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History Lessons from the Late Joseon Dynasty Period of Korea: Human Technology (*Ondol*), Its Impacts on Forests and People, and the Role of the Government

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Abstract

Historical analogies can help us contextualize new technical developments with social, cultural, and political forces at work. The late Joseon Dynasty period of Korea (1639–1910), a closed economy with detailed written records, provides a rare opportunity to examine a social-ecological system (SES) responding to drivers of change over a long period of time. Based on historical records and reconstructed data, we aim to: (1) characterize how the expansion of human technology, *Ondol* (traditional underfloor heating system), affected different subsystems and their interactions within the SES over time; (2) examine the role of the government in promoting the technology and regulating its impacts; (3) summarize the pertinent lessons learned from old Korea for governing a modern-day bioeconomy. *Ondol* allows various forest biomass to be utilized as household fuel, including fuelwood, forest litter, and grass scraped from forest floor. Continuous biomass harvesting over 250 years to feed *Ondol* contributed to forest degradation and forest ecosystem condition trapped in the early successional stage in the Korean Peninsula. The ecological changes were exacerbated by the Pine Policy with a singular focus on reserving Korean red pine (*Pinus densiflora*) for government uses. The policy failed to recognize basic needs of the public while countenancing an expansion of *Ondol* and a cultural preference for heated floors that propagated an increased use of biomass fuel. This case illustrates the importance of recognizing potential technology traps where a human innovation opened opportunities for more resource use. The lessons learned from old Korea show that bioeconomy transitions would require multifaceted governance responses, while being cautious about being too closely tied to the dominant national agenda.

Keywords: bioeconomy; forest history; Joseon Dynasty; Korea; *Ondol*; social-ecological system

Introduction, scope and main objectives

Transitioning to a bioeconomy, using renewable biological resources as feedstocks for energy generation and bio-based products, has been one of the most prominent solutions for achieving sustainable development around the world [1]. Such transition would require innovative governance responses to guide the transformation of a social-ecological system (SES) with technological advances, as well as sustainable management of renewable resources [2,3]. Understanding forest landscapes as SESs can help us recognize not only social and ecological components within the system, but also different spatial and temporal scales on which each component operates and their cross-scale interactions [4]. There have been a number of historical analyses to understand long-term changes of forest landscapes as SESs [5–7]. The body of literature on the ecological and economic aspects of a bioeconomy has been also growing, although governing a bioeconomy as an SES has not received sufficient academic attention [8]. It is critical and urgent to understand how human technology affects different social and ecological components and their interactions within an SES [9,10]. Historical thinking and analogies can help us learn from history and contextualize current scientific and technical developments with the social, cultural, and political forces at work [11,12].

To contribute to our understanding of a bioeconomy as an SES, this paper examines the late period of the Joseon Dynasty of Korea (from the early 17th century to 1910), which provides a rare example of a closed economy with detailed written records, including daily reports and discussions in the royal court, as well as other publications. These historical records allow close examinations of interconnectedness and interactions among technology, social and biological processes, ecosystems, and the services that they provide. This period coincides with significant climate anomalies of reduced temperature, i.e., the "Little Ice Age". The population of Joseon also increased during this time. *Ondol* is a heating system in traditional Korean architecture that uses direct heat transfer from smoke generated by woodstoves or outdoor furnaces (*Agungi*, which allow fires for cooking to be used for heating but can also be constructed for heating purposes only) to heat the underside of the floor in the adjacent room. Forest degradation of the Korean Peninsula before the Japanese occupation in 1910 has been frequently attributed by several historians to the "astronomical" amount of fuelwood demand due to *Ondol* [13–15]. The specific research objectives of this study are: (1) to characterize how the expansion of human technology, *Ondol*, affected different subsystems and their interactions within the SES over time; (2) to examine the role of the government in promoting the technology and regulating its impacts; (3) to summarize pertinent lessons learned from old Korea for governing a modern-day bioeconomy.

This paper is organized as follows: We characterize the SES of the late Joseon Dynasty period, in terms of the four core subsystems following the SES framework by Ostrom [16,17], then present the results based on our analysis of historical documents. We conclude with salient lessons from old Korea for governing a modern-day SES.

Methodology/approach

In this study, we characterized the late Joseon Dynasty period of Korea as an SES to organize social and ecological components of the study area, which is defined both spatially (the Korean Peninsula, which was the Joseon's territory) and temporally (the late Joseon period from the early 17th century to 1910). The focal Resource Systems in this case are the forest ecosystems in Joseon's territory that contain Resource Units, such as different tree and plant species, biomass, and other resources. The focal Resource Units here are biomass fuel, including fuelwoods, forest litter, grass, and other biomass materials collected for burning. Governance Systems include Joseon's governing structure, and the formal and informal rules that define property rights and forest uses. The focal Actors are households collecting forest biomass. We conceptualize that the human technology *Ondol* affected the mode and extents of interactions between Resource Units and Actors with two prominent drivers of change: the Little Ice Age and population growth (Figure 1).

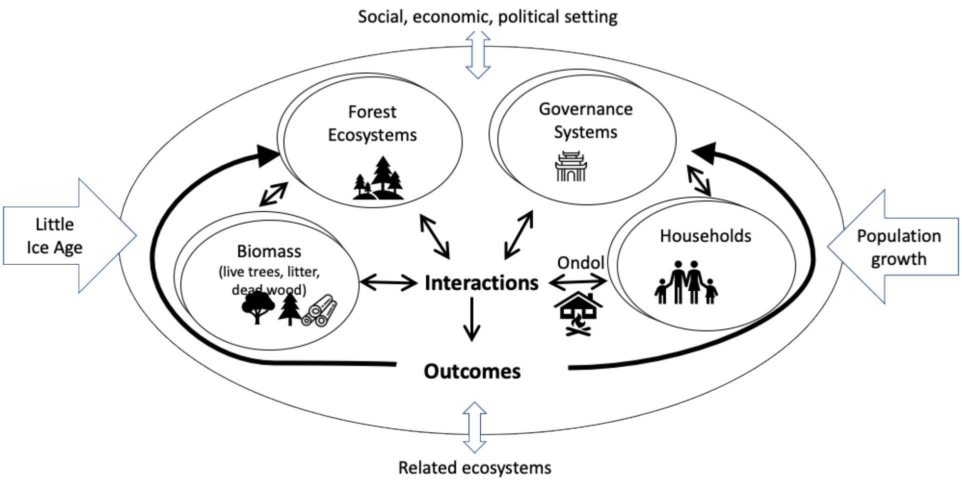

Fig. 1: The late Joseon period as a social-ecological system (SES) with four core subsystems: (1) forest ecosystems within Joseon's territory as Resource Systems; (2) forest biomass for fuel as Resource Units; (3) Joseon's governing structure and formal and informal rules as Governance Systems; (4) households as Actors.

Resource Systems and Units: The Korean Peninsula (approximately 22,000 km2) has a temperate climate with four distinct seasons. More than 70% of the Korean Peninsula is mountainous with over 900 tree species. The most common trees species throughout the peninsula are various pine, especially Korean red pine (*Pinus densiflora*), and oak species, with a greater representation of conifer species in the north [21] and deciduous broad leaf species in the south, as well as some evergreen species in the far south [22].

Governance Systems: The Joseon Dynasty (1392–1910) established its Constitution (*Gyeongguk Daejeon*) in 1397. The Constitution specified one of the governing principles as "Sharing nature's benefits among people" and banned the private possession of forests. The late Joseon Dynasty period was heralded by devastating invasions by Japan (1592) and China (1636) that ravaged the whole kingdom. Post-war reconstruction and warships built to secure national defense sharply increased timber demand, especially for large old growth pine.

Drivers of Change: The Little Ice Age: Although there are no accurate meteorological data, the kingdom of Joseon left detailed written records of reports and discussions in the royal court and daily affairs of the kings. These records reported incidents of unusual cold spells with increasing frequencies from the 16th to the 18th centuries (peaking in the 17th century).

Population growth: Kwan and Shin [33] estimated the population size of the late Joseon period based on the records of the official population census conducted every three years from 1631 to 1861 with other records, including family tree books and provincial land registries. The population in the late Joseon period increased over time with periodic declines due to wars, epidemic diseases, and famines followed by rapid recoveries.

Research Approach and Data Sources: We have analyzed various historical records, as well as contemporary literatures to characterize social and ecological subsystems in the late period of Joseon Dynasty of Korea as an SES. The main data sources include: (1) the databases of forest-specific historical documents, maps and forest inventory records that the National Institute of Forest Science, Republic of Korea, has been building in the last 20 years (Resource Systems and Units); (2) historical records, laws and regulations, and others classics translated by the Institute for the Translation of Korean Classics (Governance Systems and Actors); (3) records of population and climate variations in official census, archives of the royal court, as well as popular literature at the time (Drivers of Changes).

The historical records employed for our analysis include (1) The Annals of Joseon Dynasty (*Joseon Wangjo Sillok*), collections of daily reports and discussions in the royal court from 1413 to 1865 [39]; (2) The Records of the Border Defense Council (*Bibyeonsa deungnok*), annual reports of the government agency (*Bibyeonsa*) that oversaw national security and internal affairs, including protection and management of natural resources, from 1617 to 1892 [40]; (3) Joseon Dynasty's Constitution (*Gyeongguk Daejeon*) [41] and other written records of laws and regulations for forest management (*Songgeumjeolmog*) [42], and (4) other historical and modern publications as cited.

Results

Social and Cultural Impacts of Ondol on Households

Ondol efficiently uses both radiative and convective heat transfer from fire without polluting indoor air quality with smoke [43]. However, the lack of thermal insulation in traditional houses requires higher floor surface temperatures and encourages residents to sit or lie down to increase their body temperatures, shaping the unique residential culture of Korea [48]. *Ondol* is often referred to as the cultural womb of Korea, giving birth to a shared sense of culture and identity. The cultural significance of *Ondol* can be traced in idioms and expressions in Korean language [49]. For example, being happy is often expressed as "having a warm backside and a full tummy", and seeking warmth as "wanting to be sizzled [on a hot floor]". The preference for *Ondol* and heated floors with high temperatures is still prevalent in modern Korea, as heated floors constitute normal residential architecture [43]. The Republic of Korea (ROK, South Korea) officially recognizes *Ondol* as a national cultural treasure (Number 135) [50].

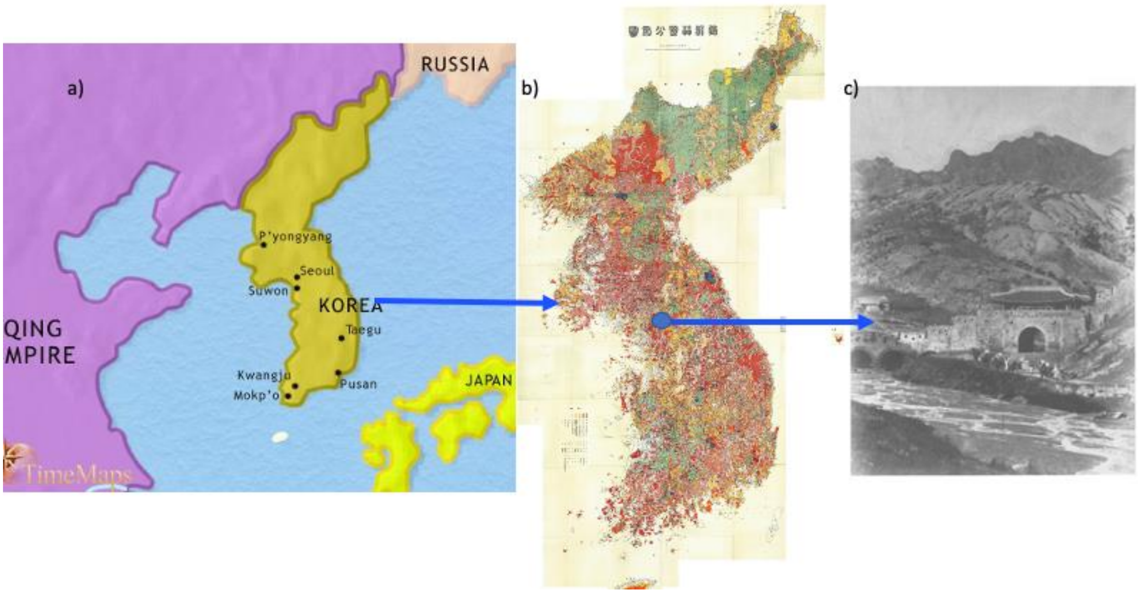

Fig. 3: (**a**) A map of East Asia in the 17th century (source: Timemaps). (**b**) A map of Joseon in the year 1910 with the general tree species distribution observed and hand-drawn by the Japanese forest administrator, Saito (color code: red for Korean red pine (*Pinus densiflora)*, green for other conifer species, yellow for deciduous species; source: Bae and Kim, 2019). (**c**) A picture of Joseon's capital (current day Seoul, Republic of Korea (ROK)) in the early 19th century (exact date unknown; source: Bae 2002). Mountainous sides in the background with exposed bedrock show the extent of forest degradation.

Impacts of Ondol on Forest Ecosystems

The extended biomass fuel demand had two main ecological consequences: forest degradation, especially around populous areas, and a forest ecosystem condition trapped in an early successional stage. To understand the magnitude of the fuelwood demand and its impacts, we assume that the forest stock level in the 16th century was approximately twice that in 1927 (~500 million m^3) after the two devastating foreign invasions (in 1592 and 1636). The mean growing stock level would be approximately 15 million m^3 per year with a 3% natural growth rate. This means that household demands for fuelwood alone consumed 60–70% of the total annual growth of forests, even without accounting for the timber demands of buildings and ships and other non-domestic fuelwood demands for, e.g., pottery making and blacksmithing. However, the pressures on forest biomass would not have been evenly distributed throughout the Korean peninsula, as the lands with a lower elevation and a gentler slope in the south had been historically more densely populated (Figure 4). Fuelwood harvests would have exceeded the annual growing stock level in the forests near densely populated areas, resulting in forest degradation (Figure 4d).

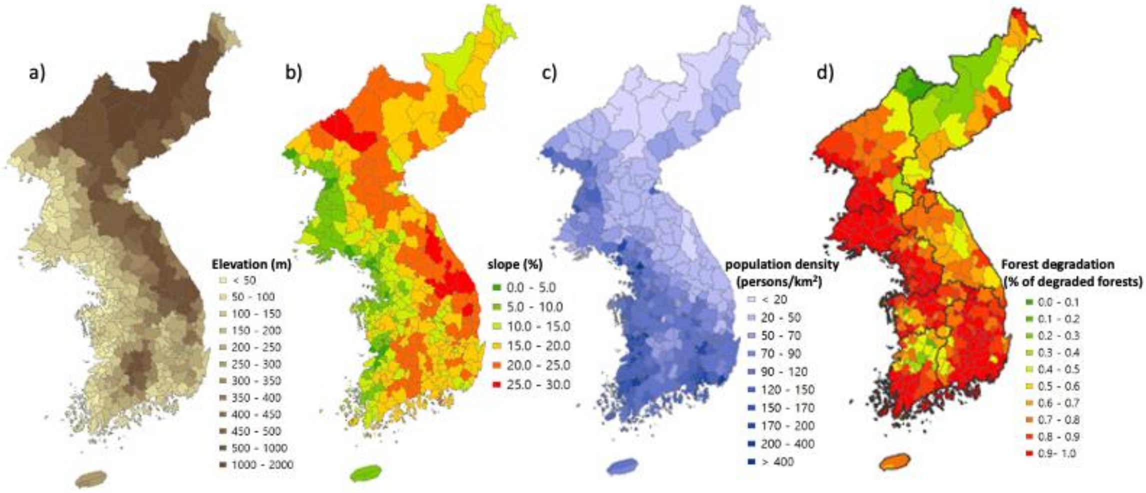

Fig. 4: By district, as of 1910: (**a**) average elevation; (**b**) average slope; (**c**) population density/km^2; (**d**) deforestation rate (source: Bae and Kim 2019).

Unlike other heating methods generating direct heat from indoor fireplaces (e.g., Europe) or stoves (e.g., Japan), *Ondol* allows for an extensive use of inefficient fuels with high amounts of soot and smoke, such as forest litter, grass, and agricultural by-products for heating. The continuous and widespread collection of forest litter caused by scraping the forest floor profoundly affected the forest ecosystem in the Korea Peninsula over time through changes in depth, organic matter, and soil chemistry, leading to changes in forest structure and composition [60]. These slow-moving changes are hard to detect over the short term, even though they control the dynamics of fast-moving variables, such as tree species, the level of biomass, and other ecosystem services, which are often the focus of management [61]. Mismatches of spatial and temporal changes in ecological processes and human responses when governing forest landscapes may generate unintended consequences in forest management [4]. Based on the digital reconstruction of hand-drawn maps and other historical records left by a Japanese colonial forest administrator named Saito, Bae and Kim [62] argued that Korean red pine (*Pinus densiflora)* was the dominating tree species across the Korean Peninsula in 1910. Pine-dominated forests were observed to comprise 43% of the total forest area and 78% of the forests in the south-central regions (current day ROK) (Figure 5a).

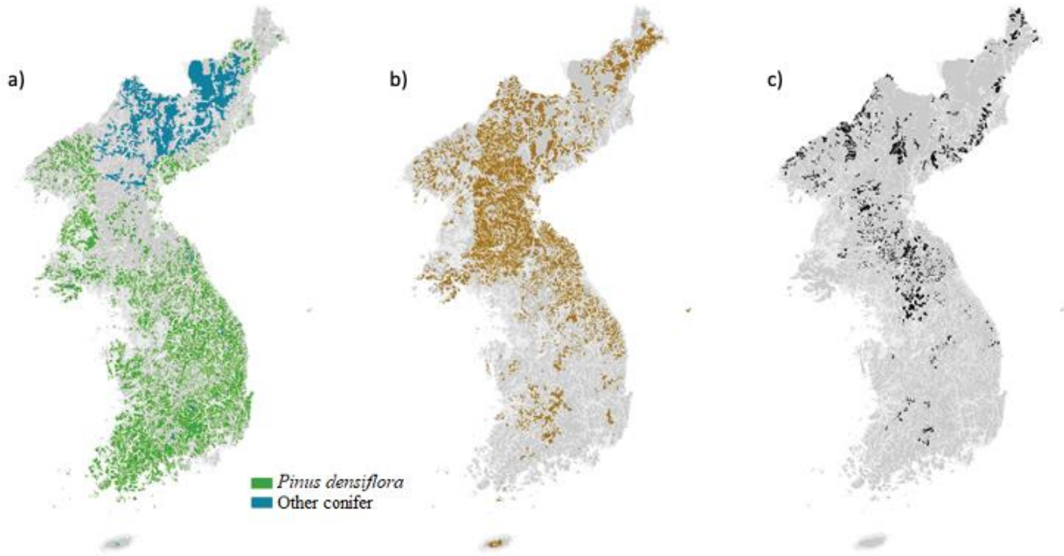

Fig. 5: Distribution of forests (total 15.7 million ha) by dominant species observed by Saito in 1910: (**a**) coniferous forests (41% of total forest land, 30% of which is forest dominated by Korean red pine (*Pinus densiflora)*, shown in green); (**b**) deciduous forests (30%); (**c**) slash and burn farming fields (3%) (source: Bae and Kim 2019).

The Role of Governance Systems

As increasing and competing demands for pine intensified over time, the central government also tried to reduce the demands for pine by extending the periods between repairs of warships and adopting new technologies (e.g., replacing wooden nails with iron ones), as well as limiting the number and sizes of new constructions of government buildings, as noted in the Records of the Border Defense Council in 1787 [40]. However, these policies for reducing demands had little impact because they provided no incentives for local officials who oversaw shipyards to reduce their requests of timber.

The government not only determines the social distribution of forest resources (structural power), but also intentionally and unintentionally promotes human technology by affecting people's preferences and culture (ideational power) [10]. The ideational power of the governance system was exercised by the intentional promotion of *Ondol* as well as unintentional normalization through its extensive uses in government buildings.

Discussion

When the Japanese forest administrator Saito arrived in Korea in 1910, one of his first observations was the open access situation driving forest degradation [77]. Poor forest conditions were later framed by the colonial government as evidence for the irresponsible nature of Koreans and a rationale for Japanese occupation and closing the common [55]. However, failures are common throughout human history for balancing fast-growing demands for forest resources responding to the drivers of changes with renewable, yet slow-growing and limited, supply from the forest ecosystem [4,78]. The lessons from the case of the SES that evolved over 250 years are salient for understanding how human technologies can affect the resource dynamics of an SES. We summarize four main lessons learned from old Korea below.

First, technological innovations may open opportunities for more efficient, but not necessarily less, resource use. Jevon's paradox occurs when the increase in energy efficiency per unit leads to an overall higher level of production and energy demand and more resource competition [79–84]. While highly active in promoting new technologies, most states promoting the bioeconomy do not recognize the potentially negative consequences of bioenergy development beyond food security linked to land and water resources, which include inequality and poverty, climate, or health risks [1]. If the adoption of new technologies increases inequality and policies ignore the needs of the poor, unintentional technological traps can intensify conflicts over resources and drive slow-moving yet profound changes in Resource Systems. The case of Ondol illustrates the importance of recognizing a range of social and ecological issues when promoting new technologies.

Second, a single policy instrument, such as the Pine Policy, is rarely effective in addressing multifaceted issues related to bioenergy development [85,86]. Joseon's policy offered limited immediate benefits to their constituencies living through the Little Ice Age and provided little motivation and incentives for bureaucracies at different levels to exceed policy requirements and explore alternatives for reducing timber and fuelwood demands. The concentrated decision-making power in the royal court (the central government) limited the engagement of provincial and local level institutions. The policy was ultimately exploited by the bureaucrats to expand their power and secure resources, which brewed resentments among the public, perceiving the policy as self-serving of the ruling class.

Third, governance responses focusing on a single species, even with native species, present high risks of unintended ecosystem-wide consequences. With growing global enthusiasm for a bio-economy, the search for high-yielding crops thriving in marginal conditions is intensifying, as well as the warning for the invasive potential of such crops [87]. As seen in this study, social and ecological changes may not be detected in the short term, as controlling variables, such as soil and landscape conditions, climate, and culture, change slowly, typically over centuries [88]. Ecological changes occurring through disruptions of social systems, such as wars, rapid industrialization, and changing populations, may also create a discrepancy between human perceptions and ecological realities [89,90].

Fourth, the Pine Policy framed under the national security agenda allowed the design of policy instruments and implementation to be inflexible to changing demands and evolving contexts of climate and population changes. Energy policy discourse is still often linked to the core national agenda, such as national security. Many scholars have argued that a low carbon economy cannot be realized without reframing energy policies either to be more tightly linked to the dominant national agenda or to override it [91]. Although it is hard to directly compare the kingdom of Joseon with modern democratic societies, promoting a bioeconomy by linking the need for national security may be a risky proposition considering the rigidity of policy that such framing may invite.

Conclusions/ wider implications of findings

The lessons learned from the late Joseon Dynasty period of Korea are not just a cautionary tale of failed resource management that happened someplace else long ago. The case provides illustrative examples of known concepts, such as Jevon's paradox and wicked problems of resource management, as well as the new insights on the drawbacks of rigid policy framing and the role of the government in shaping human preference and culture over time.

We face the Anthropocene age, where human dominance over climate and the environment is increasing, with multiple intertwined forces at work driving ecological and social changes [92]. The need for new and reformed institutions in multiple scales is critical now more than ever, although institutions still tend to focus on single problems and ignore system-wide interactions [93]. We argue that the field of environmental history has much to offer for understanding the social and ecological systemic risks of current scientific and technical developments. However, historical data sets recording environmental changes outside the Western world were often constructed with colonial narratives [11]. Examining long-term changes of human-nature relationship based on such data sets would require critical inspections of how and why they were constructed [11]. Employing the systems' perspective in historical analyses of environmental changes can help discern social, economic, political forces at work with ecological changes and place the lessons learned in the contexts of contemporary bioeconomy developments. We call for more historical analogues from different parts of the world to "move forward by looking back".

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