansion of the use of these knives represents the Lungshan cultural expansion from China, and along with it rice cultivation into Korea and into Japan. Based on the movement of stone agricultural tools, Choe estimates the development of rice in Korea at around 2400 cal yr BP(Choe, 1982)

Crawford and Shen(1998) suggest a much earlier period for the start of rice agriculture than Choe, at around 4300 cal yr BP at Locality 1, Kawaji site, in Ilsan. Nearly 300 grains of rice were recovered from peat bogs there. Based on this it has been suggested that rice was introduced to the west coast of Korea around 5000 cal yr BP and from there spread through the Han River basin. A later study by Crawford and Lee(2003) report the presence of rice remains in over 50 sites in Korea in peat layers, along with Poaceae pollen and Oryza type phytoliths, suggesting rice cultivation began on the Korean peninsula as early as 3500-5000 cal yr BP. Rice grains found at Oun archaeological site were dated 3900 cal yr BP and 3000 cal yr BP. The rice dated to 3000 cal yr BP was contextually consistent with the early Mumun context in which it was found. Furthermore, 10 archeologically identified paddy fields have so far been identified in Korea, the two oldest, Okhyun and Yaumdong, are dated to the Early Mumun period. The authors suggest, based on evidence of the presence of millet and barley in Korea, and a similar mixed grain economy in China during the Neolithic, that Korea also had rice agriculture during the Late Chulmun, though the evidence for it needs strengthening(Crawford and Lee, 2003).

Shin et al.(2013) found rice grains, along with millet, barley and other grains in the floor fill of a large house in Daecheon-ri, near Daejeon City in south-central Korea. Four radiocarbon dates taken from wood charcoal found at the same depth put the age of the rice remains at around 5200 cal yr BP, in the Mid-Neolithic period. The authors note though that individual rice grains were not directly dated in the site. Ahn(2010) suggests that the rice grains could be a later intrusion as the rice appear with barley and wheat, neither of which appear in China until after the late 3rd to early 2nd millennium B.C. However, carbonized rice grains were found in other Chulmun sites including the peaty layers of Daehwa-ri, Gahyeon-ri, in a shell midden in Nongso-ri, and rice plant opal in Juyeop-ri and Jodong-ri, all dating to the Late-Neolithic.

Two other sites reportedly containing rice husks have been dated to the Late Chulmun period, Gahyeon-ri (AMS date 4010±25 cal yr BP) in Gimpo, and Seongjeo-ri (AMS date 4070±80 cal yr BP) in Ilsan. Both samples come from the lower Han River in Midwestern Korea, where rice husks were recovered around an area with no archeological features present or direct radiocarbon dates of rice, leaving open the question of whether rice was actually grown in the area during the Late Chulmun. Ahn notes that so far, only Daechon-ri has yielded rice remains. No other sites from the Chulmun period have yielded rice remains, leaving the evidence inconclusive(Ahn, 2010).

During the late second millennium BC, Korea saw a dramatic shift in culture. People became heavily reliant on crops, including rice. By the mid-first millennium B.C., during the Middle Mumun period full scale agricultural villages were established. Rice remains became much more prevalent, appearing in over 100 sites dating from the early and middle Mumun period, including charred grains, impressions on pottery and rice phytoliths, indicating this was the likely period when rice agriculture became dominant in Korea. During the late Mumun, during the third century B.C. rice agriculture disappeared, only to reappear 200 years later with the emergence of urban societies. This was likely due to a change in climate that was not favorable to rice agriculture(Ahn, 2010).

Biological Evidence for Rice Cultivation in Korea

The study of pollen microfossils offers another opportunity for determining when agriculture intensified. By examining the types and amounts of pollen in a sediment sample it is possible to estimate what types of vegetation grew in a given area and their relative densities, as well as reconstruct the climate based on the ecological characteristics of the species present. When attempting to determine the beginning of agriculture, it is not always easy to find direct pollen evidence of domesticated species due to small numbers of pollen. However, evidence of human disturbance is not limited to what is planted, but also by what grows naturally in disturbed environments. *Artemisia, Pinus* and others can all be indicator species of human disturbance. Oryza type Poaceae can also indicate agricultural intensification in a region.

In the Central Western region of Korea, rice cultivation began to appear at around 3000 cal yr BP. Yi et al.(2008) report increases in *Pinus* and *Fagopyrum*(buckwheat), indicators of human activity, in Gwantong A trench, Cheonggye-cheon, a tributary of the Han River. This corresponds with findings by Yi and Kim(2012) in the Paju Unjeong area, where signs of rice paddy cultivation began to appear at the commencement of the Bronze Age (3000-2300 cal yr BP), and was intensified around 2100 cal yr BP, when human induced forests became dominated by Gramineae. Samples from three sites; Paju, Cheonggye, Gwangtong Trench-A, and Hanam indicate human disturbance from 3000 to 1400 cal yr BP, characterized by a marked increase in Gramineae pollen and a reversal of arboreal and non-arboreal (AP/NAP) ratios, which suggests people at the site intensely used the area(Yi and Kim, 2011).

In the Southwest, Choi et al.(2005) found evidence for full scale rice cultivation starting around 4050 cal yr BP. They note the rapid expansion of *Pinus densiflora* and the appearance of Oryza type pollen. Hwang et al.(2012) examined phytoliths from a core taken in the Nabokri valley plain, Buyeo. Their findings indicate that Oryza sativa occurred for the first time at the site around 3000 cal yr BP, and shows relatively high rates of O. sativa by 2000 cal yr BP, indicating that intensive and stable rice farming was taking place by then. Near the Boseong area, there was an increase in open woodland and *Pinus* and Polypodiaceae, indicators of human impact, from around 3700 to 2900 cal. yr BP(Chung, 2011). J. Park et al.(2013) found evidence for an increase in Castanea(chestnut) pollen from around 3050-2350 cal yr BP and suggest that the increase in Castanea may be associated with a natural population increase that arose with the start of herbaceous crop agriculture in the area. The later decrease in Castanea between ca. 2350-1750 cal yr BP may indicate the decline in interest of chestnuts as a crop as new iron tools flooded into the area and made herbaceous type agriculture more appealing. The pollen composition at Woljeong-ri(Park and Kim, 2015) also showed a dramatic shift around 3050 cal yr BP, with a significant rise in Castenea, along with an abrupt increase in the frequency of Poaceae and *Artemisia*. There was a particular increase in cultivated type Poaceae at this time, indicative of full scale rice agriculture taking place at this time. Chang and Kim(1982) found high percentages of Gramineae, Artemisia and other herbaceous pollen indicators of rice agriculture in Wolhamji, near Buyeo city, around 2100 cal yr BP.

In the Southeast, rice agriculture first appeared in Bangeojin(Chang and Kim, 1982) around 2300 cal yr BP, as indicated by the dominance of *Pinus* and herb pollen. Choy and Richards(2009) used stable isotope analysis on human bone remains found in the Nukdo shell midden near Busan to determine whether the plants in their diet originated from C_3 or C_4 plants. Measurements from the bone collagen in the shell midden indicate that humans consumed C3 plants, such as rice, starting from the late Mumun to Iron Age.

Rice agriculture seems to have developed later on the east coast of Korea than in other areas, suggesting it spread down the west coast first and then eastward. At Lake Youngrangho in Sokcho City, the appearance of *Oryza* type and *Fagopyrum* in the pollen record indicates that between around 4000-1000 cal yr BP, human disturbance became more and more apparent in the region, indicating intensification of agriculture around the lake(Chang and Kim, 1982)

At Lake Hyangho, roughly 40 kilometers to the south, a more detailed study suggests that agricultural disturbance began around 2000-600 cal yr BP, indicated by the appearance of *Fagopyrum* at the same time that Gramineae was increasing. After 600 cal yr BP, land usage became even more intensive in the area, suggesting full scale agriculture(Fujika and Yasuda, 2004). A study at Soonpoegae, a few kilometers south of Lake Hyangho, also suggests a similar time frame for the beginning of rice agriculture in the region. The authors suggest that human impact and agriculture became evident after around 2100 cal yr BP (Park et al, 2012a). Agricultural indicators also appeared at around this same time at Lake Gyeongpo(Yoon et al., 2008), a few kilometers south of Soonpoegae.

A study of Bongpo Marsh(Park et al., 2012b), found that from 3200-2600 cal yr BP the area was in its pre-agricultural phase as evident by high pollen concentrations and little variability in *Pinus* and *Quercus*. High variability in *Quercus* and *Pinus* percentages and low anthropogenic herb pollens from 2600 cal yr BP indicate human disturbance in the area before agriculture. From 1350 – 80 cal yr BP, evidence indicates full scale agriculture taking place in the area around the marsh. The authors contend that it is unlikely that agriculture would have started at the study site later than others on the east coast as there were no evident geographic barriers. Instead, the late appearance of indicator species may represent the intensification of agriculture. Similarly, studies done on Lake Ssangho and Lake Cheojinho (Park and Shin, 2012), in relative proximity to each other, found a comparable discrepancy in the timing of the start of agriculture. At Lake Cheonjinho, Holocene climax taxa remained undisturbed and total organic content (TOC) remained high until around 910 cal yr

BP. At Ssangho, to the south, agricultural activity becomes apparent much earlier, at around 2100 cal yr BP. The authors suggest that rather than there being such a large temporal difference in agricultural intensification at two sites with such close proximity, it is more likely that rice agriculture only appears in the pollen record after it has become sufficiently intensified.

Table 2.1. Palynological evidence for the end of the HCO and appearance of agriculture activity on the east coast of Korea(Coordinates from www.maps.google.com).

Author	Location	HCO	Agriculture
Chang and Kim, 1982	Lake Youngrangho 38.218259, 128.582085	∽9500-4500 cal yr BP	∽4000-1000 cal yr BP
Fujiki and Yasuda, 2004	Lake Hyangho 37.910920, 128.809481	∽5800 cal yr BP End of HCO	∽2000-600 cal yr BP
Park et al., 2012a	Soonpoegae Lagoon 37.819854, 128.887937	∽5900 cal yr BP End of HCO	∽2100 cal yr BP to modern
Park et al., 2012b	Bongpo Marsh 38.248452, 128.564349		∽1350 cal yr BP
Park and Shin, 2012	Lake SSangho 38.085792, 128.662317		∽2100 cal yr BP
Park and Shin, 2012	Lake Cheonjinho 38.254176, 128.556312		∽910 cal yr BP
Yoon et al., 2008	Lake Gyeongpo 37.798691, 128.904065	∽6000 cal yr BP End of HCO	∽2000 cal yr BP

Chapter 3: Methodology

For this study, a twelve meter long core in one meter length sections was taken from the north side of Lake Pomeho in the center of a farm access road using a hydraulic coring machine. The core was taken to the cold room at the physical geography laboratory at the Department of Geography, Seoul National University for storage. It was split into two halves, with one half archived and the other cut into 1 centimeter slices for analysis. Analysis used in this study includes organic content analysis, grain-size analysis, magnetic susceptibility analysis, radiocarbon dating, and pollen analysis.

Table 3.1. Brief description of the methodology used in this study and their purposes.

Methodology	Purpose
Organic Content Analysis	To determine the amount of organic material deposited
Grain-size analysis	To determine the type and strength of sedimentation
Magnetic Susceptibility	To determine precipitation and erosion levels
Radiocarbon dating	To create a chronology of the sediment core
Pollen Analysis	To determine the tree and vegetation profile of the site

3.1 Sedimentation Characteristics

The top 4.16 meters of sediment consisted of clastics and sand used to build the access road where the core was drilled. It did not contain useful sediments and was not used in this analysis. The bottom ~6.84 meters of sediment consisted of dark, organic sediment interspersed with grey anoxic layers. The sediment characteristics consisted of very fine silt and mud interspersed with medium silt. The core sample contained freshwater and marine shell fragments throughout its entire length.

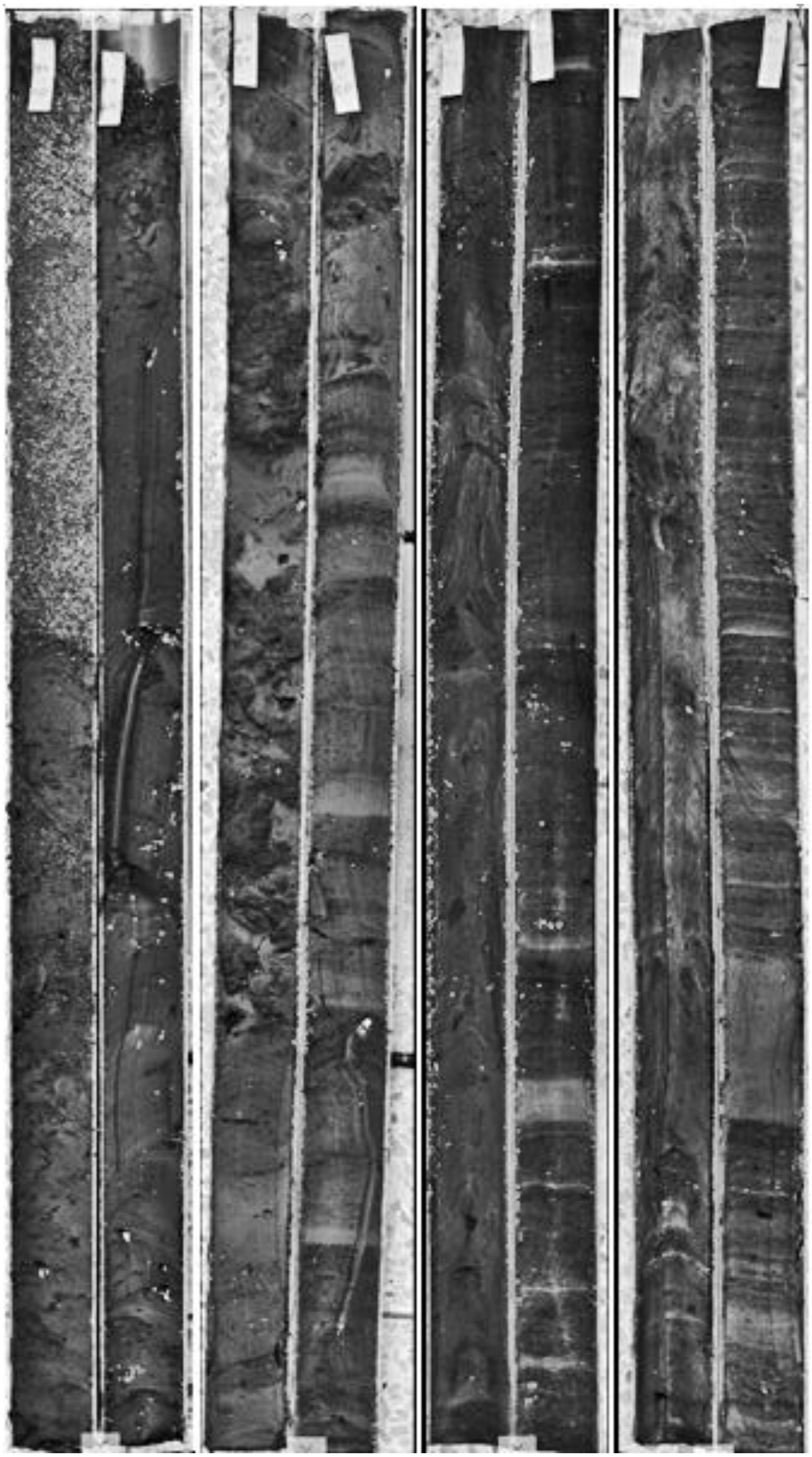

Figure 3.1. Core segments 4-12 after being split for sampling. The upper approx. 4 meters consisted of sand and other clastics used for road infill and was not sampled. The photo contrast and color have been enhanced to show lighter and darker regions in the sediment profile. The uppermost section of the core(400-500 cm) is on the far left, followed by progressively lower segments to the right(500-1200 cm).

3.2 Radiocarbon Dating

Radiocarbon dating of sediments is used to determine the age of plant and animal fragments found in sediments. In order to obtain an accurate timeline for the core, multiple samples are taken at varying depths. In this study, three samples were taken from depths 487 cm, 831 cm, and 1184 cm. Sample PM 487 and PM 831 both consisted of shell fragments. Sample 487 cm had very low δ13C in it. Sample PM 1184 consisted of woody plant material. Both shell fragments were calibrated using the Marine 13 marine curve calibration technique(Reimer et al., 2013). The woody plant fragment was calibrated using the Intcal 13 atmospheric calibration technique(Reimer et al., 2013). Age calibration for the samples was determined using the CalPal software program (http://c14.arch.ox.ac.up/embed.php?Fileoxcal.html). A radiocarbon chronology was established by Accelerator Mass Spectrometry (AMS) dating of the two shell fragments and one piece of woody plant material at the Korea Institute of Geoscience and Mineral Resources (http://www.kigam.re.kr/).

3.3 Organic Content Analysis

Organic content consists of various organic materials such as plants, leaves, roots, animal remains, et cetera. The amount of organic material in the sediment can reflect past productivity of the environment in and around the lake. In this study, organic content was analyzed at 4 centimeter intervals. In each sample, 2-3 grams of material were dried at 105°

for 24 hours to remove moisture, then the samples were transferred to ceramic crucibles and weighed. They were then combusted in a furnace (Fisher Isotemp Muffle Furnace Model 550-126) at 550℃ for one hour. The furnace was used to combust organic material in the sediments, leaving only nonorganic material remaining. The difference in this weight represents the amount of organic material present in the sediments. After combustion, the samples were allowed to cool for one hour, then the contents were weighed using the following formula.

$$Organic\ Content(\%) = \frac{PreWeight - Post\ weight}{PreWeight}\ X\ 100$$

(Pre-weight is the sample weight before combustion. Post weight is the sample weight after combustion)

3.4 Grain Size Analysis

Grain size analysis is a useful tool for determining sediment classification and hydrological dynamics of a system. Understanding the mechanisms of past depositional environment can help assess changes in the hydrology of the environment, as well as climate, precipitation rates, source area and limnology of aquatic environments. Grain size analysis is used to determine the particle sizes and frequency of distribution and to calculate a statistical description of the sample that adequately describes its characteristics(Last and Smol, 2001). In this study, samples were tested every 4 centimeters using a Beckman Coulter LS230 particle size distribution measuring device, which uses laser diffraction to measure particles.

Prior to processing the samples using the measuring device, samples were chemically treated using the following procedure:

1. Refrigerated samples were placed in a conical tube.

2. Organic matter was removed using a 10-20 ml of 30% solution of Hydrogen Peroxide (H_2O_2). The amount of H_2O_2 varied depending on the amount of organic material present in the sample and was continuously added until the chemical reaction stopped.

3. A 0.2% solution of Sodium Hexametaphosphate (Na.H.M.P) aqueous solution was added to each sample to act as a diffusion agent and left for 4 days. Each sample was shaken vigorously before being added to the measuring device.

4. Each sample was measured using the laser refraction technique, which measures the grain-size distribution by measuring angle dependency of light's intensity from the laser light that shines through the particles.

3.5 Magnetic Susceptibility

Magnetic susceptibility is one of the basic ways of measuring magnetism in the environment. Magnetic data collected from sediment cores, paleosols, and loess can be used as an indicator of environmental change over time. The concept behind it is simple; MS is dependent on the amount of iron oxide found in a sediment. MS gives an indication of erosion based on how much iron rich material has washed out of parent materials and settled in sediments.

Where sediments are stable, it can give an indication of precipitation change over time(J.A. Dearing, 1999).

In this study, magnetic susceptibility samples were measured at the Department of Geography in Chonnam National University using an MS2 Bartington Magnetic Susceptibility Meter. The samples were measured at 1 centimeter intervals while in their original coring tubes.

3.6 Pollen Analysis

The analysis of pollen spores is the principle method for determining vegetation response to past terrestrial environmental change. Pollen grains are found in angiosperms and gymnosperms, and contain both the female nucleus and the male nucleus in an ovule that can be used for fertilization. Spores are produced by ferns and mosses as well but are somewhat different in their reproductive process. However, they are the equivalent of plant pollen in their role. Wind dispersed pollen tend to be more numerous than those of insect dispersed pollen. Pollen grains are typically spherical or elliptical, and vary in diameter from 10μm (0.01 mm) to 100μm (0.1 mm). The majority of pollen is not used, in the sense that it does not find its intended target and eventually falls to the ground, is washed into lakes, rivers, swamps and the like where it settles to become a part of the sediment. The walls of pollen grains are composed of a substance called sporopollenin, a tough polymer, which tends to allow pollen to last indefinitely in anaerobic environments. Because of their various shapes and sizes, pollen can be identified to various taxonomic levels. Pollen spores are mixed in the atmosphere during dispersal, resulting in an even distribution of pollen rain over a given area. The proportion of pollen in a given sample depends on the abundance of its parent plant. Therefore, the composition of a given pollen sample is a function of the plant's relative abundance in the local environment, providing a snap-shot of the environment at the time of dispersal. Combined with a radiocarbon dating sequence, the vegetation environment at a given time can be identified. With pollen samples taken from a sequence of sediment layers, vegetation change over time can be inferred(Bennett and Willis, 2002) .

Pollen in this study was identified using the Illustrated Flora and Fauna of Korea Vol. 29, Pollens(Nam-Kee Chang, 1986) and with the Atlas of pollen, spores and further non-pollen palynomorphs recorded in the glacial-interglacial late Quaternary sediments of Lake Suigetsu, central Japan (Demskea et al., 2013) .

In this study, Oryza type pollen was distinguished from Poaceae by its length along its longest axis. Pollen grains larger than 35µm were considered to be Oryza type while those smaller than 35µm were considered to be Poaceae (Park et al., 2012b; Yi and Kim, 2011).

For this study, one hundred and sixteen samples were taken for pollen analysis at intervals of 3-10 centimeters. A minimum of 300 pollen grains were counted per slide. Eight samples (516 cm, 572 cm, 628 cm, 636 cm, 668 cm, 698 cm, 838 cm, 1170 cm) lacked sufficient pollen concentrations to permit counting to 300. In those samples, a minimum of 100 pollen were counted. The following procedure was used to prepare pollen samples for analysis following the standard palynological procedures as described by Fageri and Iverson(Fageri and Iverson, 1989).

1. Approximately 2 grams of sediment per sample were put into conical tubes, along with one tablet of Lycopodium spores, an exotic spore to facilitate estimation of total pollen and spores in the sample.

2. 10% HCL Process – 10 ml of HCL and distilled water solution were added to the sample to remove calcium carbonate.

3. 180 μm Sieving – samples were passed through a 180 μm sieve to remove organic materials larger than pollen grains. Samples were washed repeatedly with distilled water until clear.

4. 10% KOH Process – KOH and distilled water, at a ratio of 1:9 was used to remove humic acid. Samples were placed in a hot water bath for thirty minutes.

5. 10 μm Sieving – An additional sieving process using a 10 μm sieve was used to remove excess humic acid from the samples. Previous attempts using only the KOH process resulted in samples with too much humic acid remaining, making accurate identification of pollen samples difficult.

6. HF Process – a solution of 51% Hydrofluoric Acid was used to remove mineral content from the samples. Samples were placed in a hot water bath for 60 minutes, then left at room temperature for 24 hours for reactions to occur completely.

7. Acetolysis Process – a solution of H_2SO_4 and CH_3CO_2 mixed at a ratio of 1:9 was used to remove cellulose from the solution. The samples were placed in a hot bath for 2 minutes

and 30 seconds.

After the chemical processes were complete, the samples were stained and mixed with glycerin jelly before being mounted on slides for viewing. Pollen grains were identified and counted with a Leica DM 2500 light microscope with a 40x oil immersion lens objective for a total magnification of 400x. For each slide, a minimum of 300 grains were counted, except for some samples where there was total pollen concentrations were low. Then a minimum of 100 pollen grains was counted.

Pollen concentration was determined using the following formula: (Bennet and Willis, 2002)

$$Fossil\ pollen\ concentration = \frac{exotic\ pollen\ added\ x\ fossil\ pollen\ counted}{exotic\ pollen\ counted}$$

Lycopodium from CAP batch number 177745 (18,584 pollen per tablet) was added to each sample in order to determine the relative pollen concentration. All samples had a volume of 0.81 cm^3.

Chapter 4: Results

In this chapter, the results of multi-proxy analysis of the core are discussed. In order to facilitate description of environmental changes, five assemblage zones were established based on similarities in pollen types using the constrained incremental sum of squares clustering(CONISS) program in the Tilia software package. CONISS is a statistical procedure that works by searching for the two most similar, stratigraphically-adjacent, samples, and combining them. The combined data are then treated as a single unit and the search is repeated. These zones are characterized by their natural assemblages of pollen and spores and help facilitate interpretation of changes in vegetation over time(K.D. Bennett, 1999).

4.1 Zonation

Zone PM 1 (1197-1180 cm) (?-∽6700 cal yr BP)

Zone PM 1 is characterized by the dominance of *Quercus* pollen, which reached approximately 55%. *Pinus* pollen was lower than at any other point in the core. *Juglans*, *Tilia*, *Alnus*, and *Ulmus* were also present. *Artemisia* percentages were relatively low, and Poaceae was slightly higher than in PM 2. Monolete and Trilete spores were also low. Organic content in this zone averaged approximately 13%, and pollen concentrations averaged between ∽200-300/mg sample weight. Average grain size was ∽6 ϕ with one large spike at the top of the zone increasing to greater than 10 ϕ. Magnetic susceptibility was relatively high and variable throughout the zone.

Zone PM 2 (1180-998 cm) (∽6700-4000 cal yr BP)

Zone PM 2 is characterized by a decrease in *Quercus* to an average of 30.5% and an increase in *Pinus*(∽55.5%). *Juglans*, *Fraxinus* and *Ulmus* also decrease somewhat. *Artemisia* pollen, and Monolete and Trilete spores increase relative to the previous zone. At the beginning of PM 2, organic content decreases to around 9% and pollen concentrations decreased from 300/mg to less 100/mg before recovering at around 5000 cal yr BP, increasing to a maximum of approximately 17% at ∽4900 cal yr BP. Pollen concentrations also follow the same increasing trend, reaching a maximum of over 400 grains/mg sample weight. MS levels are very high and variable from the beginning of PM 2 until a sudden drop at around 4900 cal yr BP. Mean grain size was high and variable in this zone until ∽5200 cal yr BP, ranging from ∽3-6.6 ϕ.

Between ∽4300-4100 cal yr BP, there is a sudden drop in Arboreal Pollen/Total Pollen(AP/TAP) ratio from approximately .88 to .68. *Quercus* and *Pinus* both show a decrease at this level. *Alnus*, *Fraxinus*, and *Ulmus* pollen suddenly disappear. *Acer* and *Tsuga* pollen both appear briefly at this level. *Artemisia* and Poaceae pollen increase slightly. Monolete and Trilete spores also increase. Between 4300-4000 cal yr BP, organic content also shows a significant decrease from around 15% to approximately 11%. Pollen concentrations decrease to less than 100/mg sample weight. Mean grain size increases at around 4200 cal yr BP cm to 5.23 ϕ. MS shows a sudden increase at ~4200-4000 cal yr BP.

Zone PM 3 (998-892 cm) (~4000-2500 cal yr BP)

Zone PM 3 is characterized by a relatively high variability in *Quercus* pollen. *Alnus* reappears and increases after disappearing briefly at the top of PM 2. *Betula* appears much more frequently than in the previous zone. *Acer* and *Tsuga* both disappear. *Artemisia* and Poaceae both decrease relative to PM 2. Monolete and Trilete spores also decline after their increase at the top of the previous zone. Organic content and pollen concentrations both reached their highest levels of any point in the core before dropping off towards the top. Mean grain size shows several increases in size at ~3700 cal yr BP, ~3500 cal yr BP, and ~2950 cal yr BP, corresponding with relatively large increases in *Quercus* pollen percentages. AP/TP ratio increased to its highest point in the core, before dropping off near the top of the zone. Mean grain sized spiked at ~3700 cal yr BP and 3500 cal yr BP to ~5-5.5 ϕ but showed relatively little variability in this zone compared to the previous one.

Zone PM 4 (892-639 cm) (~2500-850 cal yr BP)

Quercus declined significantly in this zone to around 20% before increasing again. *Pinus* remained the most common type of pollen present. Shade tolerant *Tilia*, *Fraxinus*, and

Ulmus all decreased. *Betula*, a heliophilic tree, appeared sporadically. *Artemisia* and Poaceae, disturbance indicators, increased significantly. *Oryza* type pollen, an indicator of intensified rice farming, also increased. Amaranthaceae, which had appeared sporadically in lower zones, increased in frequency and amount. *Periscaria*, *Geranium*, and Cyperaceae also appear with greater frequency. Monolete spores increased significantly and Trilete spores increased relative to Zone PM 2. There was an overall decrease in organic content from the previous zone. Pollen concentrations dropped significantly at the beginning of the zone to less than 100/mg sediment weight. Arboreal pollen as a percentage of total pollen decreased from approximately .9 to .75 at the top of the zone. Sediment at the beginning of the zone showed a change in color from black to gray, indicating less organic material present. Mean grain size increased significantly, indicating heavy erosion of the area around Lake Pomeho. MS showed an increase at the beginning of the zone, also indicative of erosion.

Zone PM 5 (639-516 cm) (∽850-350 cal yr BP)

Quercus showed a further decline(∽17%) in this zone to its lowest average in the core, while *Pinus* increased to its highest percentage in the core(>60%). Shade tolerant species such as *Juglans*, *TIlia*, and *Fraxinus* all continued to decline. Sun loving *Betula* continued to increase. Disturbance indicators *Artemisia* and Amaranthaceae increase more from zone PM 4, as did Cyperaceae. Monolete and Trilete both continued to show relatively high percentages. Organic content showed a precipitous drop at ~800 cal yr BP to less than 10% before increasing again to an average of around 13 percent. Pollen concentrations remained low at below 200/mg sample weight. AP/TP continued to decrease to a low of .6 at the top of the zone. Mean grain size increased to less than 5 ϕ contiguously with drops in AP/TP and Pollen concentration levels.

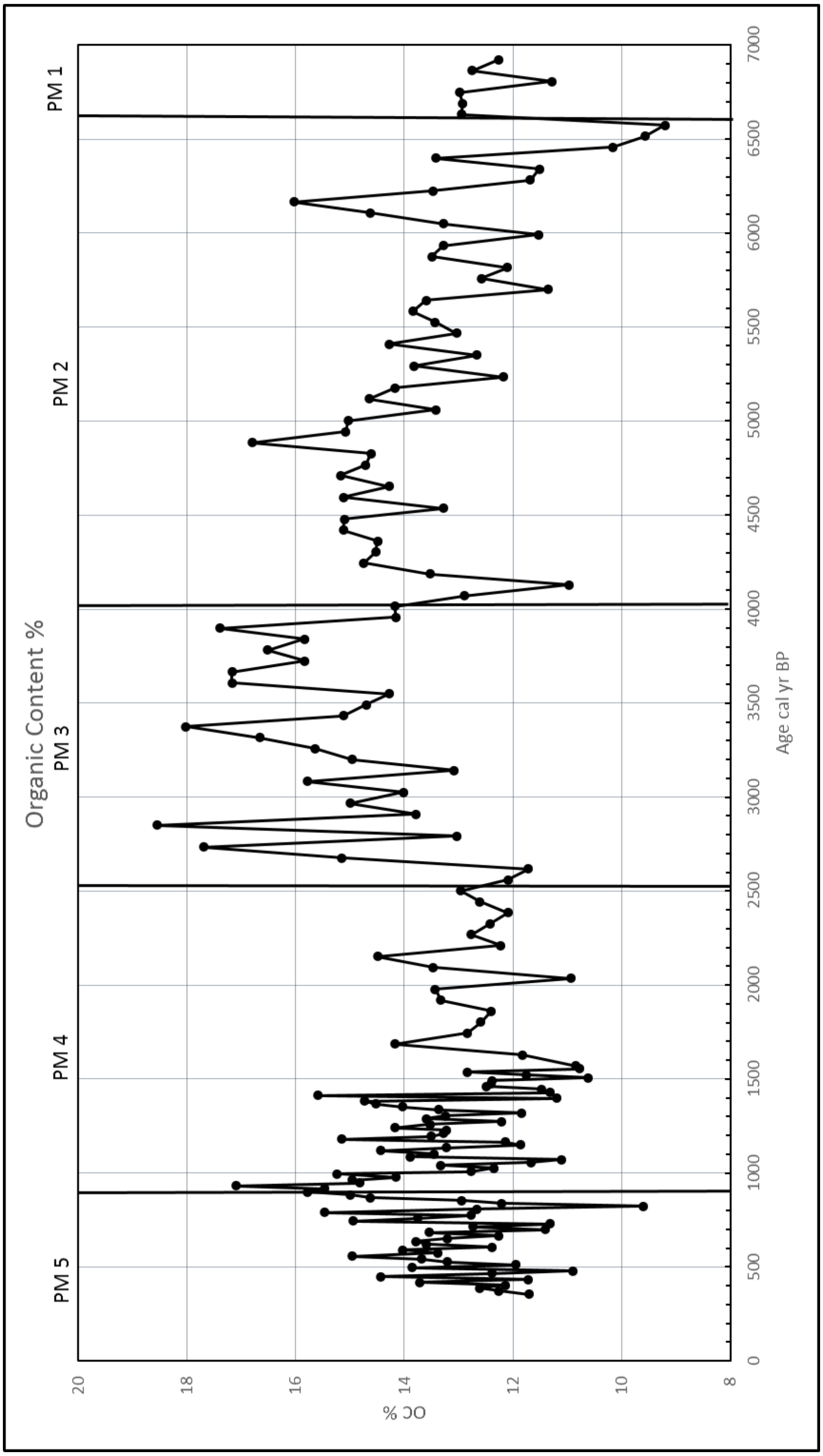

Figure 4.1. Organic content for Lake Pomeho

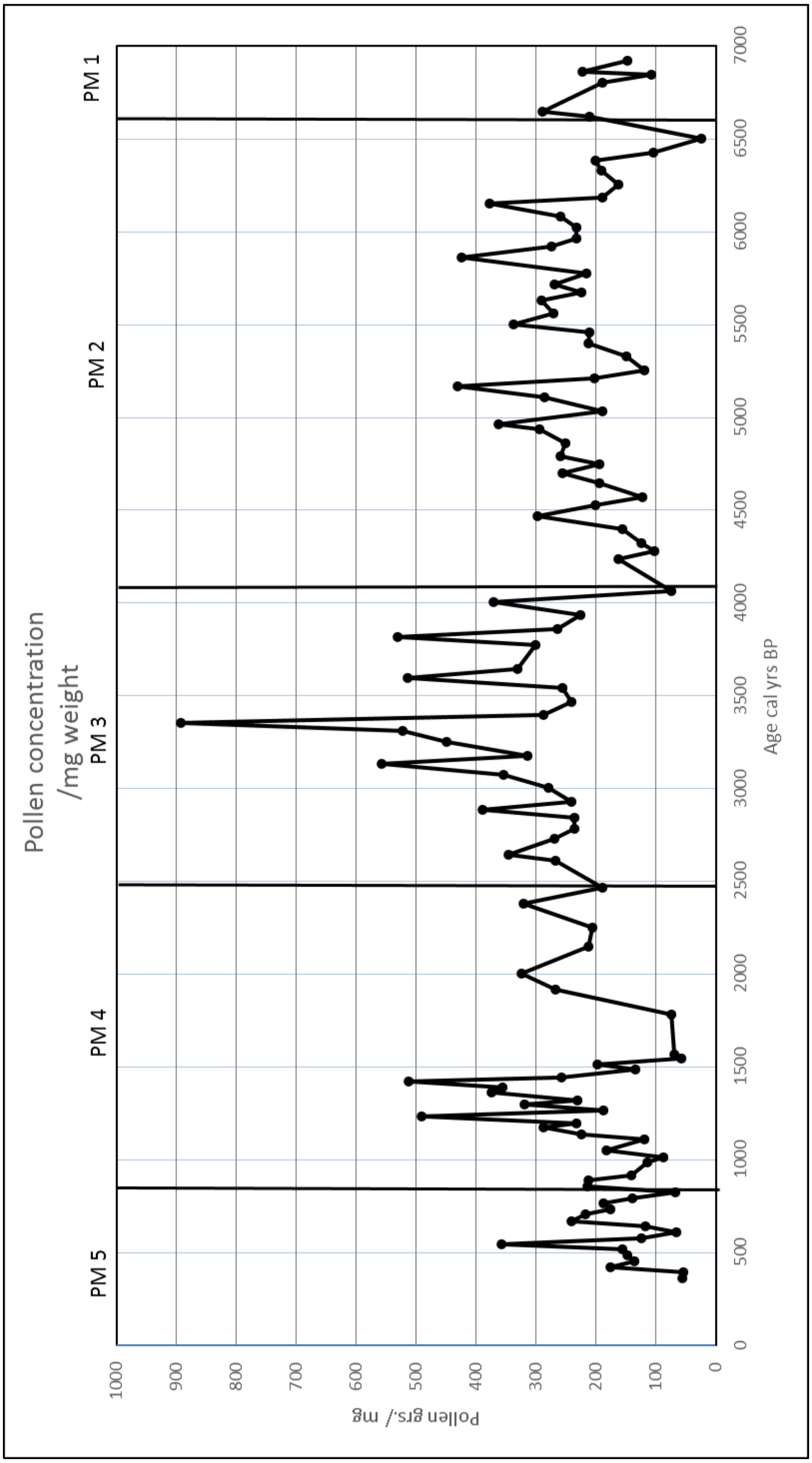

Figure 4.2. Pollen concentration/mg sample weight for Lake Pomeho

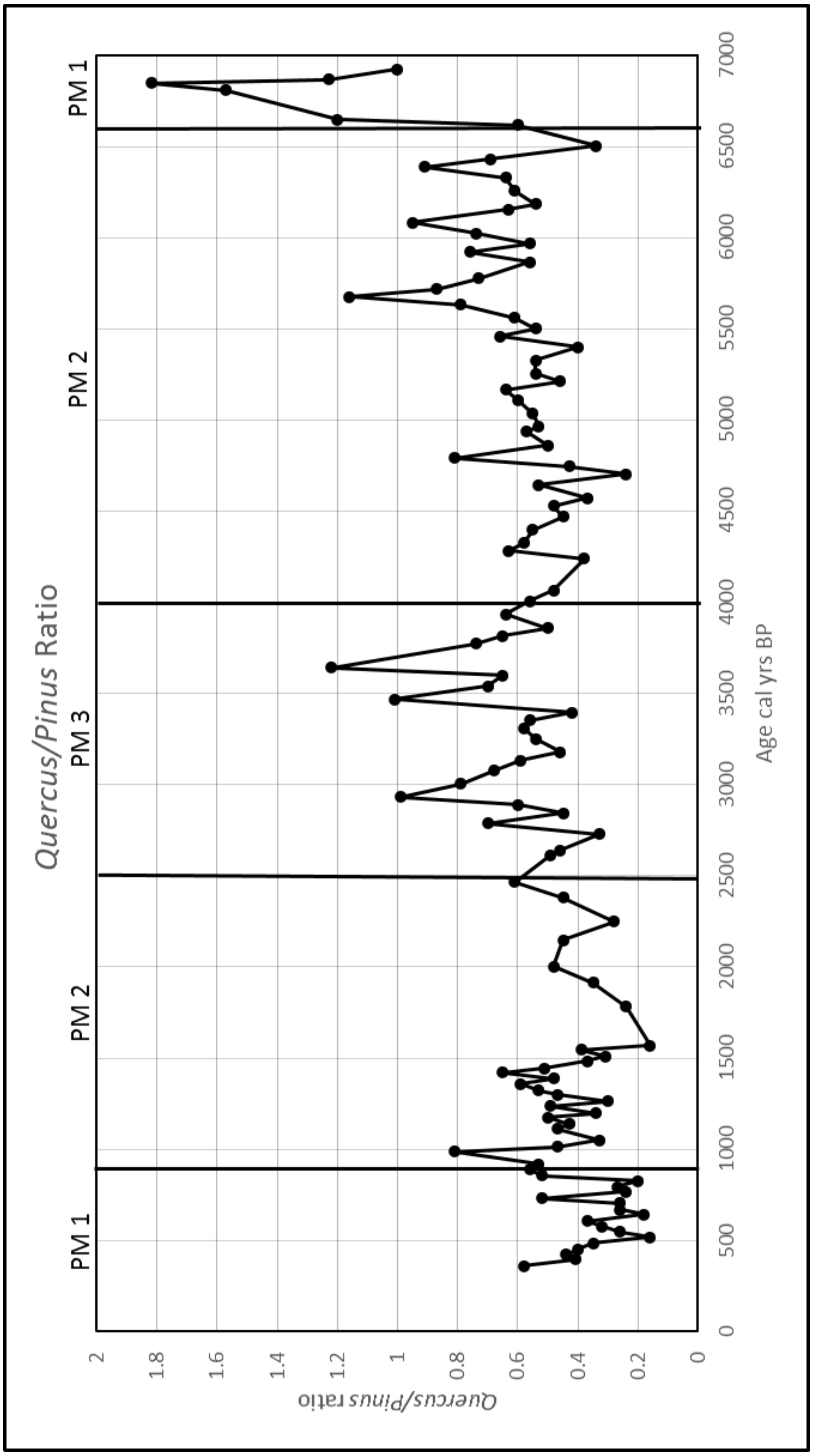

Figure 4.3. ***Quercus/Pinus* Ratio for Lake Pomeho**

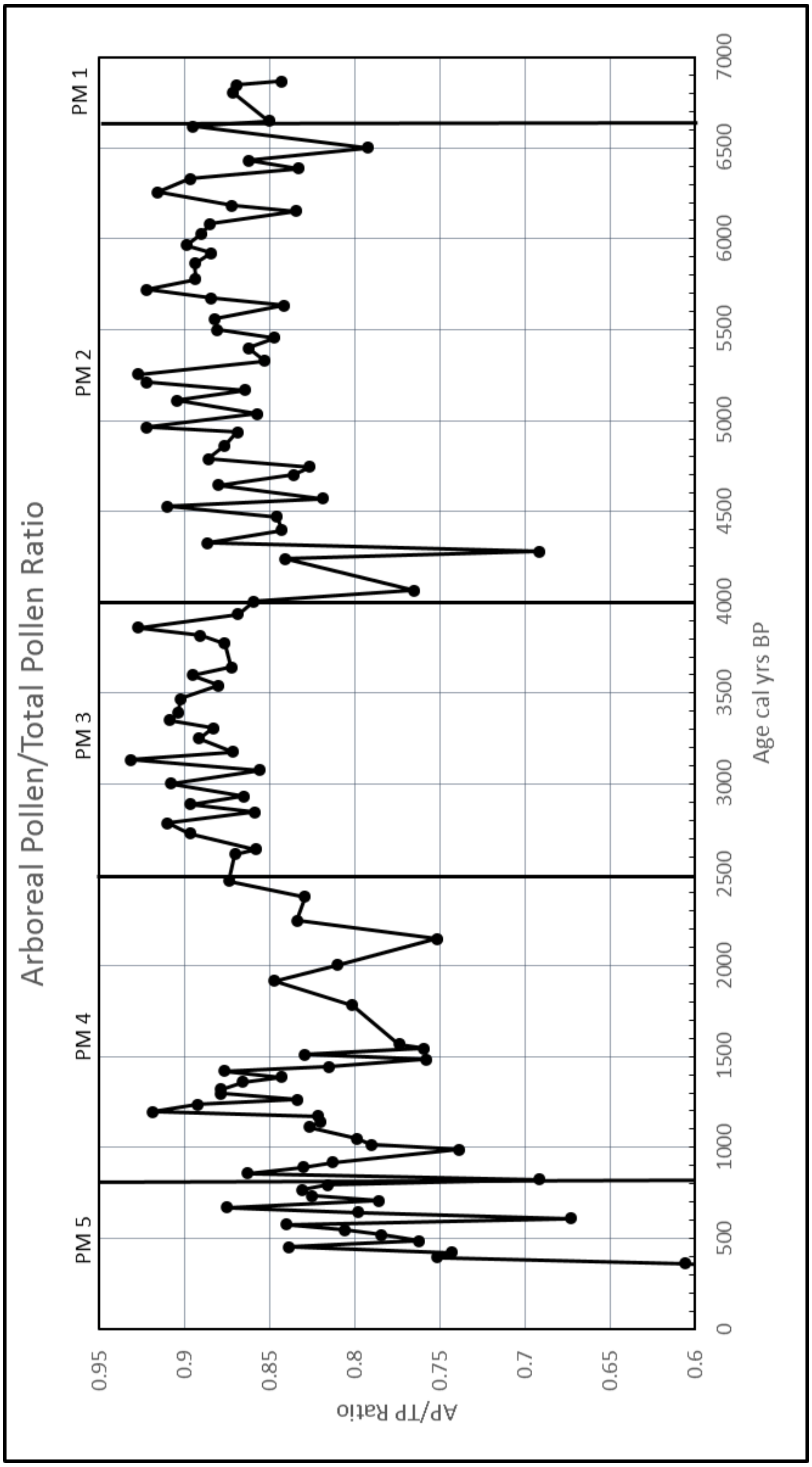

Figure 4.4. **Arboreal Pollen/Total Pollen Ratio**

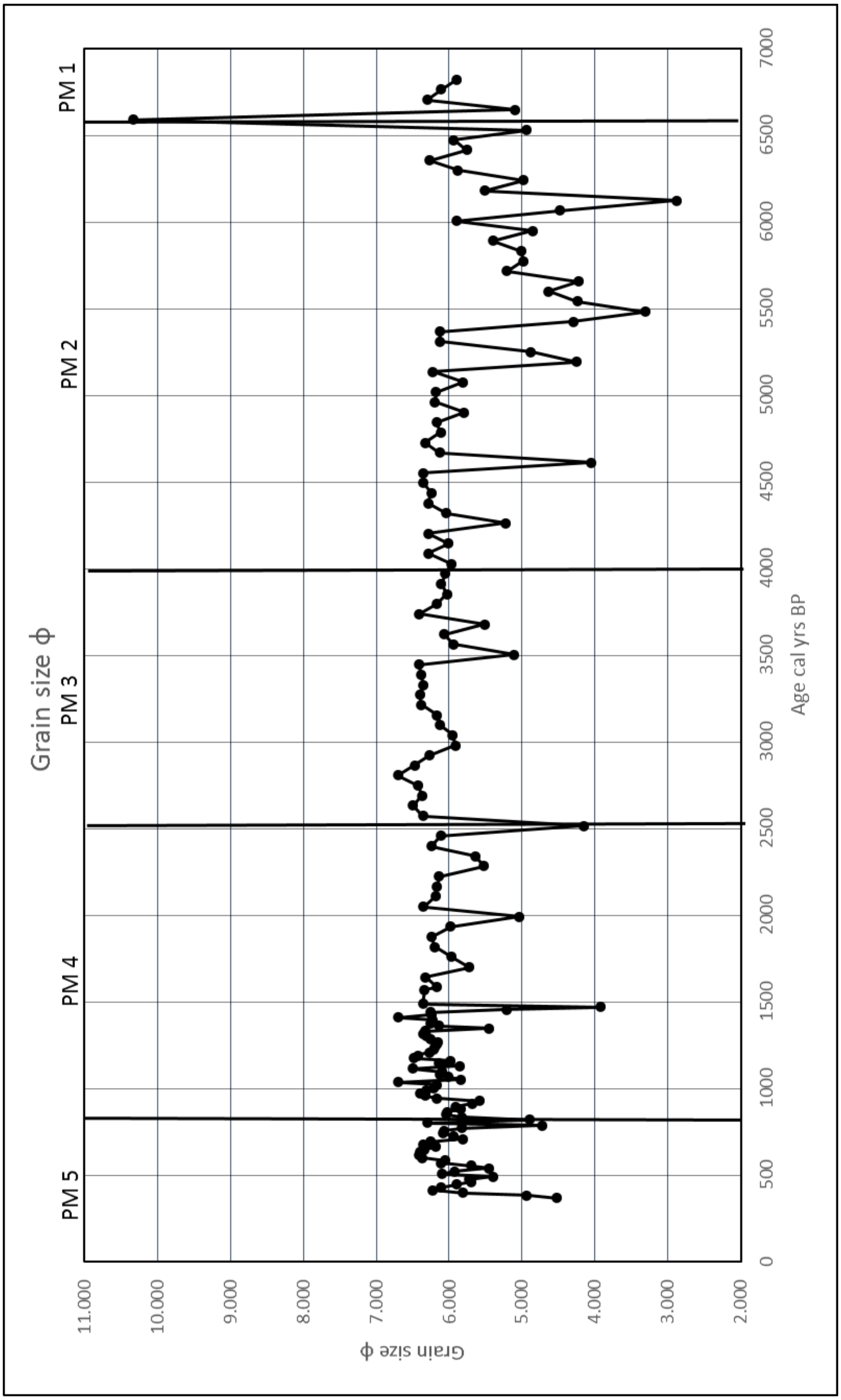

Figure 4.5. Mean Grain Size ϕ for Lake Pomeho

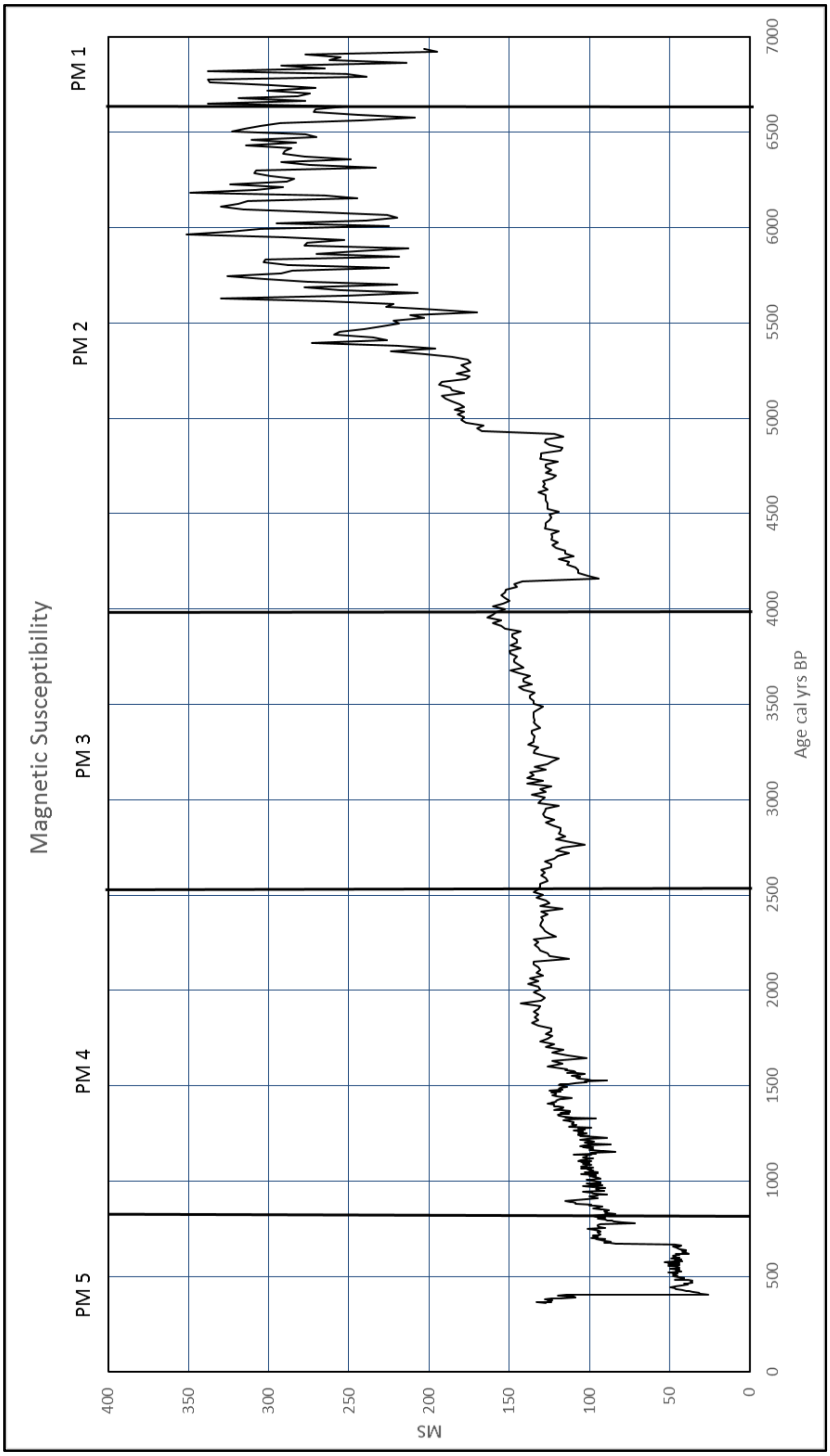

Figure 4.6. Magnetic Susceptibility for Lake Pomeho

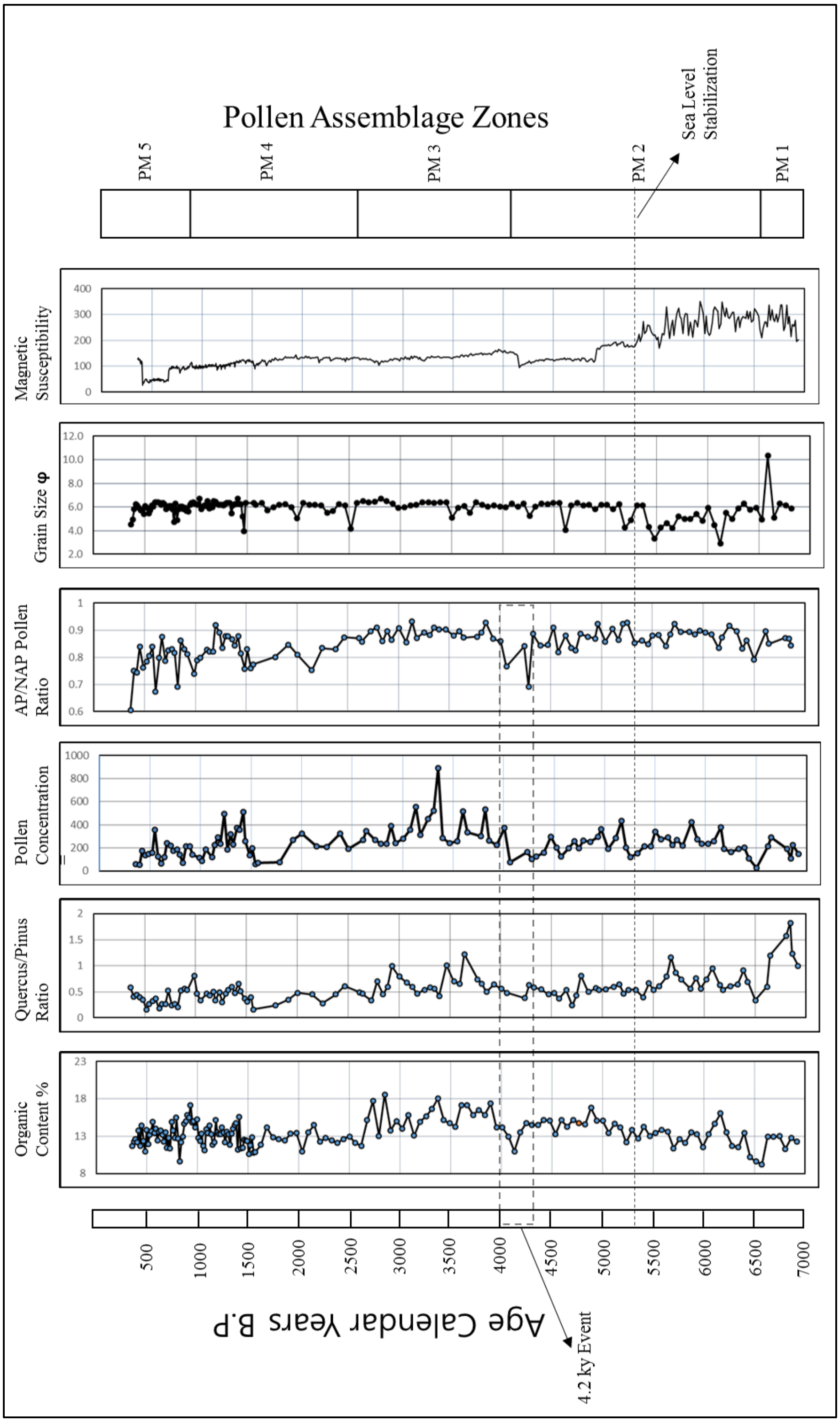

Figure 4.7. Combined chart showing Lake Pomeho proxy data

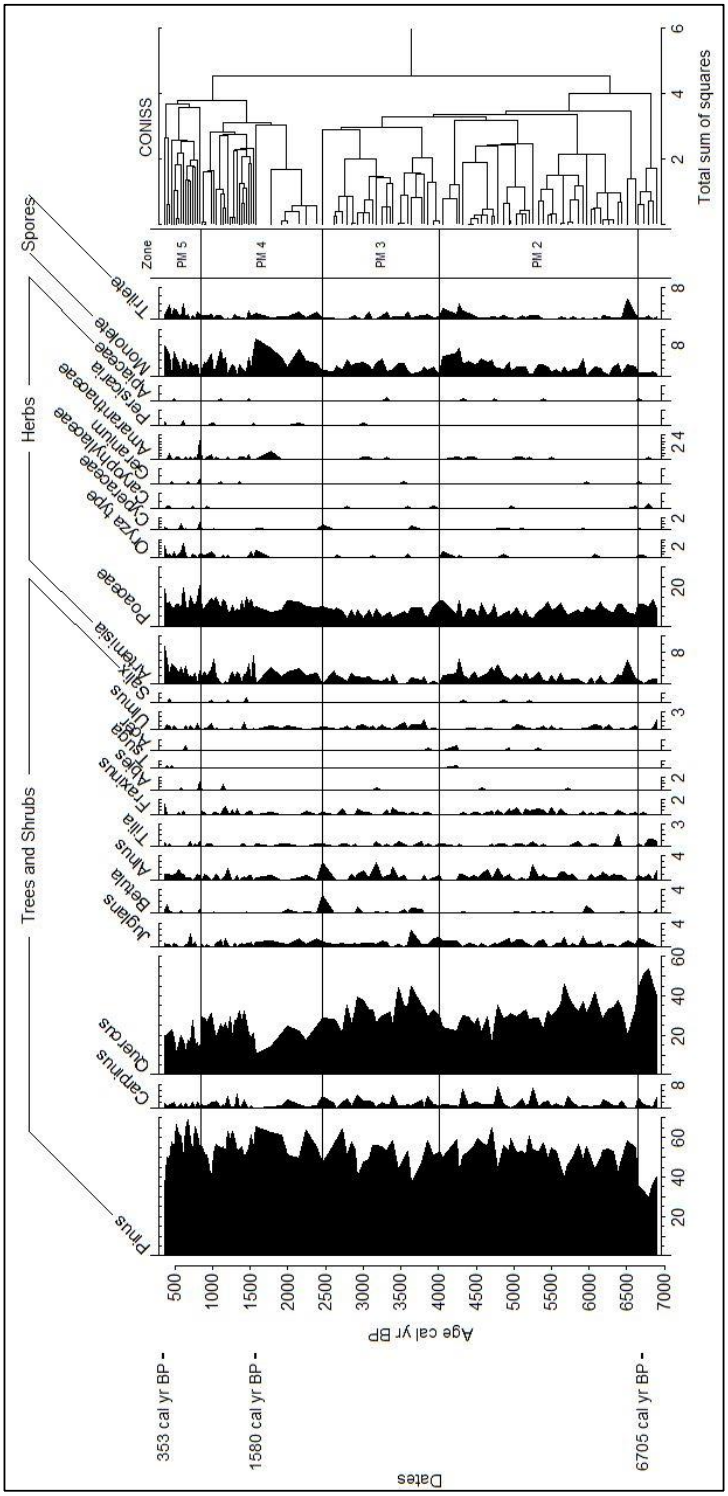

Figure 4.8. Pollen Diagram for Lake Pomeho

4.2 Radiocarbon Dating and Sedimentation Rate

Three samples were dated (487 cm, 831 cm, 1184 cm) using the ^{14}C age dating method. PM-487 and PM-831 were calibrated using the Marine 13 marine curve(Reimer et al., 2013) and PM-1184 was calibrated using the IntCal13 atmospheric curve(Reimer et al., 2013). The dated core samples show that the respective sediment depths date from the middle to late Holocene.

Table 4.1. Radiocarbon dating results for Lake Pomeho

Sample ID	Depth (cm)	Sample No.	Material	$\delta^{13}C$ (‰)	Age (^{14}C yrs BP)	2 sigma cal yr BP
PM-487	487	KGM-OCa150061	Shell(Marine 13 marine curve)	-12	370 ±30	72-291 cal yr BP
PM-831	831	KGM-OCa150062	Shell(Marine 13 marine curve)	2.90	1990 ±30	1510-1390 cal yr BP
PM-1184	1184	KGM-OWd150387	Wood fragment(Intcal13 atmospheric curve)	-27.30	5880 ±40	6750-6660 cal yr BP

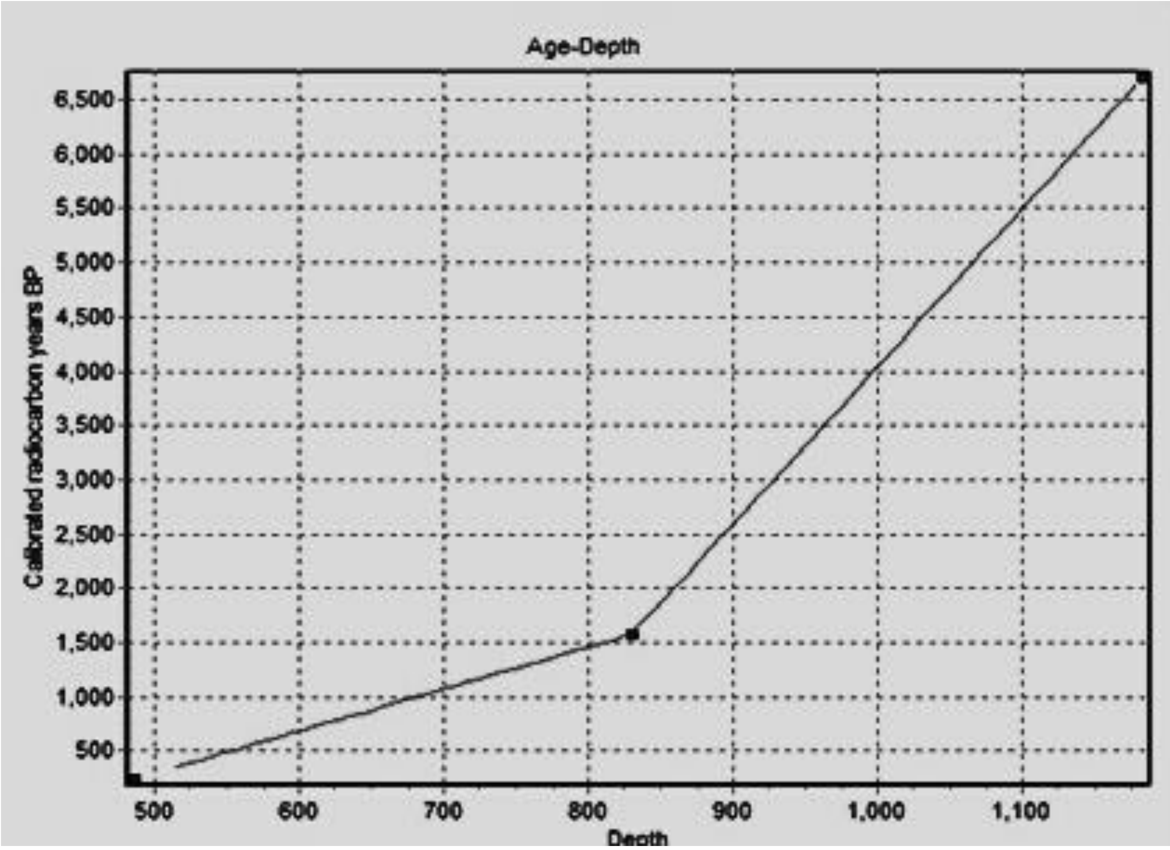

Figure 4.9. Age-depth model for Lake Pomeho

Sedimentation Rate

Linear regression was used to calibrate ages between each stratigraphic layer sampled. The sedimentation rates were determined by calculating the slope of the curve between the radiocarbon dated samples. Between 487 cm and 831 cm, the sedimentation rate was 2.53 mm/yr. Between 1184 cm and 831 cm, the sedimentation rate was 1.452 mm/yr. The sedimentation rate for the upper part of the core (487cm-831cm) was higher than the lower part (831cm-1184cm).

Chapter 5: Discussion

In total, the core sample taken from Lake Pomeho was 12 meters long. In this study, 6.84 meters were used for analysis. The upper part of the core was not analyzed because it consisted of sand and other large clastic materials that were used to build the access road where the sample was taken. A multi-proxy analysis was performed on the remaining 6.84 meters of the core at various intervals from 1-11 centimeters. In total, 22 genus and family of arboreal and non-arboreal pollen were identified, along with monolete and trilete spores.

In this chapter, each zone of the Lake Pomeho sediment core is interpreted in order to describe how the paleoenvironment and paleoclimate around Lake Pomeho changed during the mid- and late-Holocene. The beginning of human disturbance and intensification of agriculture in the area surrounding the lake will also be discussed.

Zone PM 1: ?-∽6700 cal yr BP (Holocene Climate Optimum)

This zone is characterized by a dense hardwood forest. *Quercus* was at its highest percentage of any point in the core. High MS values before 6700 cal yr BP suggest the influx of ocean sediment into the lake because a barrier island would not yet have been able to form before the stabilization of rising sea levels. The low percentage of *Pinus* could be the result of a lack of suitable habitat present before the barrier island developed. The low percentage of Cyperaceae and spore pollen may further indicate the presence of a hardwood forest. Other hardwood species such as *Alnus, Juglans,* and *Fraxinus* appear throughout the zone as well, characteristic of the cool, temperate deciduous forests of Korea. Low percentages of *Artemisia* further indicate dense, shaded forest. Despite high MS levels indicating significant precipitation, organic content and pollen concentrations are both relatively high, suggesting dense vegetation growth indicative of HCO conditions. Other research sites in the vicinity also suggest this period to be part of the Holocene Climate on the east coast of Korea(Kim and Chang, 1982; Fujiki and Yasuda, 2004; Yoon et al., 2008; Park et al., 2012a). A similar timeframe for the HCO was established on the Yellow Sea(West Sea) side of Korea. Several studies from this region suggest the HCO took place from roughly 8400-4500 cal yr BP(Yi et al., 2012; Yi and Kim, 2011; Nahm et al., 2013; Yang et al., 2007).

Zone PM 2: ∽6700-4000 cal yr BP (Post HCO, Sea Level Stabilization, 4.2 kiloyear Event)

Quercus decreases suddenly at the beginning of PM 2 and continues to decline throughout the zone. *Pinus* becomes the dominant arboreal pollen. The increase in *Artemisia* indicates a drying of the climate. Monolete and Trilete spores also show a marked increase in this zone, which could suggest habitat degradation(Hogan, 2013). The *Quercus/Pinus* ratio and total arboreal pollen both exhibit a decreasing trend from around 5700 cal yr BP, suggesting the climate was drying out and becoming less conducive to mesic hardwood growth. Other studies carried out on the east coast further support this time period as the end of the HCO.

Fujiki and Yasuda (Fujika and Yasuda, 2004) and Park et al. (Park et al., 2012a) propose an end date for the HCO of around 5900 to 5800 cal yr BP on the east coast. Yang et al.(2007) found similar results on the west coast, suggesting an end date around 5600 cal yr BP. Records of EASM activity from China (Dong et al., 2010) also indicate an decrease in monsoon intensity during this time period, resulting in an overall drying of the climate.

Heavy erosion rates characterized by high MS and large mean grain size values at the beginning of the core decrease rapidly after approximately 5200 cal yr BP, suggesting the slowing of sea level rise to modern levels. Previous studies(Jo, 1980; Park et al., 2012a) suggest sea level rise stabilized at around 6000 cal yr BP, approximately 800-1000 years earlier than findings at Lake Pomeho.

From ∽4300-4000 cal yr BP there appears to have been a sudden deterioration in the climate. All arboreal species decreased or disappeared at this level except for *Acer* and *Tsugu*, both hardy, cold tolerant trees. The decrease in organic content also appears to suggest harsher conditions less favorable to dense forest growth. *Artemisia* and Poaceae both increase, indicating a thinning of the forests and a colder, drier climate. The further increase in Monolete and Trilete spores are also indicators of climate deterioration. This data corresponds with the timing and conditions of the 4.2 kiloyear centennial scale climactic event. Evidence for the 4.2 ky event has been found in Europe, North America and Asia, with linkages to North Atlantic climate and changes in solar output(Bond et al., 1997; Mayewskia et al., 2004; Robert K. Booth, 2005). Civilization collapse in central China (Wang et al., 2005; Huang et al., 2011) and in Egypt (Stanley et al., 2003) are partly attributed to sudden climate catastrophes temporally associated with the 4.2 ky event. Direct evidence for the 4.2 ky event has not yet been reported in Korea. However, numerous studies of lake sediments and peat from Northeastern China (Hong et al., 2001; You and Liu, 2012; Shi-yong Yu, 2013) suggest a centennial scale cold event occurring around 4200 cal yr BP. Sagawa et al.(Sagawa et al., 2014) also identify a decrease in SST off the coast of Hokkaido that corresponds to a drop in solar irradiance, corresponding with a weakening of the EASM around 4300-4100 cal yr BP. The sudden decrease in monsoon strength could have led to a drier climate in Korea, which might explain the decrease in arboreal species and increase in cold, dry weather tolerant herbs.

Zone PM 3: ∽4000-2450 cal yr BP (*Climate Amelioration or Deterioration)

Two alternative interpretations exist concerning the data in Zone PM 3. The first interpretation suggests that the increase in *Quercus* and decrease in *Pinus* could signify a cooling of the climate. Results from Lake Hyangho (Fujiki and Yasuda, 2004), Lake Gyeongpo (Yoon et al., 2008) , and Lake Youngrangho (Chang and Kim, 1982) show a similar increase in *Quercus* and decrease in *Pinus* during this time period. Fujiki and Yasuda suggest that the increase in *Quercus* could indicate a cooling of the climate. *Pinus* in the area around Lake Pomeho may have belonged to the species *Pinus thunbergii*(Kim and Kil, 1983), warmth-loving coastal pines, rather than *Pinus densiflora*. *Pinus thunbergii's* current northern boundary lies to the south of the study area with its main distribution located south of Gangneung city (37°72’ N 128°87’ E). A cooling off of the climate after 4000 cal yr BP could explain the reduction in *Pinus* thunbergii. The decrease in herb taxa in this zone might have been caused by reduced pine tree density and consequent dune soil disturbance. The relative decrease in grain size and MS would also seem to indicate less relative precipitation. Numerous studies in Northeastern China (Hong et al., 2000; Hong et al., 2001; You and Liu, 2012; Shi-yong Yu, 2013; Stebich et al., 2015) also show a general decrease in average temperatures and humidity levels from 4000 cal yr BP. They suggest the climate dried out as the EASM weakened in the East Asian region after around 4000 cal yr BP.

Alternatively, PM 3 could be characterized by warming phase indicated by the reappearance of several hardwood species that disappeared in PM 2. *Quercus* showed a significant increase from the previous zone, indicating more temperate conditions than those existing at the end of zone PM 2. *Quercus* pollen around Lake Hyangho(Fujiki and Yasuda, 2004), Lake Gyeongpo(Yoon et al., 2008), and Lake Youngrangho(Chang and Kim, 1982) show a similar increase during this time. *Alnus, Fraxinus,* and *Ulmus* all reappear, indicating the climate could have warmed somewhat after the cold event in the PM 3. The decrease in *Artemisia* and Poaceae in this zone could be the result of a return to greater forest density. The relative decrease in grain size and MS would also seem to indicate less relative precipitation or the return of stable forests that could hold topsoil. Increases in pollen concentration and organic content, which tend to be higher in finer grained sediments(Caballero, 2005), support evidence of denser forest growth. Sea surface temperatures off the western coast of Honshu, Japan increase around 4100-3800 yr BP, corresponding to an increase in solar irradiance(Steinhilber et al., 2009). Leipe et al.'s(2013) study of the pollen record in southwestern Hokkaido suggests a localized warming trend in the Sea of Japan region resulting from a weakening of cold water masses in the Sea of Japan during the last 6900 years, which could explain the higher temperature and precipitation data. Their results suggest slightly cooler temperatures than present between about 5500-3600 cal yr BP, then similar or slightly warmer conditions to present after 3600 cal yr BP. This interpretation conflicts with data from the wider region and Northern Hemisphere, but could be explained by changes in water currents in the Sea of Japan, specifically the expansion of the Tsushima Warm Current during the middle and late Holocene. The increase in *Quercus* around Lake Pomeho, Lake Hyangho, and Lake Youngrangho, could also be indicative of this more localized warmer, wetter trend.

Zone PM 4: ∽2450-850 cal yr BP (Human Disturbance and Agriculture)

PM 4 is characterized by the destruction and reshaping of the environment by humans. Hardwood pollen percentages decrease rapidly from the beginning of this zone while disturbance indicator species such as *Artemisia,* Poaceae, Amaranthaceae, and spores increase. *Quercus* pollen decreased abruptly at around 1600-1700 cal yr BP. Pinus increased in PM 4 and PM 5 to its highest level in the core. This is likely due to land clearance for agriculture. *Pinus* is tolerant of poor and soil conditions that would have resulted from deforestation. *Alnus* percentages decreased somewhat at the beginning of this zone as well, likely the result of manmade land clearance for the construction of agriculture. *Alnus* showed a similar decrease from around 2000 cal yr BP at other sites in the vicinity of Lake Pomeho(Yoon et al., 2012). The appearance and continued presence of *Oryza* type pollen in the middle of the zone indicates that rice agriculture had become sufficiently intensified on the surrounding land by around 2000 cal yr BP. Other proxy data also indicates human disturbance. Low pollen concentrations and high mean grain size could signify destruction of vegetation by humans, resulting in increased erosion. The decline in arboreal pollen further indicates the clearance of land around the lake. Together, this suggests humans began clearing the land around Lake Pomeho and began practicing agriculture beginning around ∽2500-2100 cal yr BP. In proximity to Lake Pomeho, rice agriculture appeared around Lake Hyangho at around 2000 cal yr BP(Fujiki and Yasuda, 2004), around Lake Soonpoegae around 2100 cal yr BP(Park et al., 2012a), and around Lake Ssangho at around 2100 cal yr BP(Park and Shin, 2012). The similarity of timeframes for the introduction of rice agriculture in the region supports this study's interpretation that agriculture began at Lake Pomeho at the same time.

Zone PM 5: ∽850-350 cal yr BP (Intensification of Agriculture)

PM 5 is characterized by high concentrations of Poaceae and *Artemisia*, and low concentrations of *Quercus*. The further decline of hardwood species and increase in *Pinus* is probably related to the widespread adoption of intensified rice agriculture in the region. Land clearance by this time would have resulted in significant erosion, leading to poor soil conditions conducive to the growth of species that can survive in thin soils and direct sunlight. This could explain the further increase in *Pinus* and *Betula*. The continued rise in both wild and domesticated Poaceae also indicate that agriculture was becoming more intensified in the region. At Lake Gyeongpo(Yoon et al., 2008), Bongpo Marsh(Park et al., 2012b), Lake Cheongjinho(Park and Constantine, 2015), and Lake Hyangho(Fujiki and Yasuda, 2004) there is a marked increase in Poaceae/Gramineae pollen from around 800-1000 cal yr BP, suggesting agriculture intensified in the east coast region around this time. Monolete spores and Cyperaceae in this zone occurred commonly and probably occupied disturbed areas around rice paddies. The continuously low pollen concentration, along with relatively low organic content seem to suggest that the surrounding forests were mostly cleared by this time. Relatively high mean grain size provide further evidence for this supposition, indicating high levels of erosion as a result of land clearance.

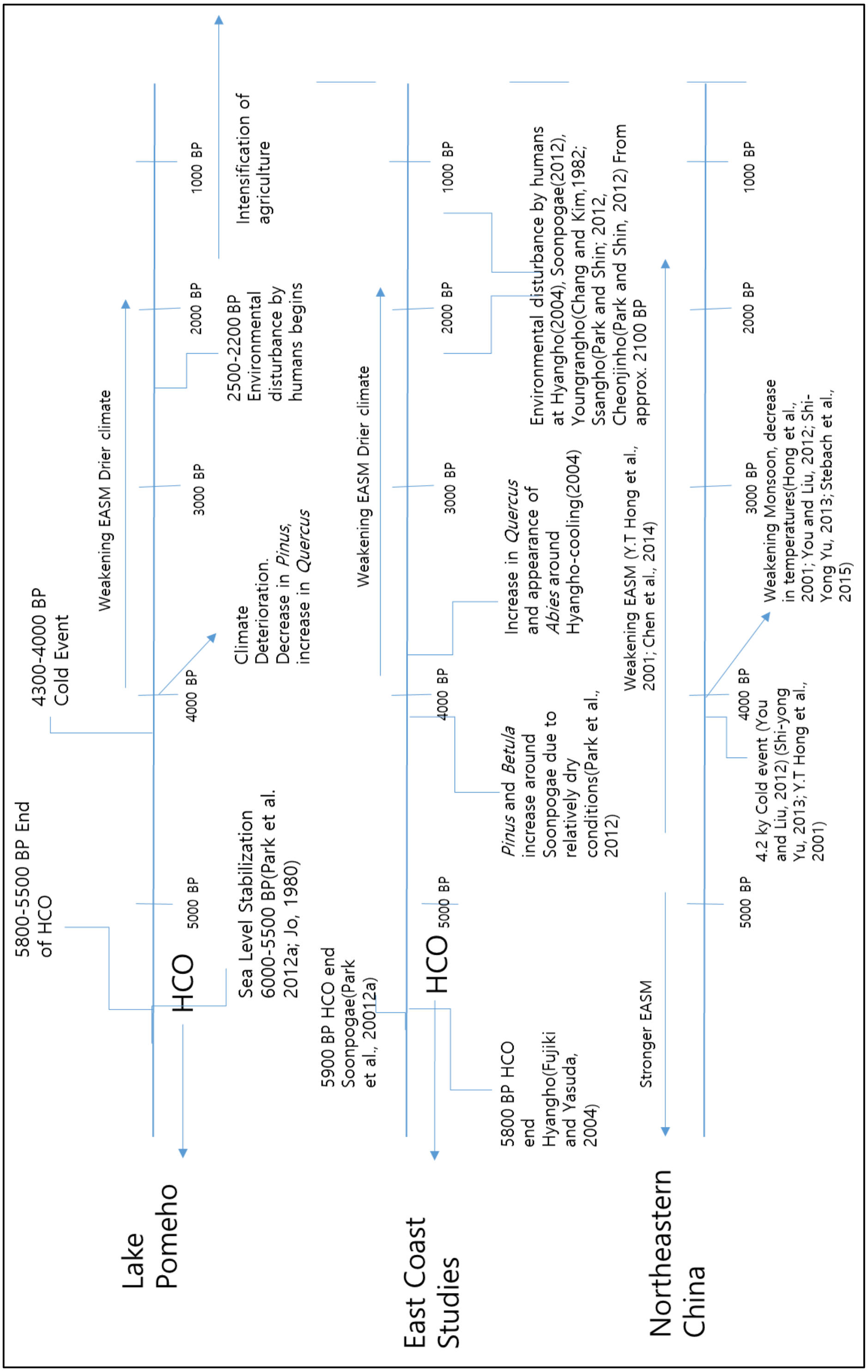

Figure 5.1. Climate events and environmental changes around Lake Pomeho and related sites.

Chapter 6: Conclusion

This study examined paleoenvironmental changes and attempted to determine when agricultural activity began and intensified during the mid- and late-Holocene around Lake Pomeho, a lagoon on the east coast of the Korean Peninsula. Climate research on the east coast is important not only to improve our understanding of local changes in the paleoenvironment but also to increase our understanding of climate change in the greater East Asia region. Relatively few paleolimnological studies have been done on the Korean peninsula due to a lack of natural lakes and areas where suitable sediments can be found. Suitable conditions exist in lagoons on the eastern coast however, making Lake Pomeho an important resource for paleoclimate research. The sediment core recovered for this study covers the past ∽7000 years, encompassing the middle and late Holocene time periods. This period spans several important climatic events including the end of the Holocene Climate Optimum(HCO), the weakening of the East Asian Summer Monsoon(EASM), the stabilization of sea level rise, and the 4.2 ky cold event. It also encompasses the period of human induced environmental change due to agricultural development and intensification, an area of study still not yet well documented and understood in Korea.

Climate change and human impact around Lake Pomeho was reconstructed using multiple proxy data analysis techniques: pollen analysis, organic content, magnetic susceptibility, grain size analysis, and radiocarbon dating. These methods were used in combination to create an accurate representation of climate and environmental change over the past 6700 years.

After laboratory analysis, five zones were constructed based on constrained incremental sum of squares cluster analysis(CONISS) found in the Tilia software program. PM 1 corresponds to the HCO. Zone PM 2 to the end of the HCO and the 4.2 kiloyear event. Zone PM 3 corresponds to the either the weakening of the EASM or it suggests a possible localized warming event caused by the Tsushima Warm Current. Zone PM 4 to the beginning of agriculture. Zone 5 corresponds with the intensification of agricultural activities.

The results of the various proxies analyzed in this study correspond well with each other. Grain size analysis and magnetic susceptibility both show similar trends in the precipitation and erosional characteristics of the area. Pollen analysis and organic content analysis both show broadly similar trends in climate induced vegetation change. The resulting reconstruction of the environment around Lake Pomeho corresponds with previous studies done on the east coast of Korea in describing Holocene environmental change. In addition, this study was able to identify the 4.2 kiloyear event in Korea for the first time, therefore providing new and significant data for the advancement of paleoclimate research in the region.

The results of this study corresponded well with other paleolimnological studies on the east coast of Korea, suggesting the findings are accurate. In addition, new data has been presented which provides the first evidence for the 4.2 kiloyear event in Korea, as well as evidence for a possible localized warming event caused by the TWC. This study also found evidence that sea level stabilization occurred 800-1000 years earlier than other studies, suggesting more research might be needed to clarify this discrepancy. In the future, more studies need to be done in order to verify these finding as well as to continue to expand on the knowledge of the paleoenvironment and paleoclimate in Korea and the greater East Asian region.

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Abstract

기후변화는 전세계적인 정치적 논쟁거리일 뿐 아니라 매력적인 연구의 주제로 오랫동안 세간의 관심 대상이었다. 미래 기후 변화의 패턴을 예측하고 이해할 수 있는 능력은 매우 중요하다. 미래 기후 변화 예측을 위한 선행 단계로 고기후 복원을 제안한다. 과거 기후 현상들의 정밀한 검토는 미래 기후 변화를 예측할 때 필수적인 과정이다.

한국에서는 자연 호수와 교란되지 않은 퇴적물의 부족으로 고육수학(古陸水學)적 연구 결과들이 많지 않다. 그러나, 한국의 동해안에 위치한 석호들은 비교적 원형으로 남아있어 풍부한 고기후 정보를 제공할 수 있다.

이 연구의 목적은 한국의 동해안에 위치한 포매호 주위 홀로세 중반과 후반 때의 기후와 환경적 변화를 복원하는 것이다. 대략 7 미터 길이 코어 퇴적물에 화분 분석, 입도 분석, 유기물 함량 분석, 자화율 분석, 그리고 방사성 탄소 측정법을 실시했다. 화분 데이터의 통계분석(CONISS) 결과, 5 개의 군집대로 나눠졌다.

PM 1(??-6700 cal yr BP)존에서 보이는 다양한 수목들과 높은 비율의 *Quercus* 는 HCO 를 지시한다. PM 2(6700-4000 cal yr BP) 존에서는 약 5800-5500 cal yr BP 에 *Pinus* 의 비율이 증 가한 반면 *Quercus* 의 비율은 감소한다. 한반도에서 HCO 가 끝난 시기를 지시하는 것으로 보인다. 자화율 데이터 분석과 입도 분석 결과, 해수면 상승으로 인해 운반된 퇴적물 들이 대략 5600 cal yr BP 정도까지 유입된 것을 알 수 있었다. 약 4300-4000 cal yr BP 에 서 수목들의 갑작스런 감소와 내한성 식물의 증가가 관찰되었으며, 이는 북반구의 다 른 장소들에서 발견되는 4,200 년 전의 냉각기에 상응하는 기후변화를 지시한다.

PM 4 (2500-850 cal yr BP) 존은 포매호 근처 지역의 농업의 시작을 보여준다. 이 구역에서 *Oryza* 속의 꽃가루가 증가함과 동시에 교란 지표 종들인 Artemisia, Poaceae 그리 고 Amaranthaceae 식물이 증가했다. PM 4 에서의 꽃가루 농도는 매우 낮았다. 이 데 이터는 농업이 약 2500-2100 cal yr BP 에 이 지역에서 시작되었음을 알려준다.

PM 5 (850-350 cal yr BP)존은 포매호 근처의 농업 활동의 심화를 특징적으로 보여준 다. Artemisia 의 비율의 증가와 함께, 야생 벼과 식물과 재배된 벼과 식물 모두가 증가

했다. 햇빛을 필요로 하는 식물인 *Pinus* 와 *Betula* 모두가 증가한 반면에 *Quercus* 는 지속적으로 감소했다. 교란지표 종들의 증가는 농경 심화로 늘어난 토지 개간 때문일 것으로 생각된다.

이 연구는 한국의 동해안에 위치한 포매호 주위 홀로세 중반과 후반 당시의 환경을 복원하려는 목적으로 진행되었다. 교란되지 않은 퇴적물을 가진 지역이 한국에는 많지 않기 때문에, 이 연구는 한국과 고기후 연구에 의미 있는 기여가 될 것이다. HCO 시기, 해수면 안정 그리고 농경 시작 등에 대한 정보들은 인근 지역에 대한 연구의 데이터들과 부합한다.