Conditions for coal dependence in preindustrial societies

—An agent-based analysis of the transition from fuelwood to coal—

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Abstract

This study examines the conditions under which a transition from fuelwood to coal emerges in preindustrial biomass societies, using a simple and abstract agent-based model (ABM). The model incorporates resident agents, forests, farmland, and coal fields, with each resident agent obtaining food and procuring fuel under the constraints imposed by the metabolic energy derived from food. The simulation results show that coal use can reduce dependence on fuelwood and, by shrinking the fuelwood supply base through forest conversion to farmland and population growth, can generate a positive feedback mechanism that promotes further coal dependence. However, the results also show that, depending on per capita fuel demand, the convertible forest rate, the marginal cost of coal extraction, and fuel transportation conditions, a large-scale transition from fuelwood to coal may fail to occur even when coal is available. These findings indicate that the emergence of a coal economy depends not only on the physical presence of coal but also on the interaction among land use, population dynamics, fuel demand, and procurement costs.

Key words: Coal dependence, Preindustrial societies, Fuelwood-to-coal transition, Agent-based modeling

JEL Classification: N50, O13, Q23

1 Introduction

The Newcomen steam engine, often regarded as the starting point of the modern practical heat engine, was developed to pump out groundwater that flowed into coal-mine shafts and hindered extraction. In eighteenth-century Britain, where the steam engine came into widespread use, coal occupied a central position in the heat-supply structure, and a coal-dependent economy had taken shape in which coal played an indispensable role in both daily life and industrial activity (Warde, 2007; Wrigley, 2013). In fact, the shift toward a coal economy in Britain had already become apparent by the mid-sixteenth century (Kander et al., 2014), and in London and other urban areas coal had become the main fuel for heating by the seventeenth century (Fouquet, 2008). Therefore, the emergence of the steam engine did not suddenly create a coal-dependent

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economy; rather, it was a phenomenon built upon the historical foundations prepared by several centuries of expanding coal consumption.

However, from the perspective of human history, the emergence of a coal economy is an extremely recent phenomenon. Although coal existed long before the appearance of humankind, why was it not widely used as a primary fuel at a much earlier stage? It is certainly true that Britain was geologically endowed with coal, but, as Nef (1954) notes, Britain was not the only region possessing favorable coal-resource conditions. In Europe, except for the Mediterranean region, coal fields are widely distributed across the northern, central, and eastern areas (Fernihough and O'Rourke, 2021). Moreover, viewed globally, although coal fields are unevenly distributed, they exist across broad areas, especially in the Northern Hemisphere (Kander et al., 2014), and are by no means a privileged resource available only in Europe.

Indeed, the history of coal use as a fuel is not necessarily short or limited. Traces of coal used as fuel have been identified at Paleolithic habitation sites in France (Théry et al., 1996). At Bronze Age sites in China, evidence has been found of coal being systematically used as both domestic and metallurgical fuel (Dodson et al., 2014; Qiu et al., 2023), and coal use was also attested during the Han period (Andrews-Speed, 2024). In Roman Britain, coal was used for diverse purposes and was transported overland and over long distances by sea and river routes (Dearne and Branigan, 1995; Travis, 2008).

Nevertheless, in many of these cases, coal remained a fuel that merely supplemented fuelwood and did not become the primary fuel sustaining the economy as a whole. One of the few exceptions is China during the Northern Song period (Andrews-Speed, 2024), where coal appears to have become a major fuel for ordinary people in the capital city Kaifeng (Miyazaki, 1957). Another case that should not be overlooked is the peat dependence of early modern Holland, which temporally overlapped with the rise of coal dependence in Britain. Against the background of scarce forest resources, Holland underwent a transition toward an economy that used peat as the primary alternative fuel (De Vries and Woude, 1997; Soens, 2011; Karel, 2013; Karel et al., 2015). Even allowing for these exceptions, however, it remains the case that instances in which coal became a primary fuel in preindustrial societies were extremely rare.

Why, then, did a coal economy emerge in only a very small number of regions, but not in many others? A common explanation is that rising fuel demand, mainly caused by population growth, and a decline in the supply capacity of forest resources promoted coal dependence (Nef, 1932; Galloway, 1969; Wilkinson, 1973; Cipolla, 1976; Hatcher, 1993; Fouquet, 2008; Kander et al., 2014). If rising fuel demand and the decline of forest-resource supply capacity were sufficient explanations, coal dependence might be expected to have spread more widely in regions where coal was available than is actually observed. This is because preindustrial societies were, in general, stagnant economies trapped in the "Malthusian trap" (Clark, 2007).

In a Malthusian economy, potential population growth is constrained by the photosynthetic productivity of land (Wrigley, 2010, 2016). Conversely, when this constraint is relaxed, there is room for population growth. In traditional biomass societies, both food and fuel depend on photosynthetic products, that is, forest resources. If usable coal is present under such conditions, its use may relax, at least to some extent, the constraints imposed by the land productivity. Of course, coal itself is not food, and therefore it does not directly relax the food constraint. However, coal use can make it possible to convert forests that had previously served as fuel sources into farmland, thereby expanding the scope for population growth (Wrigley, 2016). Consequently, population growth and forest decline together increase the scarcity of fuelwood, further strengthening the dependence on coal. If coal use has such a positive feedback mechanism, in which coal use promotes further coal use, the shift from a biomass economy to a coal economy may appear, at first glance, to be a likely development.

What, then, prevents this shift? The expansion of coal use is governed by the difference in procurement costs between coal and fuelwood. Procurement costs broadly consist of extraction costs in the case of coal, harvesting costs in the case of fuelwood, and transportation costs in both cases. Because forest resources are renewable, fuelwood can be harvested sustainably under relatively stable conditions, as long as forests are maintained. In contrast, coal is an exhaustible resource, and the marginal cost of extraction tends to rise as cumulative extraction increases. Thus, even if coal initially has a procurement-cost advantage over fuelwood, this advantage may be lost in the long run.

Even when the extraction cost of coal is sufficiently low, transportation costs restrict the geographical expansion of coal use (Nef, 1932; Langton, 1979; Flinn and Stoker, 1984; Hatcher, 1993; Fouquet, 2008; Wrigley, 2010). This is because forests are widely distributed, whereas coal is spatially concentrated. Consequently, if coal transportation costs are high, coal use tends to be confined to areas near the coal mines. In Britain, even before the diffusion of the steam engine, the conditions for coal transportation were relatively favorable, allowing a wide-area supply. However, what matters here is the relative transportation cost of coal and fuelwood. Even if the transportation cost of coal remains unchanged, changes in the procurement conditions of fuelwood can alter the spatial spread of coal use. When forests are abundant near each settlement, the fuelwood transportation costs are low. However, as forest conversion to farmland proceeds and population growth increases fuel demand, settlements must rely on more distant forests for fuelwood, causing fuelwood transportation costs to increase. As a result, the relative disadvantage of coal procurement compared to fuelwood diminishes, and the incentive to use coal strengthens endogenously.

As discussed above, whether coal use expands depends on the balance between coal and fuelwood procurement conditions, and this relationship is dynamic. At the micro level, whether a given resident agent chooses coal or fuelwood as a fuel source is strongly shaped by local environmental conditions, including the locations and states of coal fields and forests, and competition over resources with neighboring resident agents. Moreover, each resident agent's fuel-choice behavior affects forest distribution and land-use patterns, thereby further changing the environmental conditions surrounding future choices. In addition, resident agents are not homogeneous but differ in their fuel preferences and locational conditions. Under such heterogeneity, outcomes differ across resident agents, and those with relatively advantageous fuel choices or locational conditions are more likely to maintain their production and population. Consequently, the choices of individual resident agents do not remain isolated events; they accumulate through the interaction between choice and environmental change, evolutionarily transforming spatial configurations and resource-use patterns. Therefore, whether coal dependence emerges should be understood as the outcome of interactions among heterogeneous agents, changes in land use, reorganization of resource distributions, and the cumulative process of selection through these channels. To the best of the author's knowledge, the conditions under which coal dependence proceeds as an evolutionary, spatial, and interactional process have not been sufficiently examined[1].

This study examines this issue using an agent-based model (ABM). ABM is a method that places agents within a model and analyzes the macro-level patterns that emerge through interactions among agents and between agents and their environment (Hamill and Gilbert, 2016; Gallegati et al., 2017; Railsback and Grimm, 2019). Its advantage lies in its ability to simultaneously handle heterogeneity among agents, local interactions, spatial structure, feedback effects, and the cumulative process of selection. Therefore, ABM is particularly useful for analyzing processes in which population, forests, land use, and fuel choice mutually determine one another and evolve through the accumulation of choices.

ABM has already been used across a wide range of academic fields, and a substantial body of research also exists in archaeology and history-related fields. For example, ABM has been used to analyze the mechanisms through which markets and trade networks emerge (Graham and Weingart, 2015; Watts and Ossa, 2016; Chliaoutakis and Chalkiadakis, 2020; Kim et al., 2024), the processes through which money emerges (Marimon et al., 1990; Duffy, 2001; Hasker and Tahmilci, 2008; Moran et al., 2013; Nioche et al., 2019), and the formation of cultural traits and diversity (Flache, 2018; Puig, 2024). This study is positioned within the Human Ecology type in the classification of Cegielski and Rogers (2016). Studies in this lineage seek to clarify the interdependence between humans and the natural environment and its evolutionary processes through ABM, with representative examples including Barton et al. (2011), Altaweel and Watanabe (2012), Haas and Kuhn (2019), Sikk and Caruso (2020), and Garg et al. (2021). These studies generally incorporate spatial structure explicitly and pay close attention to the coevolution of land use and landscape. However, at least to the author's knowledge, no study within this framework has explicitly incorporated fossil fuels and examined the conditions under which coal dependence emerges through mutually dependent changes in land-use and landscape change.

The distinctive feature of this study's research question is that it does not remain confined to the case-specific historical question of why coal dependence advanced in Britain. Rather, it directly addresses the more general question of why the shift from fuelwood to coal did not occur widely in preindustrial societies. Of course, as Nef (1932) argued, understanding the rise of coal dependence in Britain requires consideration not only of the timber crisis but also of institutional and historical specificities particular to Britain, such as changes in landownership institutions involving coal mines. The concern of this study, however, is not to deny such case-specific historical conditions but to clarify the more general conditions underlying fuel transitions.

Against this background, this study aims to clarify, through an ABM, the conditions under

[1] Evolution here is understood in terms of Universal Darwinism, characterized by the three elements of variation, selection, and inheritance (Hodgson, 2002, 2003, 2004, 2005).

which a shift from fuelwood to coal emerges in traditional biomass societies. In particular, this study focuses on whether a positive feedback mechanism is formed that allows coal dependence to progress in a self-reinforcing manner as population dynamics, deforestation, land-use conversion, and transportation conditions mutually influence one another. Through this analysis, this study aims to offer a more general theoretical perspective that complements the single-country historical explanations of preindustrial fuel transitions.

The remainder of this paper is organized as follows. Section 2 presents the basic structure of the model used in the analysis. Section 3 reports the simulation results. Section 4 discusses the implications of the findings. Finally, Section 5 concludes the paper.

2 The Model

2.1 Overview

The ABM developed in this study is designed to examine the conditions under which a preindustrial biomass society that depends primarily on fuelwood shifts toward a coal economy. The flowchart of the model is shown in Figure 1.

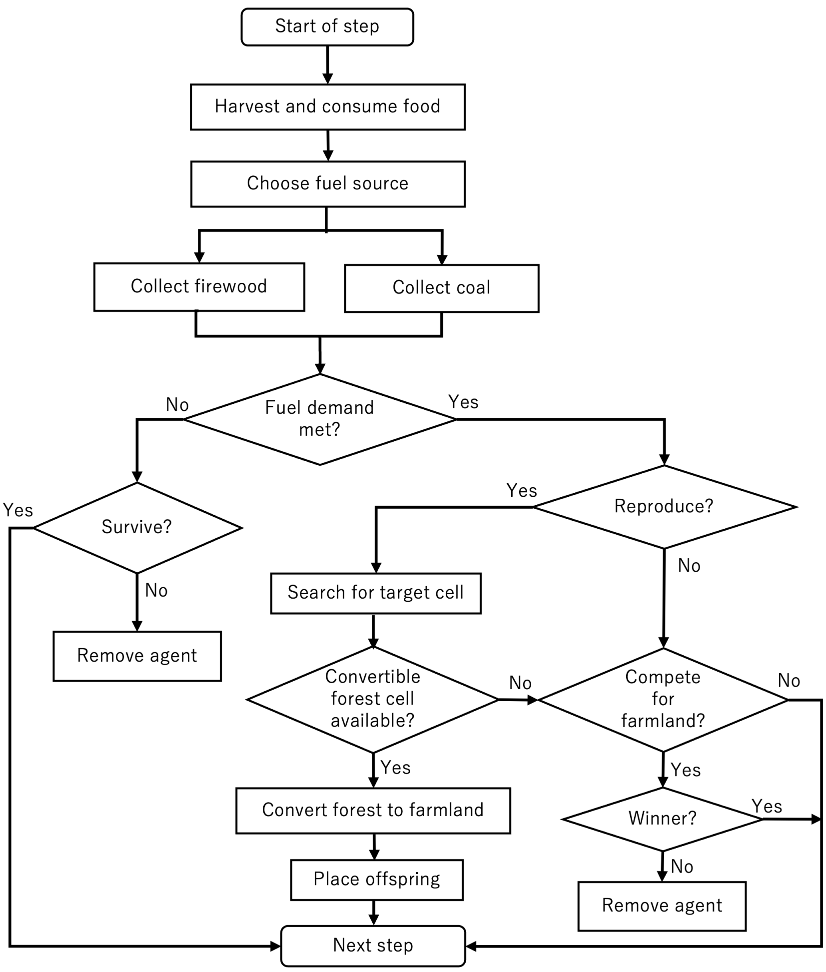


Figure 1: Flow diagram of one simulation step in the ABM.

The model consists of two main types of components: resident agents and land cells located in a two-dimensional space. In each step, resident agents consume food and fuel using the surplus energy obtained by subtracting the resting metabolic energy from the energy derived from food to obtain food and procure fuel. The lower the amount of fuel obtained relative to the demand required for survival, the higher the probability of death. In general, resident agents with a larger surplus energy have an advantage in survival and reproduction. The time advances through repeated steps.

Land cells are classified as forests, farmlands, degraded lands, or coal fields. Farmland cells also serve as the residence for resident agents. Forest cells are fuel-supply sites that can become food-production sites when converted into farmland. Farmland cells that are no longer occupied by resident agents become degraded land for a certain period and then regenerate into forests. In general, forests are spatially widespread, whereas coal is spatially concentrated in certain areas.

The available fuels are fuelwood and coal. Each resident agent has an inherent preference for either fuelwood or coal and collects fuel from its neighborhood in accordance with that preference. Resident agents can access forests and coal fields as long as the supply capacity of those sites is not exceeded. Because fuel preferences and surrounding landscapes are heterogeneous, the energy costs of fuel procurement, particularly transportation energy costs, vary across agents. In general, each resident agent preferentially collects fuel with a lower procurement cost while considering its inherent preference.

After collecting food and fuel, resident agents that retain more surplus energy are more likely to produce offspring. Offspring agents inherit the attributes of their parents, although mutations occasionally occur. New offspring agents are placed in the neighborhood of the parent, and when the destination is a forest, they attempt to settle by converting it into farmland. If no forest convertible into farmland exists in the neighborhood, competition for existing farmland occurs. The outcome of this competition is governed by the amount of surplus energy available.

When forests are sufficiently abundant, it is clearly more advantageous for many resident agents not living near a coal field to harvest fuelwood from nearby forests than to use distant coal fields. However, when population growth leads to the conversion of forests into farmland, the increasing scarcity of fuelwood raises the procurement cost of fuelwood, and the cost difference between coal and fuelwood may narrow. Consequently, coal use may begin to spread outward from the coal field and generate a positive feedback mechanism that promotes further coal dependence.

However, such a positive feedback mechanism does not always arise. The extent of coal use expansion depends on parameters such as the unit procurement costs of food and fuel, food and fuel demand, the land productivity of food and fuelwood, and the convertible forest rate. Therefore, the emergence of a coal economy is determined endogenously by a combination of these conditions.

2.2 Resident agents

Resident agents are located in a two-dimensional space represented by a 21×21 square lattice and occupy a single cell that serves as their residential base. Food and fuel demands are specified exogenously as parameters. Food production occurs only within the cells occupied by resident agents. Accordingly, the transportation cost of food is assumed to be zero.

Because the primary analytical focus of this model is on fuel choice and its consequences, the food sector is simplified. Specifically, a resident agent living in a cell where food production is possible is assumed to satisfy the specified food demand within that cell. However, food production entails a fixed energy cost, which is subtracted from the surplus energy of the resident agent. Under this assumption, the main constraint governing the survival and reproduction of resident agents is not the success of food production per se, but the conditions of fuel procurement using the surplus energy that remains after food production.

Resident agents cannot use all the energy obtained from food for resource procurement. In this model, the residual after subtracting the fixed energy required for bodily maintenance is defined as the surplus energy that the resident agents can use for food production and fuel procurement. This surplus energy is allocated to food production, fuelwood harvesting, coal extraction and fuel transportation. Accordingly, resident agents with larger surplus energy can secure fuel from wider areas or under higher procurement costs.

This model does not assume the use of power devices, such as heat engines. Thus, the muscular power of resident agents is the source of mechanical energy for food production and for procuring fuel. Fuel procurement consists of harvesting fuelwood, extracting coal, and transporting these fuels.

Each resident agent has an inherent preference for using either fuelwood or coal. This fuel preference determines the extent to which the agent attempts to satisfy a given fuel demand for each fuel type. Based on this, the resident agent searches neighboring cells for available fuel-supply sites and procures fuel. For fuelwood, the agent collects from the available forest cells in ascending order of procurement cost. For coal, the agent extracts coal from an available coal-field cell and transports it to the residential cell. Thus, actual fuel procurement is determined by both the resident agent's fuel preference and the procurement costs of the fuelwood and coal.

Fuel procurement ends when one of the following occurs: (1) fuel demand is satisfied, (2) surplus energy reaches zero, or (3) no procurable fuel remains in the vicinity. A resident agent that fails to satisfy the fuel demand faces a probability of death proportional to the shortage. Specifically, if the initial fuel demand is $\bar{h}$ and the collected fuel is h, the death probability Pr_d is given by

$$Pr_d = \max\left(\frac{\bar{h} - h}{\bar{h}}, 0\right). \tag{1}$$

If the surplus energy remains positive after fuel procurement, the resident agent may produce an offspring agent. The probability Pr_b of producing an offspring agent is given by the following expression, where surplus energy is Δe, the intake energy, that is, food demand, is $\bar{e}$, and k is a positive constant:

$$Pr_b = k\frac{\Delta e}{\bar{e}}. \tag{2}$$

Thus, in this model, resident agents with higher surplus energy are more likely to produce offspring agents.

Offspring agents inherit the attributes of their parent agents. However, with a fixed probability, an offspring becomes a mutant and randomly acquires attributes that differ from those of the parent. An offspring agent selects a residential site from cells that are neighboring the parent agent. Priority is given to forests that can be converted into farmlands. When such forests exist, the offspring agent selects one of them as a target and migrates. After migration, the offspring agent converts the forest into a farmland. The energy cost required for farmland conversion is not explicitly considered in the model.

If no forest convertible into farmland exists in the neighborhood, the offspring agent competes with other resident agents for existing farmland. Specifically, among neighboring cells occupied by other resident agents, the offspring agent selects the cell occupied by the resident agent with the lowest surplus energy as its target. The outcome of competition for the target cell is governed by the surplus energy of both parties. If the surplus energy of the parent agent of the offspring agent is Δe_o and the surplus energy of the resident agent in the target cell is Δe_t, the probability Pr_m that the offspring agent migrates to the target cell is given by

$$Pr_m = \frac{\Delta e_o}{\Delta e_o + \Delta e_t}. \tag{3}$$

An offspring agent that fails to migrate to the target cell dies.

2.3 Forest cells and farmland cells

Forest cells are land cells that supply fuelwood. Each forest cell has a maximum fuelwood supply capacity at each step. However, the model assumes that forest cells fully recover their fuelwood-supply capacity at the end of each step. Consequently, harvesting fuelwood does not cause forest cells to become degraded land.

Harvesting and transporting fuelwood incurs energy costs. The energy cost required to harvest one unit of fuelwood and the energy cost required to transport one unit of fuelwood over one unit of distance are each assumed to be constant. The procurement cost of fuelwood is calculated as the sum of the harvesting and transportation costs.

Some forest cells can be converted into farmland, whereas others cannot be converted. When a convertible forest cell is converted into farmland by a resident agent, food production becomes possible in that cell; however, the cell can no longer supply fuelwood. In this sense, forest cells function both as fuel-supply sites and as potential food-production sites, creating a land-use conflict between fuelwood supply and food production.

Farmland cells also have a maximum food-supply capacity per unit time. Similar to forest cells, the food-supply capacity of farmland cells is assumed to fully recover at the end of each step. Thus, the model does not explicitly consider the decline in productivity caused by farmland overuse.

A farmland cell that becomes unoccupied by resident agents for any reason turns into a degraded land. Degraded land is a cell that produces neither food nor fuel, and after a specified period, it regenerates into a forest cell that can be converted into farmland.

Under these settings, forest decline in the model results primarily from forest conversion to farmland and not from resource depletion caused by fuelwood harvesting. In other words, as population growth increases the demand for farmland, forest cells are converted into food-production sites, thereby reducing the fuelwood-supply capacity. This land-use conversion is the principal mechanism through which fuelwood procurement conditions deteriorate, and the relative advantage of coal use may increase.

2.4 Coal-field cells

Coal-field cells are land cells that supply only coal. Unlike forest cells, coal-field cells cannot be converted into farmland and do not produce food.

Coal is an inherently exhaustible stock resource. However, this model does not impose an explicit upper bound on the coal stock. This setting reflects the model's focus on extraction and transportation costs as constraints on coal use, rather than on physical depletion. If an explicit upper bound is imposed on the coal stock, it becomes difficult to distinguish whether the limitation on coal use arises from resource exhaustion or rising procurement costs. Therefore, the model assumes that coal resources are sufficiently abundant and analyzes whether coal dependence emerges under the specified procurement and land-use conditions.

In general, the marginal cost of coal extraction tends to rise as cumulative extraction increases. However, the relationship between cumulative and marginal extraction costs depends on geological conditions, such as seam depth and thickness, drainage conditions, mining technology, and institutional arrangements, and is therefore difficult to generalize. Moreover, this study does not aim to reproduce the process of coal resource depletion, but to examine how differences in extraction conditions may hinder the transition from fuelwood to coal. Accordingly, the model treats the marginal energy cost of coal extraction as an exogenous variable. By varying this parameter, the analysis examines how differences in extraction conditions affect the emergence of coal dependence. This approach also allows the implications of rising marginal extraction costs associated with cumulative extraction to be considered by comparing alternative parameter settings.

In the model, a single coal-field cell is located at the center of a two-dimensional spatial grid. This setting represents the spatial concentration of coal deposits, in contrast to the widespread distribution of forests. Coal procurement entails transportation costs, in addition to extraction costs. Therefore, resident agents located farther from the coal-field cell incur higher transportation costs when procuring coal. Consequently, the spatial diffusion of coal use is constrained not only by extraction costs but also by the distance between the coal-field cell and residential locations.

The model does not impose an explicit upper limit on the amount of coal that can be extracted per step. However, the number of resident agents, their fuel demand, and surplus energy are finite. Thus, the amount of coal used in each step is endogenously constrained by the demand and surplus energy of the resident agents.

2.5 Parameter settings and initialization

Table 1 presents the baseline settings for the model's main parameters. The following explanation focuses on the parameters that are particularly important for understanding the behavior of the model.

In the baseline, the food-supply capacity of one farmland cell per step is defined as one metabolic energy unit (MEU). Metabolic energy refers to the energy derived from food and used by resident agents for bodily maintenance, resource procurement, and reproduction. The resident agent occupying the corresponding farmland cell consumes this food.

Resident agents cannot use all the metabolic energy obtained from food for their activities. The model assumes that 75 percent of one metabolic energy unit is consumed as fixed energy for bodily maintenance, while the remaining 25 percent becomes surplus energy available for other activities. Thus, when one resident agent consumes one metabolic energy unit of food, its surplus energy is 0.25 MEU.

The energy input required to obtain one metabolic energy unit of food must be lower than the surplus energy. Otherwise, the resident agent would exhaust its surplus energy simply by acquiring food and would be unable to procure fuel or produce offspring. The energy return on agriculture varies across periods and regions, but according to Smil (2017), the energy return on wheat production in Europe was around 20 near the beginning of the Common Era, around 40 in the medieval period, and over 100 in the nineteenth century. The model adopts 50 as the

Table 1: Baseline model parameters

Parameter	Value	Description
Number of grid cells	441	Total number of grid cells in the simulation space (21×21).
Convertible forest rate	1.0	Fraction of forest cells that can be converted into farmland.
Number of coal-field cells	1	Number of coal-field cells in the simulation space; the coal-field cell is located at $(10, 10)$.
Food yield per farmland cell	1.0	Maximum food production per farmland cell per time step, measured in MEUs.
Fuelwood yield per forest cell	1.0	Maximum fuelwood production per forest cell per time step, measured in FUs.
Marginal cost of food production	0.02	Energy cost required to produce one MEU of food, measured in MEUs.
Marginal cost of coal extraction	0.01	Energy cost required to extract one FU of coal, measured in MEUs.
Marginal cost of fuelwood harvesting	0.01	Energy cost required to harvest one FU of fuelwood, measured in MEUs.
Coal transportation cost	0.005	Energy cost required to transport one FU of coal over one cell distance, measured in MEUs.
Fuelwood transportation cost	0.01	Energy cost required to transport one FU of fuelwood over one cell distance, measured in MEUs.
Per capita fuel demand	1.0	Fuel requirement of one resident agent per time step, measured in FUs.
Per capita food demand	1.0	Food requirement of one resident agent per time step, measured in MEUs.
Metabolic maintenance share	0.75	Share of one MEU consumed as fixed energy for bodily maintenance.
Mutation rate	0.05	Probability that an offspring inherits a mutated trait rather than exact parental characteristics.

baseline value and sets the energy cost required to produce one MEU of food at 0.02 MEU. This cost is subtracted from the surplus energy of the resident agents at each step.

According to Smil (2017), the power density of phytomass production in forests is approximately five times greater than that of grain production in agricultural fields. Based on this relationship, the model defines the amount of fuelwood that one forest cell can supply per step as thermal energy equivalent to five times 1 MEU and calls this 1 fuel unit (FU). The FU unit refers to the thermal energy consumed as fuelwood or coal. Because metabolic energy derived from food and fuel energy differ in that only the former is metabolized by the body and used for labor in resource procurement, the model represents them using different units.

In the baseline, the fuel demand of one resident agent is set at 1 FU. The real-world interpretation of this setting can be understood as follows: If the daily food intake per person is regarded as approximately 11 MJ, 1 FU is five times that amount, or approximately 55 MJ of fuel energy. Since the average energy content of dry wood is approximately 18 MJ/kg, 55 MJ corresponds to roughly 3.1 kg of fuelwood (Smil, 1983; Jenkins et al., 1998). This falls within the range of per capita daily fuelwood consumption in Northern Europe, 2.7–4.3 kg/capita/day (Kander et al., 2014).

In the baseline, the marginal energy cost of fuelwood harvesting is set at 0.01 MEU. This is based on the following conversion. According to Pyke (1970), the energy expenditure required for sawing wood is 1.76 MJ/h. If it is assumed that cutting the amount of fuelwood equivalent to 1 FU takes approximately five minutes, the energy expenditure is approximately 0.146 MJ. If 1 MEU is regarded as approximately 11 MJ, this corresponds to approximately 0.013 MEU. For simplicity, the model sets this value at 0.01 MEU.

In the baseline, the marginal energy cost of coal extraction is set at 0.01 MEU, the same as that for fuelwood harvesting. The reason for this is as follows. According to Pyke (1970), the effort required for standard coal mining is approximately twice as large as that required for wood cutting. At the same time, the heat content of coal per unit mass is approximately twice that of fuelwood. Therefore, when measured per fuel unit, the marginal energy costs of coal extraction and fuelwood harvesting are approximately the same.

The marginal energy cost of fuel transportation, that is, the energy cost required to transport 1 FU over one cell distance, directly affects the spatial spread of fuel use. This value is also related to the interpretation of the distance represented by one cell in the simulation space. As noted above, a single coal-field cell is placed at the center of the simulation space, which is represented by a 21×21 square lattice. If transportation costs are set too high, coal use is excluded by distance constraints. The purpose of the model is to examine how fuel choice changes through the interaction among fuelwood harvesting, coal extraction, land-use conversion, and population dynamics, rather than through mere transportation-distance constraints. Therefore, the marginal energy cost of fuel transportation is set such that surplus energy is not exhausted by simply transporting coal.

In the baseline, the marginal energy cost of coal transportation is set at 0.005 MEU. This value was set based on pilot simulations so that coal use is not trivially prevented by transportation distance alone, even when the fuel demand of resident agents is increased up to five times the baseline value. In addition, considering that the heat content of fuelwood per unit mass is approximately half that of coal, the marginal energy cost of fuelwood transportation is set at 0.01 MEU, which is twice the marginal energy cost of coal transportation.

The model sets the point at which coal becomes available as a reference point. Before this point, a mature biomass society is assumed to have formed under conditions in which coal cannot be used. Thus, the population distribution and land-use state at the start of the simulation are not given exogenously but are set as the steady state reached under constraints on food and fuelwood supply. If the population is too large, excessive forest conversion to farmland makes fuelwood scarce and increases the mortality rate. Conversely, if the population is too small, there remains room for farmland conversion, and the population increases through the settlement of offspring. The steady state of the biomass society formed through this adjustment process is considered the initial state in the model.

3 Simulation results

3.1 Baseline simulation

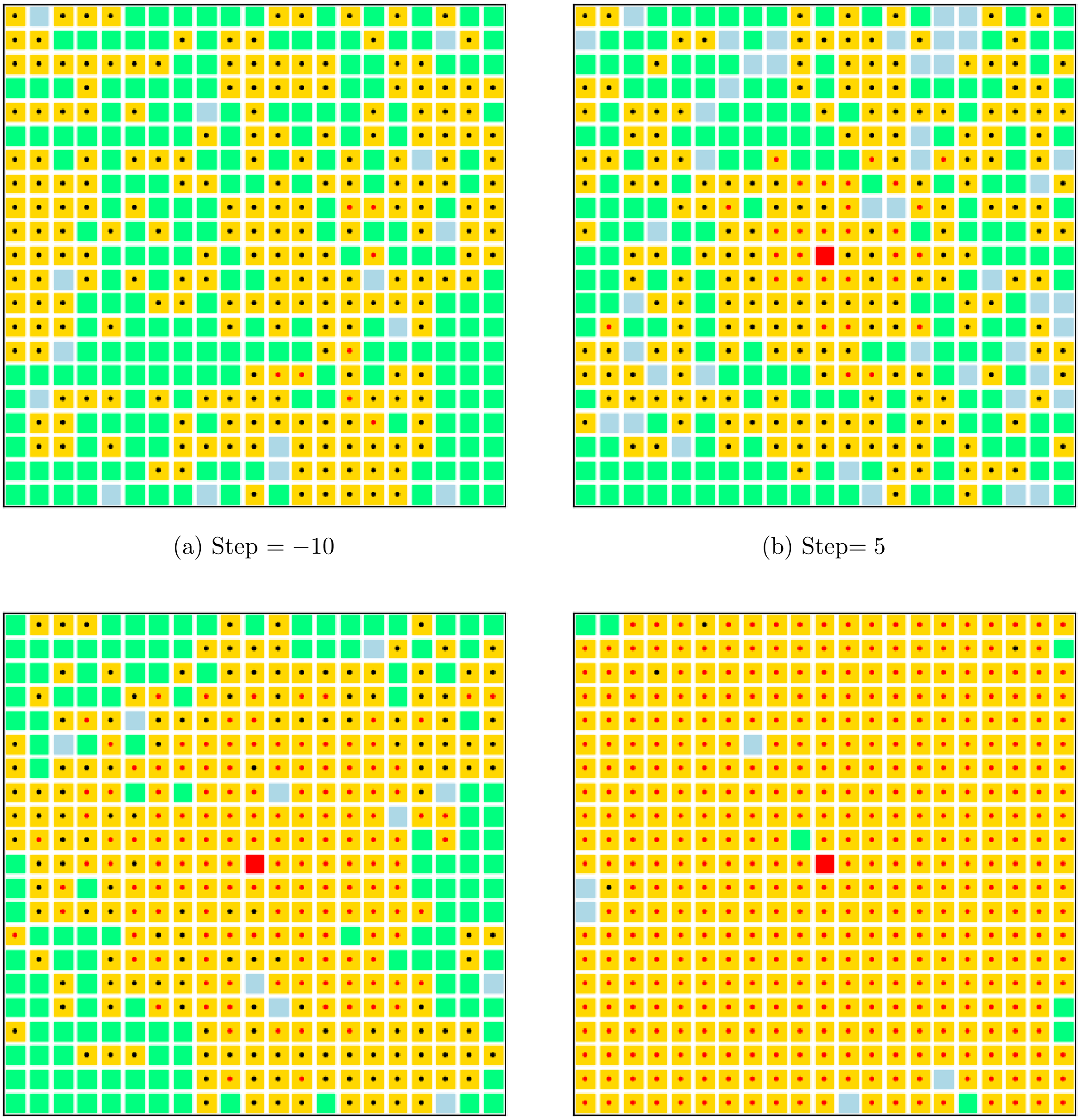
This section presents the simulation results obtained using the baseline settings. Figure 2 shows the landscape and spatial distribution of resident agents before and after coal becomes available. The color of each cell indicates the land-use state, and the color of the point on the cell indicates the fuel preference of the resident agents.

Figure 2(a) shows the state of ten steps before coal availability. At this stage, the only fuel source available to the resident agents is fuelwood, which is harvested from forest cells. Nevertheless, some resident agents with a preference for coal already exist, even though coal is not yet available in the model. This results from the model setting in which mutations occur with a certain probability through inheritance across generations.

Even before coal becomes available, at the micro level, the conversion of forest cells into farmland by resident agents and the degradation and regeneration of farmland cells following the death of resident agents occur continuously in the model. However, at the macro level population size and forest area have reached an approximate equilibrium. In other words, Figure 2(a) corresponds to a stationary biomass society formed under constraints of food and fuelwood supply. When coal becomes available, its use gradually spreads from the center to the periphery, as shown in Figure 2(b)–(d), while being constrained by transportation energy costs that depend on the distance from the coal-field cell.

Figure 3 shows the time paths of the coal share and population size under the baseline settings. Here, the coal share refers to the proportion of coal in the total fuel consumption. Once coal becomes available, the coal share rises rapidly and eventually reaches a state in which nearly all fuel demands are met by coal. Simultaneously, the population size also increases. This occurs because the expansion of coal use reduces dependence on fuelwood, allowing some forest cells previously retained as fuelwood-supply sites to be converted into farmland and used as food-production sites.

These results show that under baseline settings, coal use can expand in a self-reinforcing



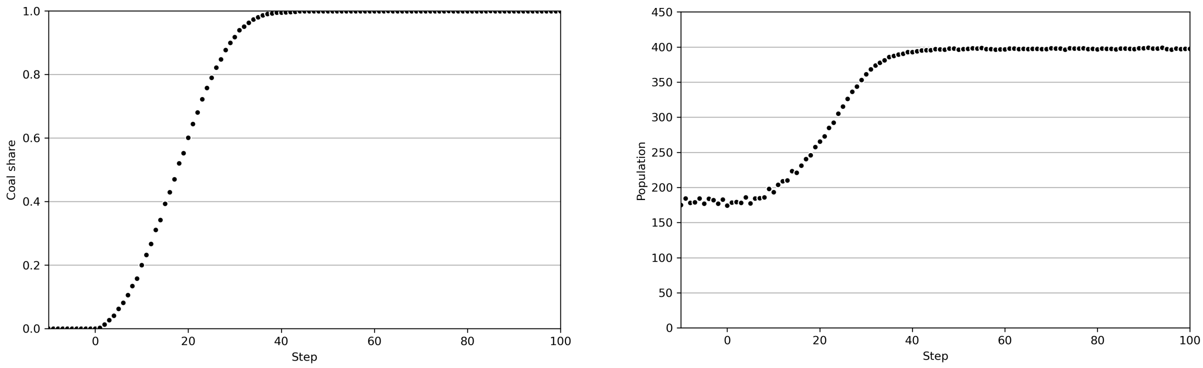
(a) Step = −10

(b) Step= 5

(c) Step= 20

(d) Step= 35

Figure 2: Spatial distribution of land cells and resident agents in the baseline simulation. Green, yellow, red, and light-blue cells indicate forest, farmland, coal field, and regenerating forest, respectively. Black and red dots indicate biomass-using and coal-using resident agents, respectively.



(a) Coal share (b) Population

Figure 3: Coal share and population dynamics in the baseline simulation.

manner through a positive feedback mechanism mediated by forest conversion to farmland and population growth. Coal use reduces dependence on fuelwood and promotes the conversion of forest cells into farmland. Consequently, the decline in forest area worsens the procurement conditions of fuelwood, further increasing the relative advantage of coal. Thus, the baseline simulation shows that coal dependence is not imposed exogenously but can emerge endogenously through interactions between the local fuel choices of resident agents and changes in land-use patterns.

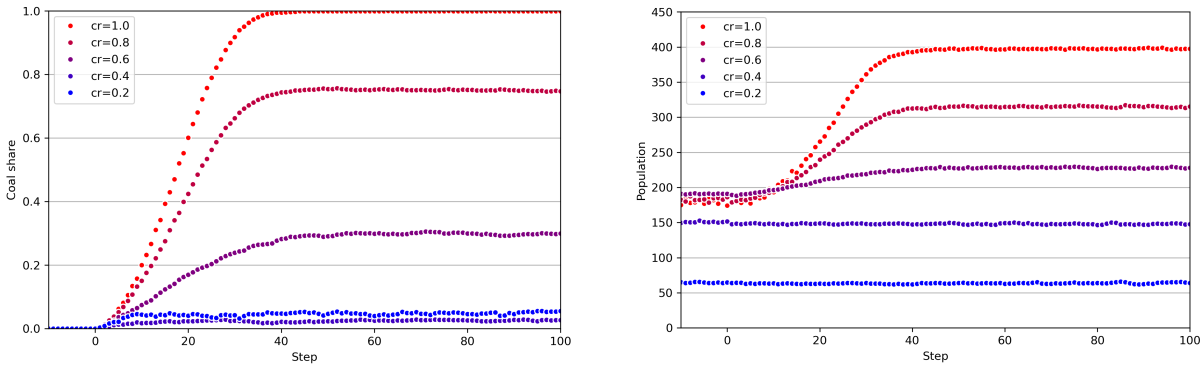
3.2 Convertible forest rate

In the baseline simulation, once coal became available, its use expanded in a self-reinforcing manner. However, such a shift from a biomass to a coal economy may not occur under different conditions. One important factor is the convertible forest rate, which is defined as the fraction of forest cells that can be converted into farmland.

The baseline model assumes that all forest cells can be converted to farmland. However, not all forests are necessarily convertible into farmland because of terrain, soil conditions, water availability, landownership institutions, or communal use restrictions (see also FAO, 1978, 1982; Zabel et al., 2014). When forest conversion to farmland is restricted, the positive feedback mechanism that drives coal use expansion is expected to weaken. This is because non-convertible forests remain in place, maintaining a certain level of fuelwood-supply base.

Figure 4 shows the simulation results for different convertible forest rates. All parameters, except for the convertible forest rate, are identical to those in the baseline model. As the figure shows, when the convertible forest rate declines from 100 to 80 percent, the long-run coal share falls from 100 to below 80 percent. When the convertible forest rate declines further from 80 percent to 60 percent, the coal share drops sharply and stabilizes at approximately 30 percent. When the convertible forest rate falls to 40 percent, the coal share approaches nearly zero, and further declines in the convertible forest rate generate only negligible changes in the coal share.

A decline in the convertible forest rate reduces the long-run coal share. However, this effect is not proportional to the magnitude of the decline in the convertible forest rate. Notably, within



(a) Coal share

(b) Population

Figure 4: Coal share and population dynamics under different values of the convertible forest rate (cr).

the intermediate range of the convertible forest rate, the coal share responds sensitively to small changes (Figure 4). This result suggests the existence of a threshold-like transition between fuelwood and coal-dependent regimes, rather than a continuous transition.

This nonlinear response arises because the convertible forest rate simultaneously determines both the population-supporting capacity and the remaining forest area. When the convertible forest rate is sufficiently low, farmland expansion is constrained, limiting increases in population size and aggregate fuel demand. Because forests are also relatively preserved, the fuelwood-supply base tends to be maintained. As a result, fuelwood procurement conditions do not deteriorate significantly, and the relative advantage of coal does not increase substantially. In contrast, when the convertible forest rate exceeds a certain range, farmland expansion leads to population growth and increased aggregate fuel demand, whereas forest contraction places pressure on the fuelwood-supply base. When these two effects coincide, fuelwood procurement conditions deteriorate rapidly, increasing the relative advantage of using coal. Therefore, within the intermediate range of the convertible forest rate, small differences can produce large differences in the long-run composition of fuel use.

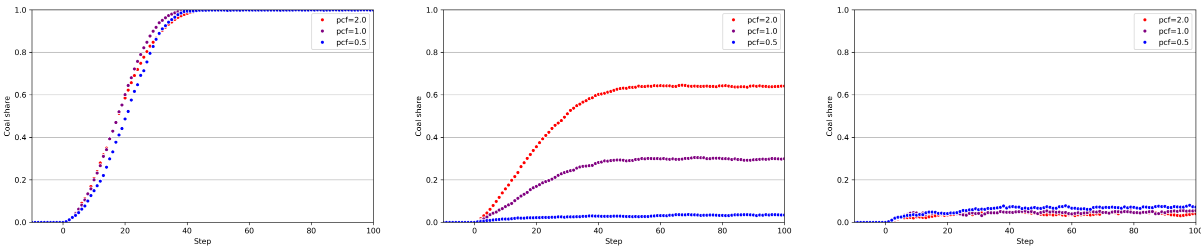
3.3 Per capita fuel demand

The previous section confirmed that the convertible forest rate is an important factor governing the emergence of coal dependence. This section focuses on per capita fuel demand as another important condition. Because per capita fuel demand affects the pressure on forest resources through the magnitude of the fuelwood demand, it is expected to have a major influence on the possibility of a transition from a fuelwood-dependent regime to a coal-dependent regime.

The greater the per capita fuel demand, the more likely it is that the pressure on forest resources will intensify. If each resident agent requires more fuel, satisfying fuel demand solely with the fuelwood supplied by forest cells becomes increasingly difficult. Under such conditions, fuelwood procurement is likely to deteriorate, thereby increasing the relative advantage of coal.

However, the effect of per capita fuel demand on the coal share may vary depending on the convertible forest rate. Because the convertible forest rate determines the scope for converting forest cells into farmland, it affects the conditions for expanding coal use through the contraction of the fuelwood-supply base and an increase in aggregate fuel demand. Therefore, to evaluate the effect of per capita fuel demand, it is necessary to examine it in combination with differences in the convertible forest rate rather than in isolation.

Figure 5 shows the effect of per capita fuel demand on the long-run coal share while varying the convertible forest rate. For the per capita fuel demand, the figure compares the baseline value of 1 FU with cases of 0.5 FU (half the baseline) and 2 FU (twice the baseline).



(a) cr=1.0 (b) cr=0.6 (c) cr=0.2

Figure 5: Effects of per capita fuel demand (pcf) on coal share under different values of the convertible forest rate (cr).

When the convertible forest rate is 100 percent (Figure 5(a)), the long-run coal share approaches nearly 100 percent regardless of the level of per capita fuel demand. This outcome occurs because all forest cells are convertible into farmland; consequently, population growth associated with coal use rapidly contracts the forest area and greatly reduces the fuelwood-supply base. In this case, differences in per capita fuel demand do not decisively determine whether coal dependence will emerge.

By contrast, when the convertible forest rate is at an intermediate level (Figure 5(b)), differences in per capita fuel demand produce large differences in the long-run coal share. When per capita fuel demand is low, a substantial part of the fuel demand can be satisfied by fuelwood supplied from the remaining forest cells. As a result, fuelwood procurement conditions do not deteriorate substantially, and the positive feedback mechanism that would expand coal use in a self-reinforcing manner is unlikely to emerge in the future. However, when per capita fuel demand is high, the pressure on forest resources intensifies, increasing the relative advantage of coal and thereby raising the coal share.

When the convertible forest rate is sufficiently low (Figure 5(c)), the fuelwood-dependent regime is maintained even when the per capita fuel demand doubles. In this case, farmland expansion is strongly constrained, suppressing population growth and increases in aggregate fuel demand. Moreover, because many forest cells remain unconverted to farmland, the fuelwood-supply base is maintained. Consequently, even with increased per capita fuel demand, conditions sufficient for the large-scale expansion of coal use are unlikely to develop.

These results show that per capita fuel demand can promote coal dependence, but its effect is mediated by the rate of convertible forests. When the convertible forest rate is high, coal dependence proceeds across a wide range of per capita fuel demands. When the convertible forest rate is low, a fuelwood-dependent regime is maintained across a wide range of per capita fuel demands. In the intermediate region between these two cases, the long-run coal share changes substantially, depending on differences in per capita fuel demand.

3.4 Marginal cost of coal extraction

A fundamental distinction between coal and forest resources is that coal is an exhaustible resource, whereas forests are renewable resources. This difference creates an asymmetry between coal-extraction and fuelwood-harvesting conditions.

Fuelwood can be supplied sustainably as long as its use remains within the rate of forest regeneration. By contrast, coal deposits that are easier to extract are likely to be used first, leading to a general deterioration in extraction conditions as cumulative extraction increases. Consequently, the marginal cost of coal extraction may increase over time, potentially undermining the relative advantages of coal.

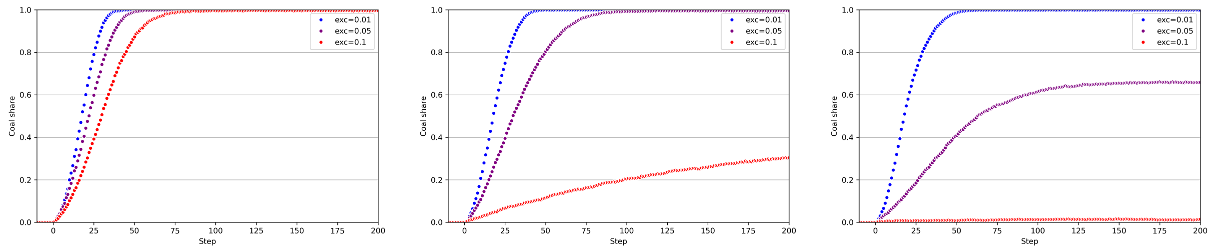
However, the model does not incorporate an endogenous mechanism by which the marginal cost of coal extraction increases with cumulative extraction. Formulating such a relationship requires accounting for geological conditions, mining technology, labor organization, drainage facilities, transportation methods, and institutional conditions. Given the difficulty of generalizing this relationship for preindustrial coal mines, and considering that marginal extraction costs may be high even at the initial stage, this section treats the marginal cost of coal extraction as an exogenous parameter. By varying this parameter, the analysis examines how differences in extraction conditions affect the long-run coal shares. This approach also allows the implications of rising marginal extraction costs associated with cumulative extraction to be considered by comparing alternative parameter settings.

As expected, a higher marginal cost of coal extraction suppresses the expansion of coal use. However, the magnitude of this effect may differ depending on the per capita fuel demand level. For resident agents with higher per capita fuel demand, the same increase in the marginal cost of coal extraction results in a larger total coal procurement cost, defined as the sum of extraction and transportation costs. Therefore, when the per capita fuel demand is higher, coal dependence may be more vulnerable to an increase in the marginal cost of coal extraction.

Figure 6 shows the effects of differences in the marginal cost of coal extraction on the long-run coal share for each level of per capita fuel demand. For the marginal cost of coal extraction, the figure compares the baseline value of 0.01 MEU with cases of 0.05 MEU (five times the baseline) and 0.1 MEU (ten times the baseline). For the per capita fuel demand, the figure compares the cases of 1 FU, 2 FU, and 3 FU.

First, when the per capita fuel demand is 1 FU (Figure 6(a)), the long-run coal share reaches almost 100 percent regardless of the level of the marginal cost of coal extraction. This result indicates that when per capita fuel demand is relatively low, the self-reinforcing process of coal dependence can be maintained even if the marginal cost of coal extraction rises.

By contrast, as per capita fuel demand increases to 2 FU and then 3 FU, the suppressive effect of rising marginal coal-extraction costs on the coal share becomes more pronounced (Figure 6(b), (c)). For example, when the marginal cost of coal extraction is 0.05 MEU, the long-run coal share reaches almost 100 percent if per capita fuel demand is 2 FU. However, when the per



(a) pcf=1.0 (b) pcf=2.0 (c) pcf=3.0

Figure 6: Effects of the marginal cost of coal extraction (exc) on coal share under different levels of per capita fuel demand (pcf).

capita fuel demand is 3 FU, the long-run coal share falls below 70 percent.

Furthermore, when the marginal cost of coal extraction is 0.1 MEU, this difference becomes even more pronounced. When the per capita fuel demand is 2 FU, the long-run coal share remains at approximately 30 percent, and coal use is still maintained to some extent. By contrast, when the per capita fuel demand is 3 FU, the coal share approaches almost 0 percent. Thus, the higher the per capita fuel demand, the more sensitive the coal share decline in response to an increase in the marginal cost of coal extraction.

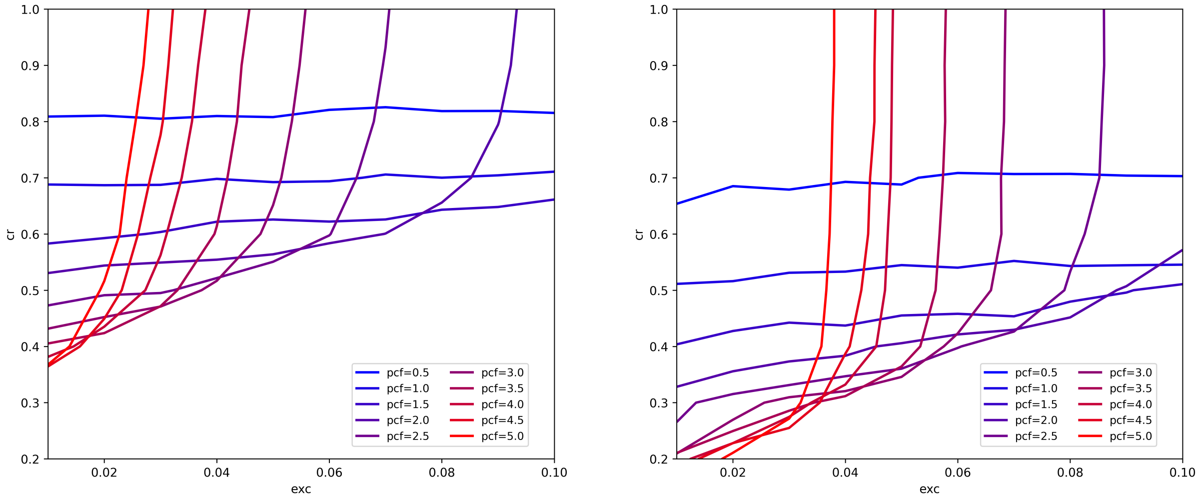
A key point in interpreting this result is that, within the simulation range considered in this section, the long-run coal share is governed more strongly by the absolute level of coal procurement costs than by the magnitude of the marginal cost of coal extraction relative to the marginal cost of fuelwood harvesting. Similar simulations conducted with a lower marginal cost of fuelwood harvesting produced almost the same qualitative results as those shown in Figure 6. In the model, when coal procurement costs, consisting of the cost of coal extraction and transportation costs, exceed the surplus energy of a resident agent, the agent cannot use coal. Therefore, as the marginal cost of coal extraction rises, coal use is first constrained among resident agents located farther from the coal field. The range within which coal can be used is determined by the maximum distance from the coal field. In two-dimensional space, the number of cells within this range changes approximately with the square of the distance. Thus, when an increase in the marginal cost of coal extraction reduces the maximum reachable distance of coal use, the number of cells from which residents can use coal declines nonlinearly. Consequently, the coal share is observed not as a linear decline in response to rising extraction costs but as a nonlinear and abrupt decline.

These results show that an increase in the marginal cost of coal extraction not only suppresses coal dependence but also has effects that differ significantly depending on the level of per capita fuel demand. When per capita fuel demand is low, coal dependence remains relatively robust even if the marginal cost of coal extraction rises. However, when per capita fuel demand is high, coal procurement costs are more likely to exceed the surplus-energy constraint, making coal dependence vulnerable to increases in the marginal cost of coal extraction. This indicates that the conditions for the emergence of coal dependence depend not only on the existence of coal itself but also on the combination of marginal extraction costs, transportation distance, surplus-energy constraints, and per capita fuel demand.

3.5 Summary of sensitivity analyses and robustness

The preceding sections examined the effects of the convertible forest rate, per capita fuel demand, and the marginal cost of coal extraction on the long-run coal share. This section summarizes these results and clarifies the conditions under which coal dependence emerges for various parameter combinations.

Figure 7 summarizes the simulation results presented in the preceding sections. The horizontal axis represents the marginal cost of coal extraction, and the vertical axis represents the convertible forest rate. Each contour line indicates the boundary at which the coal share reaches a given level for each level of per capita fuel demand. Figure 7(a) shows the contour line for a coal share of 50 percent, while Figure 7(b) shows the contour line for a coal share of 10 percent.



(a) Coal share = 0.5

(b) Coal share = 0.1

Figure 7: Contour lines for coal-share thresholds under different values of per capita fuel demand (pcf), the convertible forest rate (cr), and the marginal cost of coal extraction (exc).

As Figure 7(a) shows, for the coal share to reach 50 percent, the convertible forest rate must be sufficiently high, and the marginal cost of coal extraction must be sufficiently low. When the convertible forest rate is low, many forests remain as fuelwood-supply sites, and the procurement conditions of fuelwood do not deteriorate significantly. Consequently, even when the marginal cost of coal extraction is low, the coal share is unlikely to increase substantially. However, when the convertible forest rate is high, the population size and aggregate fuel demand increase through forest conversion to farmland, while the fuelwood-supply base simultaneously contracts, facilitating the expansion of coal use.

However, even when the convertible forest rate is high, a high marginal cost of coal extraction severely constrains the coal share. As the marginal cost of coal extraction increases, coal procurement costs approach the surplus-energy constraint of resident agents, particularly restricting coal use in cells far from the coal field. Consequently, the spatial range within which coal can be used contracts, and the long-run coal share declines. These results indicate that coal dependence is shaped not only by forest constraints but also by coal procurement conditions.

Differences in per capita fuel demand also affect the conditions for the emergence of coal dependence. When per capita fuel demand is high, the demand pressure on fuelwood increases, and the procurement conditions of fuelwood are likely to deteriorate. Therefore, an increase in per capita fuel demand promotes coal use. At the same time, however, the energy burden required to extract and transport coal also increases, making coal use more likely to be limited by the surplus-energy constraint when the marginal cost of coal extraction is high. Thus, per capita fuel demand does not simply promote coal dependence in one direction but acts through both the pressure placed on the fuelwood-supply base and vulnerability to coal procurement costs.

Figure 7(b) shows the conditions under which the coal share reaches 10 percent. Compared with the case of 50 percent, the conditions under which the coal share reaches 10 percent are satisfied over a wider range. This is because, if coal is used only partially, some coal use can arise around the coal field even without the formation of a strong positive feedback mechanism through forest conversion and population growth. For the coal share to reach 50 percent, however, coal use must go beyond local utilization: forest decline, population growth, deteriorating fuelwood procurement conditions, and expanding coal use must reinforce one another. This difference indicates a qualitative distinction between limited coal use and the transition to a coal-dependent economy.

Overall, these results show that coal dependence is not determined by a single condition but by the interaction among the convertible forest rate, per capita fuel demand, the marginal cost of coal extraction, and procurement conditions associated with transportation distance. When the convertible forest rate is sufficiently high and the marginal cost of coal extraction is sufficiently low, coal use can expand in a self-reinforcing manner through a positive feedback mechanism. However, when the convertible forest rate is low or the marginal cost of coal extraction is high, coal use remains local or limited, and the fuelwood-dependent regime tends to persist.

Robustness does not imply that coal dependence always emerges. Rather, it means that the relationship between coal dependence and the combination of the convertible forest rate, per capita fuel demand, and the marginal cost of coal extraction is confirmed under multiple parameter settings. Thus, the results in this section indicate that the coal dependence observed in the baseline simulation is not an accidental outcome dependent only on a specific parameter setting, but a general mechanism that can arise when a certain set of conditions is satisfied. Simultaneously, they also show that when these conditions are not satisfied, a large-scale shift from fuelwood to coal is unlikely to occur even if coal is available.

4 Discussion

4.1 Conditions for the emergence of coal dependence

The simulation results presented in the previous section show that the physical presence of coal does not necessarily lead to coal dependence. Although coal must be available for a shift from fuelwood to coal, its availability is not sufficient on its own. For coal use to spread throughout the economy, the fuel choices of resident agents, forest conversion to farmland, population dynamics, and fuel procurement conditions must become interconnected, forming a cumulative process that increases the relative advantages of coal.

In the model, the initial stage of coal dependence arises when, for some resident agents, the procurement cost of coal becomes lower than that of fuelwood. However, this initial cost advantage alone is insufficient to explain the emergence of the coal economy. What is crucial is that coal use changes land use and population size, and that these changes further alter the conditions of fuel choice. Specifically, as coal use proceeds, some forests previously maintained as fuelwood-supply sites are converted into farmland, making it possible to support a larger population of resident agents.

When the population size increases, the aggregate fuel demand also increases. Simultaneously, as forest conversion to farmland proceeds, the number of forest cells available as fuelwood-supply sites decreases. As a result, resident agents must procure fuelwood from more distant forests, and the transportation cost of fuelwood increases. At this point, if the procurement cost of coal, that is, the sum of extraction and transportation costs, remains within the surplus-energy constraint of resident agents, the relative advantage of coal over fuelwood increases, and coal use expands further.

Therefore, coal dependence in the model is not merely a substitution between fuels. Rather, it is a self-reinforcing process in which fuel choice, land-use conversion, population growth, forest decline, and changes in fuel procurement conditions are all mutually connected. In this process, the expansion of coal use reduces dependence on the fuelwood-supply base, which in turn further promotes coal use. In this sense, coal dependence emerges endogenously as a macro-level outcome from the interaction between the local fuel choices of resident agents and environmental change, rather than from the mere exogenous availability of coal or fixed fuel preferences.

However, this self-reinforcing process does not operate under all conditions. When the convertible forest rate is low, coal use creates only limited scope for forest conversion to farmland, and population growth and the contraction of the fuelwood-supply base are constrained. Under these conditions, fuelwood procurement conditions do not deteriorate substantially, and the relative advantage of coal does not increase sufficiently. If the procurement cost of coal is high, coal use is also restricted by the surplus-energy constraint, and the self-reinforcing expansion of coal use may stop prematurely.

Therefore, the conditions for the emergence of coal dependence cannot be explained by a single factor. Rather, they depend on a combination of coal availability, convertible forest rate, per capita fuel demand, coal procurement conditions, and the surplus-energy constraints of resident agents. Thus, the critical issue is not whether coal exists, but whether conditions arise that allow coal use to expand in a self-reinforcing manner through the interaction of resource use, land use, and population dynamics.

4.2 Why was the coal economy not widespread?

As summarized in the previous section, coal dependence emerges through a chain in which coal use changes land use and population dynamics, and these changes further alter fuel choice conditions. This perspective is important for understanding why coal economies generally failed to emerge in preindustrial societies, even though coal existed and, in some cases, was used to a certain extent.

At first glance, the shift from fuelwood to coal appears to proceed naturally as a result of rising fuel demand and forest resource constraints. As the population grows, fuelwood demand increases, placing pressure on forest resources. This pressure worsens the procurement conditions of fuelwood and is expected to promote the use of coal. However, the model results show that this intuition does not always apply.

First, when the per capita fuel demand is low, coal dependence is unlikely to emerge. In this case, because the fuel demand of society as a whole remains relatively small, a substantial part of the fuel demand can be met by fuelwood supplied from the remaining forests. Consequently, the procurement conditions of fuelwood do not deteriorate substantially, and the relative advantage of coal does not increase sufficiently. Moreover, if the convertible forest rate is low, the scope for coal use to induce forest conversion to farmland, population growth, and contraction of the fuelwood-supply base is limited. As a result, a self-reinforcing cycle that expands coal use is unlikely to form.

In contrast, when the per capita fuel demand is high, the pressure on forest resources tends to increase. Under these conditions, the procurement conditions of fuelwood are likely to deteriorate, strengthening the incentive to use coal as an alternative. However, higher fuel demand increases the energy burden required to extract and transport coal. If the procurement cost of coal is high, resident agents far from the coal field cannot use coal under surplus-energy constraints. In this case, coal dependence is hindered not by insufficient pressure on the fuelwood-supply base but by the severity of coal procurement conditions.

Thus, the relationship between per capita fuel demand and coal dependence is non-monotonic in nature. If fuel demand is too low, the pressure on the fuelwood-supply base does not rise sufficiently, and the self-reinforcing expansion of coal use is unlikely to occur. However, if the fuel demand is too high, the energy burden of procuring coal becomes heavy, and coal dependence becomes vulnerable to increases in coal procurement costs. In this sense, a coal economy is most likely to emerge when per capita fuel demand lies within an intermediate range concerning coal procurement conditions.

This result offers a clue as to why coal economies were exceptional in preindustrial societies. Even when coal existed geologically, for it to become the primary fuel of the economy as a whole, the convertible forest rate, population-supporting capacity, fuel demand, procurement conditions, and surplus-energy constraints all had to fall within a range that allowed coal use to expand in a self-reinforcing manner. If any of these conditions were missing, coal might be used, but it was likely to remain a supplementary fuel to fuelwood rather than become the primary fuel sustaining the economy as a whole.

In this regard, the agricultural usability of forests is not spatially uniform. Zabel et al. (2014) showed that only a limited portion of the world's forests is suitable for agriculture, suggesting the need to distinguish between forests available as fuelwood-supply sites and those convertible into farmland. Specifically, in mountain, tropical, wetland, and cold-region forests, steep slopes, fragile soils, poor drainage, and climatic conditions often make sustainable agriculture unsuitable, even when fuelwood harvesting is possible (FAO, 1978, 1982). For coal use to promote forest conversion to farmland and thereby encourage further coal use through population growth and contraction of the fuelwood-supply base, forests must not only exist but must also be convertible into farmland. Therefore, when forests convertible into farmland are limited, the effect of coal use in shrinking the fuelwood-supply base weakens, and the positive feedback mechanism through which coal use promotes further coal use does not operate effectively.

From this perspective, the expansion of coal use in Britain and Northern Song China can be interpreted not simply as the result of the existence of high-quality coal, but as cases in which fuel demand, land-use conditions, extraction conditions, and transportation conditions fell within a range that made coal dependence possible. Conversely, in many societies where coal existed and was used to some extent but did not develop into a primary fuel, the combination of these conditions was likely insufficient to expand coal use in a self-reinforcing manner.

In this way, the fact that coal economies were not widespread in preindustrial societies can be understood not as a simple failure or stagnation of coal use, but as a reflection of the limited conditions under which coal dependence could emerge. Coal could be used as a supplementary fuel to fuelwood, but for it to transform the fuel composition of society as a whole, both pressures destabilizing the fuelwood-dependent regime and surplus-energy conditions enabling coal procurement had to hold simultaneously.

4.3 Relation to the literature

As argued by Nef (1932), Wrigley (2010, 2016), and others, constraints on forest resources and rising fuel demand are important factors that promote the shift from fuelwood to coal. The results of this study do not reject this view. However, the present analysis shows that forest constraints and rising fuel demand are not merely exogenous conditions driving coal use; they can also change endogenously as a consequence of coal consumption.

From this perspective, this study reinterprets coal dependence not simply as an adaptation to fuelwood scarcity, but as a cumulative process arising from the interaction among land use, population dynamics, forest resources, and fuel procurement conditions. Coal use not only reduces dependence on fuelwood but also increases population-supporting capacity through the conversion of forest to farmland. Consequently, the fuel demand of society as a whole expands, while the fuelwood-supply base contracts. The transition from an organic economy to a mineral-energy economy should therefore be understood not merely as fuel substitution, but as a process involving the reorganization of land use and population size. This is one of the contributions of this study to the existing debates in economic history.

Second, this study complements the work of Stern et al. (2021), who explicitly analyzed the shift from a biomass economy to a coal economy within a growth-theoretic framework. Stern et al. (2021) construct a two-sector growth model with directed technical change for the British Industrial Revolution and examine how the relative scarcity of wood promoted innovation in coal-using technologies. They also show that when wood is initially sufficiently abundant relative to coal and the elasticity of substitution between wood-intensive and coal-intensive goods is sufficiently high, innovation incentives remain directed toward the wood-using sector, potentially generating preindustrial stagnation. In their model, population growth is exogenous, and the decline in per capita wood supply caused by population growth is the main factor governing the direction of technical change through relative scarcity of wood.

By contrast, this study presents a more general model that examines the conditions under which a shift from fuelwood to coal can occur in preindustrial biomass societies, rather than focusing on the specific British case. It does not explicitly model technological progress, nor does it treat population size as an exogenous factor. Instead, under a fixed technological level, it focuses on the conditions under which coal use can expand in a self-reinforcing manner through changes in the spatial distribution of resources, land use, population dynamics, fuelwood-supply base, and fuel procurement costs. In other words, whereas Stern et al. (2021) analyze how relative wood scarcity caused by population growth promotes a transition to coal-using technologies through directed technical change, this study shows that coal dependence can arise in the model even without endogenous technological progress, because coal use itself alters land use and population size, thereby endogenously modifying the fuelwood-supply base and fuel demand. In this sense, this study reinterprets coal dependence not only as an outcome of technological change but also as a process arising from the interaction among resource distribution, land use, population dynamics, fuel procurement costs, and surplus-energy constraints.

Third, this study extends Human Ecology–type ABM research in archaeology and history-related fields by explicitly incorporating fossil fuels. Existing Human Ecology–type ABMs have analyzed interactions between human groups and the natural environment, land-use change, resource constraints, and the coevolution of landscapes (Cegielski and Rogers, 2016; Barton et al., 2011; Altaweel and Watanabe, 2012; Haas and Kuhn, 2019; Sikk and Caruso, 2020; Garg et al., 2021). This study introduces an asymmetry between fuelwood, a renewable and spatially widespread fuel, and coal, a spatially concentrated fuel whose procurement costs depend on the distance from extraction sites. Consequently, it becomes possible to analyze, within a single spatial and evolutionary framework, the conditions under which traditional biomass societies deepen their dependence on mineral energy and the conditions under which they remain within a fuelwood-dependent regime.

As discussed above, the study contributes to the literature by reinterpreting coal dependence not as a phenomenon reducible solely to the historical specificity of individual regions, but as a general process arising from the interaction among resource distribution, land use, population dynamics, extraction and transportation conditions, and surplus-energy constraints. This perspective provides a basis for comparing cases that shifted to a coal economy, such as Britain, and cases in which coal existed but did not become the primary fuel, within the same framework. Simultaneously, the abstraction of many institutional and technological factors required for this generalization is also a limitation of the model. This issue is discussed in the following section.

4.4 Limitations and future research

The model developed in this study is an abstract framework constructed to analyze the shift from fuelwood to coal in preindustrial societies in as simple a form as possible. Therefore, it is not intended to directly reproduce the historical processes of Britain, Northern Song China, or any other specific region. Rather, by temporarily abstracting from institutional and geographical conditions specific to individual cases, the purpose of the model is to clarify how coal use, forest conversion to farmland, population growth, contraction of the fuelwood-supply base, and changes in fuel procurement costs are interconnected. However, this simplification limits the direct application of the model to specific historical societies.

First, the model treats the marginal cost of coal extraction as an exogenous variable. In general, as coal extraction proceeds, mining is expected to move from shallow and easily accessible seams to deeper seams that require greater costs for drainage and transportation, causing the marginal cost of extraction to increase. This study does not directly model such deterioration in extraction conditions, but examines its effects by comparing alternative values of the marginal cost of coal extraction. To analyze whether coal dependence can be sustained in the long run, it is necessary to incorporate mechanisms through which coal-extraction costs change endogenously with cumulative extraction, mining depth, drainage conditions, and deposit characteristics.

Second, the model represents fuel choice through the energy costs required for harvesting, extraction, and transportation, rather than through market prices. This setting is useful for analyzing the basic conditions of fuel transition in preindustrial societies. However, in actual historical processes, fuel prices, wages, landownership systems, common rights, taxation, trade networks, and the formation of urban markets may all be important factors that influence the availability of fuelwood and coal. Therefore, applying the model results to the historical processes of specific regions requires extending the model to incorporate these institutional and market conditions explicitly, in addition to energy costs.

Third, the model does not endogenously consider technological progress or the development of transportation infrastructure. The expansion of coal use depends heavily on transportation conditions, such as roads, rivers, canals, and coastal shipping. Improvements in mining and drainage technologies can also reduce coal procurement costs within the same coal field and make coal use possible over a wider area. This study examines the conditions under which coal dependence can arise in a self-reinforcing manner before technological progress and infrastructure development become fully established. Future research should incorporate changes in transportation infrastructure, mining technology, and drainage technology into the model and analyze the interactions between coal use, technological progress, and land-use change.

Fourth, the spatial structure of the model is represented by a simple, two-dimensional lattice. This setting effectively represents the basic asymmetry that forests are relatively widespread, whereas coal is spatially concentrated. However, in actual geographical space, terrain, rivers, coastlines, roads, urban locations, and the distribution of coal fields strongly shape fuel transportation costs and the formation of market areas. Therefore, applications in specific regions require the use of actual geographical information to spatially arrange coal fields, forests, farmland, cities, and transportation routes.

Fifth, the simulations primarily aim to qualitatively identify the conditions under which coal dependence emerges, rather than estimating the probability or timing of coal dependence in any specific historical society. Therefore, a comparison of the model results with the historical processes of Britain, Northern Song China, Holland, or other regions requires calibration using historical data on fuel demand, forest productivity, the convertible forest rate, coal extraction conditions, and transportation conditions. Through such calibration, the model can serve as an analytical tool for comparing, within a single framework, cases in which a coal economy emerged and cases in which coal existed but did not become the primary fuel.

Despite these limitations, the model clarifies a set of basic mechanisms for understanding coal dependence. Coal dependence can proceed in a self-reinforcing manner when coal use, forest conversion to farmland, population growth, contraction of the fuelwood-supply base, and changes in fuel procurement costs are mutually connected. However, this process can be hindered by factors such as the convertible forest rate, per capita fuel demand, extraction costs, transportation costs, and surplus-energy constraints. Future extensions should gradually incorporate institutional, technological, and geographical conditions specific to historical cases while maintaining the basic mechanism.

5 Conclusion

This study examined the conditions under which a shift from fuelwood to coal emerges in preindustrial biomass societies, using a simple and abstract agent-based model. In the model, resident agents, forests, farmland, and coal fields are located in a two-dimensional space, and the analysis considers the interaction among fuel choices under energy constraints, forest conversion to farmland, population dynamics, changes in the fuelwood-supply base, and fuel procurement costs. The model is not intended to directly reproduce the historical processes of any specific region, such as Britain. Rather, it provides an abstract framework for identifying the general conditions under which coal dependence can emerge from a fuelwood-dependent regime.

The simulation results show that coal use can expand in a self-reinforcing manner under certain conditions. Coal use reduces dependence on fuelwood and allows forests previously maintained as fuelwood-supply sites to be converted into farmland. Consequently, the population size and fuel demand of society as a whole increase, while the fuelwood-supply base contracts. When this process worsens the procurement conditions of fuelwood, the relative advantage of coal increases, further promoting coal use. Thus, even without explicitly assuming technological progress, coal dependence can emerge endogenously from the interaction among fuel choice, land use, population dynamics, and the fuelwood-supply base.

However, coal dependence does not arise automatically because coal is physically present. Whether coal dependence emerges depends on the combination of the convertible forest rate, per capita fuel demand, marginal cost of coal extraction, fuel transportation costs, and surplus-energy constraint of resident agents. When forests convertible into farmland are limited, population growth and the contraction of the fuelwood-supply base are constrained. When the per capita fuel demand is too small, the pressure on the fuelwood-supply base does not increase sufficiently. Conversely, when the per capita fuel demand is too high, the energy burden required to procure coal becomes heavy, and coal dependence becomes vulnerable to increases in procurement costs. In this sense, a coal economy is most likely to emerge when pressures destabilizing the fuelwood-dependent regime and surplus-energy conditions enabling coal procurement are satisfied simultaneously.

This result is important for understanding why coal economies were not widespread in preindustrial societies. Even if coal existed and was used to some extent, for it to become the primary fuel sustaining the economy as a whole, land use, population dynamics, the fuelwood-supply base, extraction and transportation conditions, and surplus-energy constraints had to be linked within a specific range. Therefore, the emergence of a coal economy was not a natural consequence of the existence of coal itself, but a limited historical possibility that arose only when multiple conditions were satisfied simultaneously. This perspective is useful not only for understanding cases that shifted to coal economies, such as Britain, but also for comparing cases in which coal existed but did not become the primary fuel.

The contribution of this study lies in reinterpreting coal dependence not as a phenomenon reducible solely to the historical specificity of individual regions, but as a general process arising from the interaction among fuel choice, land-use conversion, population dynamics, the fuelwood-supply base, fuel procurement costs, and surplus-energy conditions. Simultaneously, the model remains abstract and does not explicitly incorporate market institutions, property-rights arrangements, transportation infrastructure, technological progress, actual geographical space, or calibration using historical data. Future research should maintain the basic mechanism identified in this study while gradually introducing the institutional, technological, and geographical conditions of specific regions, thereby enabling comparison within a single framework of cases in which coal economies emerged and those in which they did not.

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