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REVIEWS

The forest during the Wood Age: The management of this vital ecosystem explains the origin of sustainability

El bosque durante la Edad de la Madera: la gestión de este ecosistema vital explica el origen de la sustentabilidad

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ABSTRACT

Sustainability has been part of the global agenda since the 1980s. Yet, the concept emerged alongside the origins of silviculture in early modern Europe, particularly within the German, French, and English traditions during the 17th and early 18th centuries. During that period, forest management began to be guided by principles of long-term resource use expressed in texts and ordinances. The concurrent emergence of silviculture and sustainability is explained by the essential role that wood played for pre-industrial society. The possible shortage of this material represented a threat to the economy and well-being, and could trigger a profound social crisis. Evelyn, Colbert and von Carlowitz, who broadly shared an interest in future generations, framed the issue of an alleged wood shortage through proposals implemented by the State and the elite, based on scientific, technical, and legal instruments. However, sustainability was not conceived in the modern way based on the dominant approach of the interconnected pillars of environment, society, and economy, nor did it represent a general critique of a particular style of development. The sustained yield silviculture of the 18th century transformed after 300 years into ecological silviculture. This is a key component of the current paradigm of the sustainable forest management, in which disturbance and forest complexity and dynamics constitute central contributions of the ecological theory. The retrospective analysis presented here examines the motivation and socioeconomic context of the historical development of silviculture and sustainability, which contributes to understand the present and future challenges of conserving forest as a vital ecosystem for the biosphere and our own species.

Keywords: Eighteenth century, environmental history, Europe, pre-industrial period, silviculture.

RESUMEN

La sustentabilidad ha sido un concepto de la agenda global desde la década de 1980. Sin embargo, el concepto surgió junto con el origen de la silvicultura en la Europa moderna temprana, en particular en las tradiciones alemana, francesa e inglesa durante los siglos XVII y principios del XVIII. Durante ese periodo, el manejo del bosque se comenzó a guiar a través de principios de aprovechamiento de recursos a largo plazo, que se expresaron en textos y ordenanzas forestales. El surgimiento concurrente de la silvicultura y la sustentabilidad se explica por el papel esencial que la madera desempeñaba en la sociedad preindustrial. La posible escasez de este material representaba una amenaza para la economía y el bienestar, y podía desencadenar una profunda crisis social. Evelyn, Colbert y von Carlowitz, quienes compartían en general un interés por las generaciones futuras, enmarcaron el problema de la presunta escasez de madera a través de propuestas implementadas por el Estado y la élite, basadas en instrumentos científicos, técnicos y legales. Sin embargo, la sustentabilidad no se concebía de la manera moderna que se basa en el enfoque dominante de los pilares interconectados del ambiente, la sociedad y la economía, ni representaba una crítica a un estilo particular de desarrollo. La silvicultura de rendimiento sostenido del siglo XVIII se transformó, luego de 300 años, en la silvicultura ecológica. Este es un componente clave del paradigma actual del manejo forestal sustentable, en el que los disturbios y la complejidad y dinámica del ecosistema forestal constituyen aportes centrales de la teoría ecológica. El análisis retrospectivo presentado aquí examina la motivación y el contexto socioeconómico del desarrollo histórico de la silvicultura y la sustentabilidad, lo que contribuye a comprender los desafíos presentes y futuros de la conservación del bosque como un ecosistema vital para la biosfera y nuestra propia especie.

Palabras clave: siglo XVIII, historia ambiental, Europa, periodo preindustrial, silvicultura.

INTRODUCTION

"So it may be conceived, no wood, no kingdom."
Arthur Standish (Commons Complaint, 1611)

In *Surveyor's dialogue* (1607), the English cartographer John Norden wrote that "A commodity present should not deprive future times of a better" (Warde, 2018). Echoes of this idea reappeared 380 years later in *Our common future*, where the World Commission on Environment and Development defined that "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987) (see note 1, Table S1 in Supplementary material). The modern conception of sustainability represents an environmental, social and economic ideal whose intellectual source is in the silviculture that was invented in Europe during the 18th century. The forest policy of this period represents the origin of current environmental policy (Du Pisani, 2006; Grober, 2007; Radkau, 2012; Warde, 2018; Caradonna, 2022).

The assembled emergence of silviculture and sustainability is not coincidental. The existence of pre-industrial society depended on the continuous supply of forest goods, particularly timber, and its improper use and scarcity was known to be a threat to the economy and well-being, and could trigger profound social crises (Corvol, 1987; Radkau, 2012; Warde, 2018; Auge, 2020; Keyser, 2020). Medieval Europe faced anthropogenic forest destruction and degradation that had already occurred in many ancient societies, mainly due to the increase in population and consumption (Williams, 2006). Excessive demand for natural resources was a widely recognized problem, and therefore management activities and policies were implemented very early, reflecting among other things, the desire to ensure the continuity of forest (Keyser, 2020).

The origin of pre-industrial ideas about conservation can be traced back to the first forest administrations and writers who faced with the possibility of wood deficit on a regional and national scale. They developed solutions on that scale through the invention of silviculture that became the policy of governments in many parts of the world (Keyser, 2020). Historically, societies often differentiated land based on its use, as "cultivated" land, referring to farmland, and "uncultivated" land, encompassing forests and other natural areas. Early conservation efforts were most evident in these "uncultivated" spaces, particularly when they were managed as commons. These commons, shared by multiple users, provided diverse benefits and supported various modes of use (Miglietti & Morgan, 2017; Keyser, 2020).

Historical and contemporary documents reflect the enormous value that the forest has held for society, to which contemporary works based on molecular genetics, remote sensing, and dendrochronology have been added (Rackham, 1990; Kirby & Watkins, 2015). These materials contribute to understanding the history of forest ecosystem management and addressing its future challenges (see note 2, Table S1 in Supplementary material). This text on environmental history provides a brief yet nuanced account, avoiding the oversimplification common in environmental historiography (Keyser, 2020), of the relationship between silviculture and sustainability. It examines the hypothesis that the vital relevance of forest resources in pre-industrial society is key to understanding the development of the concept of sustainability, from its beginnings to the present day. In particular, the paper describes the role of the forest in human evolution and civilization up to the beginning of the Industrial Revolution, analyses early forms of forest management and regulation, and discusses the origin of silviculture and sustainability. These concepts emerged simultaneously in Europe, which played a disproportionately significant role in shaping a global system of resource use and demand that extends to the present day (Richards, 2003).

THE AGE OF WOOD

Wood properties

"We cut up trees to cook our food, for building, to keep out the heat and cold, and also to build ships, which sail in all directions to bring us all the needs of life."
Cicero (On the Nature of the Gods, 45 BC)

The tree, the forest, and wood provided continuity to our evolutionary and geographic development from primate ancestors, and were essential for the existence of culture and civilization (Warde, 2018). In particular, Sombart (1916) coined the term "Wood Age" to highlight the role of this material in pre-industrial society and economy. Although knowledge of the distant past is strongly biased by the dominance in the archaeological record of lithic and bone objects, wooden tools, weapons, constructions, and means of transport, which were rarely preserved, played a fundamental role from pre-agricultural societies until the late 18th century. Throughout this extensive period, wood was the most important and often the only source of matter and energy (Table 1). The Stone Age, which occupies 98% of human history, should be called the Wood Age (Radkau, 2012; Lidz, 2024).

The basic explanation of our dependence on wood lies in its extraordinary properties. It is a lightweight but extremely rigid and strong material that resists stretching and compression, while when green, it is flexible and mouldable into pieces of extremely variable size that can remain unaltered for extended periods if kept dry or moist. Wood is also stronger when dry, an unusual characteristic of other solid biological materials such as bone, horn, and nail, which become brittle when dried. The combustion of wood also releases a large amount of energy that allows

Table 1. Use of wood during the eighteenth century in Europe (Richards, 2003; Williams, 2006; Radkau, 2012; Warde, 2018; Ennos, 2021).

Uso de la madera durante el siglo XVIII en Europa (Richards, 2003; Williams, 2006; Radkau, 2012; Warde, 2018; Ennos, 2021).

MATERIAL SOURCE	
Buildings	Buildings had structure, roofs, floors, cladding, terraces, fences and openings made of wood of different species
Canals	Locks, aqueducts, pipes and tunnels to transport water and for sanitation and drainage of cities, industrial areas, mines and ports had wooden structures
Cooperage	Barrels for making and transporting alcoholic beverages were mainly *Quercus*, *Castanea*, *Abies*, *Ulmus* and *Fraxinus*
Cork	Cork extracted from *Quercus* was used to cap wine and champagne bottles
Crops	Vine and hops were supported by wooden poles
Functional and decorative pieces	Furniture, ornaments, containers, coffins, chests, clocks, toys, paintings and kitchen utensils were made with native woods from *Quercus*, *Juglans*, *Acer* and exotic woods from *Diospyros* and *Swietenia*
Furniture	Furniture was built with wood
Gunpowder	Gunpowder used in hunting, warfare, and mining was made from charcoal and other components
Mills	Water and windmills (water wheel, camshaft, hammer) for pumping water, forging metals, grinding grains, and making paper, oil, textiles, gunpowder, tools, weapons, utensils, and other metal objects were largely constructed of wood
Mines	Mines had a wooden structure, pulleys and winches
Musical instruments	Wood was the main material for wind and string instruments, particularly maple, ebony, rosewood, and boxwood
Packing	Packaging for transporting products was made of wood
Paper	Paper was partly made from wood fibre
Potash	Potassium carbonate used as a fertilizer for manufacture of soap, glass, ceramics and gunpowder and in textile (bleaching, dyeing of fabrics) and metallurgical (reduction of melting point and removal of impurities from minerals) industries was obtained from leachated and evaporated wood coal
Resin	Pine resin was used to waterproof and seal boats, footwear and containers, and to manufacture medicinal products and cosmetics
Rubbers	Natural gums to make inks, watercolours and adhesives were produced from sap and latex mainly of *Acacia*
Sawmills	Sawmills consisted of vertical saws moved mainly by hydraulic wooden machines
Tannin	Tannin to confer water resistance and prevent decomposition of leather came from *Quercus* and *Castanea*
Textile machinery	Machines for spinning, carding, combing, spinning and winding wool and cotton came mainly from wood of *Quercus*, *Fraxinus*, *Ulmus* and Pinaceae
Tools	Shovels, axes, scythes, saws, wedges, mallets, axes, and plows all possessed wooden parts
Transport	Boats, docks, stagecoaches, carts, carriages, bridges, wagons and locomotives, rails, sleepers, wheels and slides for transport of people and goods were built of wood
Weapons	Handle of bladed weapons and firearms was made of wood from *Juglans*, *Acer* and *Prunus*
Wood tar	Tar used to waterproof boats and buildings, protect ropes and sails, and make remedies was produced by distilling wood of Pinaceae and other conifers
POWER SOURCE	
Alcohol	Beer, whiskey, wine, gin, cider, and other spirits were made by heating and drying a mixture of water, grains, fruits, and molasses
Alum	Alum that fixed textile dye was produced from firing of sulphur, potassium, sodium and aluminium salts with wood
Brick and tile	Bricks and tiles were made through firing of moulded clay
Ceramics	Ceramics and porcelain of artistic and utilitarian objects such as plates, glasses and sculptures were made from firing of clays with different compositions of minerals
Dyeing and cleaning	Energy to heat large cauldrons for dye baths and cleaning of fabrics and garments came from firewood or charcoal

Continue

Table 1. Continued

Food	Food was processed and preserved through cooking, smoking, dehydration and encapsulation in lime ash and water using firewood
Glass	Glass in bottles, glasses and windows came from a mixture of sand, alkali and molten and moulded lime that was cooked in glass ovens with wood from *Fagus*, *Alnus*, *Betula* and *Quercus*
Heating	Heating used firewood as primary source of energy; secondary was coal, manure and peat
Leather	Tannery used firewood as fuel
Lime and gypsum	Lime and gypsum for building and agriculture involved calcination of limestone and gypsum stone, which were also used for manufacture of cement
Metal implements	Horseshoes, cutlery, shovels, locks, bolts, scythes, ploughshares, hinges, buckles, nails, and other items were moulded at high temperature
Metals	Iron, tin, lead and copper, gold, silver, zinc and tin came from smelting of ores from combustion of charcoal
Salt	Salt for consumption and preservation of food was produced from artificial evaporation of salt water
Soap	Soap was produced through cooking of a mixture of water, animal fat, vegetable oil, and sodium or potassium hydroxide from wood ash
Sugar	Sugar for consuming and preserving food was made from dissolution, evaporation and drying of firewood
Tar	Tar to protect hull of boats was produced through combustion of wood
Transport	Steam ships and locomotives used wood as fuel

for maintaining adequate air temperature and cooking food and other materials. Considering these advantages, the key role of wood in human history is understandable and inevitable (Ennos, 2021).

Forest, human evolution and civilization

> *"Who can enumerate all of the uses of wood? Wood is the greatest and most necessary thing in the world, of which man has needed and cannot dispense with."*
> *Martin Luther (Table Talk, 1532)*

The human species retains a set of adaptations inherited from primate ancestors who lived in the forest canopy, such as binocular vision, an upright posture, and the differentiation between locomotive hind limbs and feet, and prehensile arms and hands with soft pads and nails. These characteristics, associated with the arboreal habitat, would have been key to the development of our ability to make tools. The increase in brain size and bipedalism also represent an advantage inherited from arboreal primates (Thorpe et al., 2007).

Early hominids were also arboreal. "Lucy," a 3-million-year-old female *Australopithecus afarensis* who lived in the African savanna, was bipedal and upright, although the size and robustness of her arms and the curvature of her phalanges suggest she had a great capacity to move through trees (Wade, 2007). The importance of sleep for the functioning of an increasingly large brain implies that for a relatively defenceless primitive hominid with imperfect terrestrial locomotion, trees would represent habitat and protection (Samson et al., 2017; Ennos, 2021). Humans fully adapted to terrestrial life only with the appearance of *Homo erectus* around 2 million years ago. The abandonment of the arboreal habitat would be explained in part by the expansion of the savanna, following the development of a seasonal tropical climate. From this, hominids would have made use of two properties of dry wood: its greater rigidity, which allows for the manufacture of tools to dig and obtain underground food, and its flammability, to produce fire that protects against predators and allows for cooking food. Paradoxically, the human species would have ceased to be arboreal through its relationship with wood (Ennos, 2021).

Lightning rarely causes direct fires in trees; fire usually starts when grass and surrounding dry material ignite (Pyne, 2021). Incomplete combustion transforms wood into charcoal, a process that early hominids and hunter-gatherer societies would have copied to consume a wider spectrum of cooked foods. Cooking is a technology that externalizes part of the digestive process, drastically reduces the time and chemical and mechanical energy needed for digestion, and eliminates toxic products. This process would have acted as a selection force for the incessant increase in brain size and decrease in the digestive system throughout evolution. Maintaining an energetically costly organ like the brain would have been possible due to the increased quality of the diet associated with cooking (Wrangham, 2009).

Since the last Ice Age, humans have directly (logging) and indirectly (grazing, fire) shaped the distribution, composition, and structure of Europe's forests, so that the existence of virgin forests is currently unlikely (Williams, 2006; Kirby & Watkins, 2015; Peterken, 2015). The oldest known wooden artifact is a manually polished fragment over 780,000 years old from Gesher Benot Ya'aqov (Is-

rael) (Barham et al., 2023). The oldest wooden artifact for structural purposes is from Kalambo (Zambia), represented by two logs joined transversely by a notch, dated to 476,000 years ago (Barham et al., 2023) (Figure 1). At the Schöningen archaeological site (Germany), 187 wooden artifacts were found, probably used for hunting and other domestic activities 300,000 years ago (Leder et al., 2024).

The remains of the oldest wooden dwelling come from Star Carr (England), dated to 11,000 years ago (Milner et al., 2013). The oldest log boat was found in Pesse (Netherlands) and was built with *Pinus sylvestris* (Scots pine) 10,000 years ago (Ennos, 2021). In a waterlogged terrain in Glastonbury (England), wooden causeways of *Alnus glutinosa* (alder), *Fraxinus excelsior* (European ash), *Corylus avellana* (hazel), *Ulmus* (elm), *Ilex aquifolium* (holly), *Tilia cordata* (lime), *Salix alba* (willow), *Populus* (poplar), and *Quercus robur* (oak) were discovered, dating back 5,800 years. The tools and weapons carried by Ötzi the Iceman, a 5,300-year-old mummy found in Ötztal (Austria), were made from wood of *Tilia* (lime), *Corylus* (hazel), *Larix decidua* (European larch), *Betula pendula* (silver birch), *Taxus baccata* (European yew), *Fraxinus excelsior* (European ash), *Acer pseudoplatanus* (sycamore maple), *Abies alba* (silver fir), *Pinus sylvestris* (Scot pine), *Alnus* (alder), *Ulmus* (elm), and *Salix* (willow). And the wooden quiver contained a copper-bladed axe, evidencing the use of charcoal to melt and mould this metal (Perlin, 2023).

Rise and end of the Wood Age

"Our oaks are the truest oracles of the perpetuity of our happiness."
John Evelyn (Sylva, 1664)

Wood enabled the development of the ancient civilizations of Sumer, Assyria, Egypt, China, Knossos, Mycenae, and classical Greece and Rome, and the Americas. The shifts in the centre of power in the Mediterranean and Europe, from ancient Babylon and Egypt, through Macedonia and Rome, to Spain, France, the Netherlands, and the United Kingdom, followed the availability of forest resources (Williams, 2006; Radkau, 2012; Ennos, 2021; Perlin, 2023). The 18th century, and particularly England, which had reached a comparatively high level of development for the time, represent the apogee of the Wood Age (Richards, 2003; Williams, 2006; Warde, 2018; Ennos, 2021).

The supply of wood was related to the destiny of the states themselves due to its strategic role, mainly associated with metal smelting, shipbuilding, and salt production (Radkau, 2012). However, firewood was overwhelmingly the most important product, representing up to 90% of all wood consumed. Through wood, governments and societies perceived the dependence on natural resources and the possibility that mismanagement could put them at risk (Williams, 2006; Radkau, 2012) (Table 1, Figure 2). From the 19th century onwards, matter and energy from wood became increasingly less important, due to its replacement by iron and cement as industrial materials, and by mineral coal and oil as fuel. However, the end of the Wood Age does not coincide with the beginning of the Industrial Revolution, which was first conducted based on wood resources and animal and hydraulic energy, with mineral coal being a complement to the traditional energy source. The Industrial Revolution was preceded by a large expansion of world trade that created markets and capital, and the wood trade was one of its driving forces (Grewe, 2011; Radkau, 2012).

Early industrialization was the culmination of wood technology, as evidenced by the fact that the first spinning machines were made of wood and their inventors, Patrick

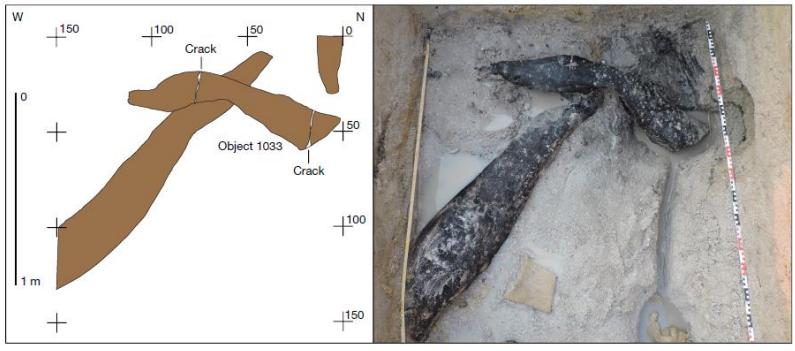

Figure 1. Diagram (left) and excavation view (right) of the structure formed by two overlapping logs of *Combretum zeyheri* through a notch from Kalambo (Zambia) dating back 476,000 years (numbers indicate distance in cm). Reproduced with permission from Barham et al. (2023).

Diagrama (izq.) y vista de excavación (der.) de la estructura formada por dos troncos superpuestos de *Combretum zeyheri* a través de una muesca hallada en Kalambo (Zambia) que data de hace 476.000 años (números indican distancia en cm). Reproducido con permiso de Barham et al. (2023).

Wyatt and James Hargreaves, were carpenters (Radkau, 2012). However, gradually, iron and mineral coal replaced wood, playing an increasingly key role in shaping society, culture, and economy, and forming the basis of state power. Finally, the dominance of mineral coal marked the transition toward an "inorganic" economy, and society ceased to bear the "wood footprint" of the pre-industrial period (Radkau, 2012; Warde, 2018; Ennos, 2021).

THE ORIGIN OF SILVICULTURE AND SUSTAINABILITY

Medieval regulations

> *"The owners of waterways and forests will make enquiries about and visit all forests and woods and will conduct sales that will allow the aforementioned forests to perpetually sustain themselves in good condition."*
> *Philippe VI (Ordinance of Brunoy, 1346)*

The forest of the European medieval period allows early forms of natural resource management to be identified. In this ecosystem with varying size and structure, from large, continuous, and closed forests to small mosaics with scattered trees and grasslands, there were users with contrasting interests and authority who basically carried out a multiple use of the forest with varying intensity. At a time when the forest was indispensable for daily sustenance and the destiny of the State, it was known that trees needed extensive periods of growth to produce limited resources that had to be protected. Consequently, forms of sustainability already existed without this idea having been conceptualized. Forest management was based on traditional practices carried out from a local perspective in which the continuous need for firewood, timber, non-timber products (honey, fruits) and livestock feed (grasses, leaves, seeds) of small villages and towns was key to conservation, rather than the need of the nobility, industry or the state (Thomas, 1983; Rackham, 1990; Grewe, 2011; Radkau, 2012; Corvol, 2017; Auge, 2020).

The first forest ordinances promoted customary norms as criteria for good practices. These norms established by the Church, the nobility and the community established regulations of varied nature and scope such as: a) the demarcation of the forest boundary, b) the realization of forest inventories, c) the payment of rights of use, d) the prohibition of wood and firewood cutting and livestock grazing at certain times and places, e) the production of charcoal only with lower quality wood, f) the punishment to those damaging timber and fruit trees, g) the obligation to planting more trees than those cut down, h) the protection of individual trees, i) the expansion of the timber and firewood supply commercial network, j) the extension of the State's jurisdiction over the forested properties, k) the sale of products in a central market with the fixing of maximum prices, l) the prohibition of the use of the plough in the vicinity of the forest, and m) the prohibition of activities that interfered with the hunting interests of the nobility (Grewe, 2011; Schmithüsen, 2013; Hartel et al., 2015; Warde, 2018; Auge, 2020).

In England, the *Edict of the forest* (Henry II, 1184) and the *Forest charter* (Henry III, 1217) provide insight into the early management of medieval forests by the king, who needed a supply of forest products and hunting grounds. Forest conservation was proposed to be achieved through fencing, prohibition of clearing and grazing, and payment of rights of use (Keyser, 2020). In the 16th century, compliance with some of these regulations was conducted by the forest ranger (*verderer*) who recorded the harvest and reported illegal actions to the courts (Morrison, 2020). Although forest plantation was not widely practiced, it became massive since the 19th century, it was known during the Middle Ages. In Germany there are records of pine, fir and birch plantations from 1368 to obtain wood, charcoal and potash (Radkau, 2012).

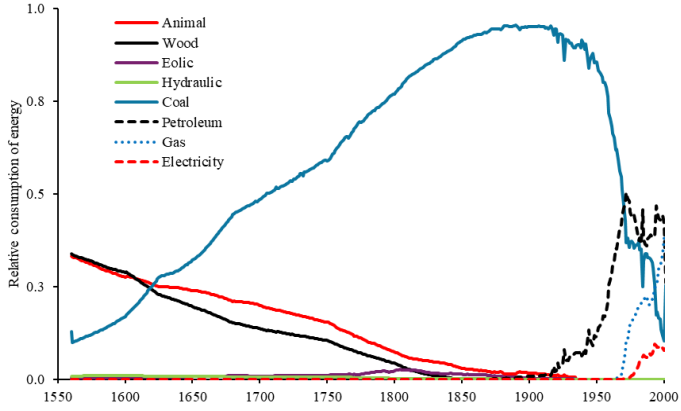

Figure 2. Consumption of different energy sources in England and Wales during 1562-2001 (source: Warde, 2007).

Consumo de diferentes fuentes de energía en Inglaterra y Gales durante 1562-2001 (fuente: Warde, 2007).

The Republic of Venice in the 15th century formed, through the forestry magistrates (*Provveditori sopra boschi*), one of the first systems in Europe dedicated to forest management to ensure the continuity of naval power that depended on constant access to high-quality wood (Williams, 2006; Warde, 2018). The *Brunoy's ordinance* (Philip VI, 1346) was the first French law to deal with the management of waterways and forests (Schmithüsen, 2013). The *Ordonnance sur le fait des eaux et forêts* (Jean-Baptiste Colbert, 1669) sought to make silviculture an economic branch that would secure the supply of timber from the royal forests for the Navy, but it was soon applied to all ecclesiastical, communal, and private forest lands in Europe. It stipulated that furnaces, boilers, and charcoal making were to be restricted, that certain trades (coopers, tanners, carpenters) were to be located at a certain distance from the forest, that cattle grazing (except for pigs) was prohibited, and that large trees and seed trees were to be marked and reserved (Williams, 2006; Cardonna, 2022).

This first generation of forest regulations in Europe tended to exert greater control by rulers over the state, communal, and individual forest through more professional management. They tended to restrict the right of usufruct and to transform collective ownership of the forest into individual and state property. The laws also determined the responsibility of the landowner to serve certain public interest purposes, such as the protection of watersheds, the maintenance of permanent forest cover, and the prioritization of timber over multiple agricultural and forestry use (Schmithüsen, 2013; Rackham, 1990; Grewe, 2011; Radkau, 2012; Corvol, 2017; Auge, 2020). This management sought the continuity of the forest resource through utilitarian social and economic rules (Auge, 2020; Trapaga-Monchet et al., 2023). However, the conservation impact varied considerably and in general, did not stop the degradation and destruction of the forest in different regions (Thomas, 1983; Rackham, 1990; Grewe, 2011; Radkau, 2012; Corvol, 2017; Auge 2020) (see note 3, Table S1 in Supplementary material).

Methods of forest use

"Nature is only to be commanded in obeying her."
Francis Bacon (Novum Organum, 1620)

One of the oldest ways to obtain wood was the "coppice method" (the precursor of the "low forest even-aged system"), that extends from the Stone Age to the present. This practice allows obtaining firewood, rods, and charcoal consisted of cutting sprouts from the base of the trunk (coppicing) or at a higher height (pollarding) after a short rotation of resprouting deciduous broadleaf trees (e.g., *Salix*, *Corylus*, *Castanea*, *Quercus*, *Fagus*, *Fraxinus*) (Buckley & Mills, 2015; Kirby & Watkins, 2015; Savill, 2015). The "coppice with standards method" (the precursor of the "low forest uneven-aged system") was also early developed, in which some individuals of the stand were preserved to reach log size after a longer rotation (Watkins, 2015; Warde, 2018; Auge, 2020; Vollmuth, 2022) (Figure 3).

These methods could be integrated into a mixed scheme for the simultaneous obtaining of forage. The "wood-pasture method" (the precursor of the "silvopastoral system") for also livestock grazing is a mixed system whose use extends from the Neolithic to the present. Farmers often preferred more open forests that favoured grazing and *pannage*, which involved feeding pigs with fallen *Quercus* and *Fagus* nuts, combined with coppicing and pollarding. This practice continued until the 20th century in many regions dominated by temperate broadleaf forests (Hartel et al., 2015; Kirby & Watkins, 2015; Savill, 2015). In 1219 in France, annual wood production was already used through the division of the forest into a number of sectors of annual firewood and timber harvesting ("coupes") determined by the rotation age (the precursor of the ancient "flachenfachwerk" and "massenfachwerk" systems, see below, and the current "high forest even-aged system") (Keyser, 2020).

Figure 3. Coppice with standards of an 18th century forest of *Fagus sylvatica* (European beech) in Germany (von Burgsdorf, 1783) (left) and of a current forest of *Quercus robur* (English oak) in Italy (right) (photograph courtesy of R. Sbrancia).

Bosque bajo con estándares de un hayedo (*Fagus sylvatica*, haya europea) del siglo XVIII en Alemania (von Burgsdorf, 1783) (izq.) y de un robledal (*Quercus robur*, roble albar) actual en Italia (der.) (fotografía cortesía de R. Sbrancia).

Wood shortage

"It is deeply saddening to see so many dead trees, whose existence nature has been contributing to for centuries. One can already sense how detestable we will be to the next generation if active remedies are not taken to ensure that the owners themselves do not abuse their rights, thinking only of profiting from the present product."
Manuel Belgrano (Economic Writings, 1810)

In Europe during the 18th century, the demand for forest products for industry, agriculture, transportation, and daily life was immense, particularly for large logs for the construction of hulls and masts of ships, and firewood around large urban and industrial centres. The causes of this demand were associated with domestic and strategic activities of the State, clearing for cultivation and grazing, and hunting, land tenure (e.g., the landowner kept the mature log wood, so there was no incentive for the tenant to conserve it) (Thomas, 1983; Richards, 2003; Grewe, 2011; Kirby & Watkins, 2015; Cardonna, 2022) (Figure 4) (see note 4, Table S1 in Supplementary material). Occasionally, crown property was deforested and the wood sold to alleviate royal finances (Corvol, 1987; Warde, 2018). This situation partly reflected the structural characteristic of the pre-industrial organic economy of reduced efficiency, in which matter and energy were obtained from the soil surface through photosynthesis of competing products (grains, firewood, meat). This scenario also developed in the colder and drier climatic conditions of the Little Ice Age which led to an increase in firewood consumption and altered the distribution, composition, and structure of the forest (Williams, 2006).

In this socio-economic context, the discourse of wood scarcity appeared and spread with extraordinary rapidity all over Europe, leading to the development of a set of forest policies. Evidence of this scarcity was the increase in the price of firewood (e.g., from a baseline of 100 during 1451-1500 to 780 during 1633-1642) and the import of wood, tar, pitch, and potash from Scandinavian and Baltic countries. The transport of large conifer logs, mainly *Abies*, *Pinus* and *Picea*, reflected the strategic role of wood, especially considering that despite the price per unit of volume or weight being very low, the load over long distances was justified (Thomas, 1983; Richards, 2003; Grewe, 2011; Kirby & Watkins, 2015).

The intervention of rulers and forest authorities, justified by the need to protect the forest against scarcity, also sought to achieve greater control over this resource. Scarcity was in many cases local, associated with specific products and places (Corvol, 1987; Rackham, 1990; Radkau, 2012; Trapaga-Monchet et al., 2023). In England, faced with the possibility that wood scarcity, especially of large *Quercus*, would threaten plans to equip the fleet of merchant and war ships, naval authorities commissioned the Royal Society to develop a proposal to solve the timber problem. As a result, John Evelyn (1662) published *Sylva, or a discourse of forest trees and the propagation of timber in His Majesty's dominions* (Figure 5). *Sylva* describes the characteristics and instructions for planting, pruning, and cutting numerous tree species and represented a stimulus for planting by landowners (Radkau, 2012; Warde, 2018; Cardonna, 2022).

Silviculture and sustainability

"The greatest art, science, diligence and institution of these countries will depend on the way in which the conservation and cultivation of wood is undertaken so that it has a continuous, stable and sustained use, since this is an indispensable cause, without which the country in its essence cannot remain."
Carl von Carlowitz (Sylvicultura oeconomica, 1713)

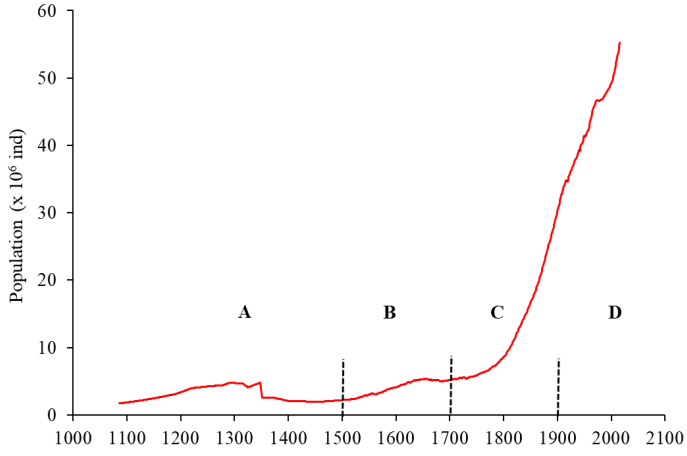

Figure 4. Population growth of the United Kingdom during 1086-2016. Growth in period B and D is linear, in C is exponential (source: OWD, 2025).

Crecimiento de la población del Reino Unido durante 1086-2016. El crecimiento en el periodo B y D es lineal, en el C es exponencial (fuente: OWD, 2025).

The book *Sylvicultura oeconomica, or domestic economy message and natural instructions for the cultivation of wild trees* by Carl von Carlowitz (1713) represents the origin of silviculture and the dominant paradigm of forest sciences in Europe and America until the late 19th century (Figure 5). In this text inspired by *Sylva* and the *Water and forest ordinance*, the terms "sustainability" (*nachhaltigkeit*) and "sustainable" (*nachhaltend*, *nachhaltig*) are printed for the first time in German, linked to the continuous and maximum extraction of wood as the central objective of forestry activity. It analyses the natural and human causes of wood scarcity (fires, population growth, and consumption), and the technical aspects for its sustained production (seed collection, planting, resprouting, silvicultural methods) (Grober, 2007; Hölzl, 2010; Grewe, 2011; Radkau, 2012; Warde, 2018).

However, for von Carlowitz and his contemporaries, sustainability did not represent a general critique of a mode of development, but a technical recalibration of government policy by a social elite with influence and training. The founders of silviculture did not articulate ideas about sustainability in relation to the environment as a whole in the current way. The destruction and degradation of the environment was not incorporated into this discourse, which stated that any problem associated with the forest was technical, and could be solved through knowledge and professional scientific experimentation. In particular, von Carlowitz considered wood to be "the inexhaustible treasure of our earth" (Grober, 2007; Warde, 2018).

In the perspective of this silviculture, the balance between wood production and consumption, mainly from mining and metallurgy, was resolved through a regime based on technical and scientific information, and trained personnel. Thus, through mathematics, stereometry, surveying, cartography, soil science, and biology, silviculture became a science (Warde, 2018). This sustained-yield silviculture was linked to a broader discourse about responsibility to posterity and descendants associated with wood. *Sylvicultura oeconomica* established not only new scientific terms but also the initial ideas of the modern concept of sustainability based on a social ethic. Through silviculture, nature as a means to wealth also contributed to the process of forming the modern state of Europe, which became the leader in planned forest management (Grober, 2007; Hölzl, 2010; Grewe, 2011; Radkau, 2012; Savill, 2015; Warde, 2018).

Traditional natural resource management systems were replaced by new forms of production, and there was a tendency to separate agricultural, livestock, and forest use with institutions that separately dealt with these activities (Hartel et al., 2015). Institutions and authorities applied forest management based on long-term technical and legal tools and large geographical areas (Trapaga-Monchet et al., 2023). This management tended to move away from domestic and rural energy and agricultural purposes, in favour of wood production for strategic purposes (e.g., mining, transportation, trade, warfare). The forest tended to transform into a monoculture of even-aged, mainly coniferous trees, managed in an economically efficient manner through the "high forest system" and "clearcutting", which replaced the pre-industrial coppice as a habitat for multiple species and uses (Radkau, 2012; Kirby & Watkins, 2015; Trapaga-Monchet et al., 2023).

Figure 5. Covers of *Sylva* (Evelyn, 1664) (left) and *Sylvicultura oeconomica* (von Carlowitz, 1713) (right).

Portadas de *Sylva* (Evelyn, 1664) (izq.) y *Sylvicultura oeconomica* (von Carlowitz, 1713) (der.).

The forest was exploited through the division into equal sectors that were planted and harvested annually, for which the rotation time determined the number of annual cutting areas and the endless cycle of wood production ("flachenfachwerk") (Figure 6). Cutting methods by annual volume allocation ("massenfachwerk") and continuous tree cover (e.g., shelterwood, single-tree and group selection systems) were introduced later (Schmithüsen, 2013; Kirby & Watkins, 2015). Livestock was considered incompatible with silviculture due to trampling and browsing of seedlings. Habitats associated with old and dead trees standing and biomass on the forest floor were scarce. Wood traders were at the forefront of an increasingly mercantilist orientation in an integrated global market associated with the extension of the land and river transport network.

In 1730, J. G. von Langen initiated the first documented forest project, in 1757 W. G. Moser published *Principles of forest economy*, in 1761 the first forest planning of a German state began planned to extent until 2050, in 1763 J. F. Stahl founded the *Forest Journal*, in 1769 J. G. Beckmann coined the term "Forest science", and in 1787 G. A. Däzel established the first forestry school (Hölzl, 2010). The most influential forester of this new generation was G. L. Hartig, who is considered responsible during the 19th century for the large-scale conversion of the medieval coppice to high forests. Later, H. Cotta, one of the most prestigious classical foresters, questioned the alleged lower productivity of the "coppice with standards system" and promoted it (Vollmuth, 2022).

The simplification of forest composition and structure had profound negative social and ecological effects that were perceived from the mid-19th century (see note 5 Table S1 in Supplementary material). Intense conflicts arose with local communities because access and traditional use of the forest were limited, and its vulnerability to pests, diseases, wind, and drought increased (Radkau, 2012; Schmithüsen, 2013). Consequently, this silviculture began to be redefined. K. Gayer (1882) and other authors early on criticized the power of the timber market and the abandonment of other forest management objectives. They proposed increasing tree diversity with the inclusion of broadleaf trees, using other management methods, and offered a new definition of sustainability that focused on the conservation of the productive capacity of the forest ecosystem, a factor that until then had been considered constant. Forest science began to conceptualize the forest and trees as a system that considered the interaction between climate, biota, relief, soil and water (Radkau, 2012; Trapaga-Monchet et al., 2023).

The "sustained-yield silviculture" transformed towards the end of the 20th century into the current "ecological silviculture". This approach integrates ecological principles into forest management, prioritizing biodiversity, resilience, and ecosystem function alongside timber production. Unlike sustained-yield silviculture, it treats forests as complex socio-ecological systems, incorporating local knowledge and participatory management. In the current socio-environmental crisis, this approach offers a more holistic and adaptive framework, ensuring forests continue to provide essential ecological, social, and economic benefits (Puettmann et al., 2009; Franklin et al., 2018; Keyser, 2020; Palik et al., 2020).

THE CURRENT USE OF WOOD

"A sustainable economy is as reasonable, just, and wise, as it is certain that man ought not to live for himself alone, but likewise for others and for posterity".
Wilhelm Gottfried Moser (Principles of Forest Economics, 1757)

Industrialization introduced new materials (steel, concrete, plastic) and new sources of energy (hydraulic, fossil),

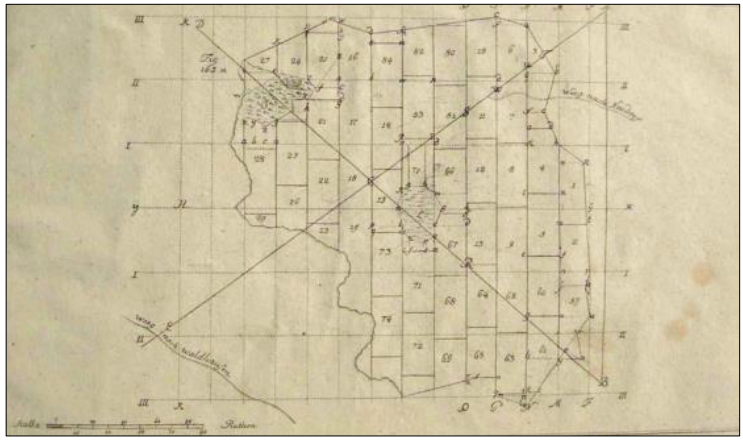

Figure 6. Imaginary forest divided into 84 annual cutting sections based on the method "flachenfachwerk" (Grünberger, 1788).
Bosque imaginario dividido en 84 secciones de tala anuales según el método "flachenfachwerk" (Grünberger, 1788).

whose properties were superior to those of wood (Ennos, 2021). From the mid-1880s, the consumption of coal, which accounted for 95% of all energy consumption in Great Britain, began to slow down, marking the shift toward oil and electricity (Warde, 2007; Richards, 2003). From then on, economies tended to decouple from the supply of matter and energy derived from biomass, a transition that represented a sharp discontinuity in the availability and use of this resource (Sieferle, 2001; Krausmann et al., 2009). The transition to industrialization was as profound as that from nomadic pastoral societies to sedentary agricultural ones (Wrigley, 2010). Since the mid-18th century, coal had been used on a massive scale in the British Isles, more so than in any other early modern society. This shift reflected, on the one hand, the growing urban scarcity of wood and, on the other, the abundance of coal outcrops accessible through river transport (Richards, 2003).

From that moment onward, the economy ceased to depend on the photosynthetic constraint imposed by the ability of plants to convert solar radiation into biologically useful chemical energy, and began to exploit the energy stored over geological timescales in the form of coal and oil (Wrigley, 2010) (Figure 2). Nevertheless, these new sources of energy have allowed wood to remain highly useful (Table 2). Evidence of this phenomenon can be seen in the rise in wood production and consumption: between 1850 and 1938, Great Britain significantly increased both wood consumption and imports, driven by population growth, urbanization, rising consumption, and substitution by other materials (Warde, 2007; Iriarte-Goñi & Ayuda, 2012). Global annual roundwood production has increased steadily since the 20th century, from about 2.2×10^9 m³ in 1970 to around 4.0×10^9 m³ today (Mantau et al., 2017; FAO, 2020). Wood from the world's forests is used for energy and industrial material in approximately equal parts (Mantau et al., 2017; Hetemäki et al., 2020).

The global use of forest biomass is increasingly diversifying as the industry undergoes major structural changes. While there is growing demand for traditional wood products, the most significant market growth includes innovative products in the construction, textile, chemical, bioplastic, and biofuel sectors, and to a lesser extent in cosmetics, food, and pharmaceuticals. By contrast, the demand for some high-volume products such as paper is declining. The diversification of forest biomass use is linked to the energy crisis, climate change, and the search for renewable and sustainable energy sources based on the circular economy (Mantau et al., 2017; Hetemäki et al., 2020).

Table 2. Current use of wood (Fengel & Wegener, 1989; McDonough & Braungart, 2002; Ek et al., 2009; Minke, 2009; Sawyer, 2010; Seifert, 2014).

Uso actual de la madera (Fengel & Wegener, 1989; McDonough & Braungart, 2002; Ek et al., 2009; Minke, 2009; Sawyer, 2010; Seifert, 2014).

MATERIAL SOURCE	
Buildings	Structure, cladding, flooring, roofing, balconies, fences, and staircases of some houses are built with solid or engineered wood (MDF, OSB, CLT, WPC)
Cooperage	Barrels for aging alcoholic beverages are mainly made from *Quercus* and *Castanea*
Cork	Cork extracted from *Quercus* is used for bottle stoppers, thermal and acoustic building insulation, fashion, and decoration
Functional and decorative pieces	Some ornaments, containers, and kitchen utensils are made from hardwoods and conifers
Furniture	Furniture is manufactured from solid or engineered hardwoods and softwoods
Musical instruments	Wood is mainly used in string and wind instruments
Packaging	The packaging of certain products is made of wood
Paper and cardboard	Paper and cardboard are produced from wood fiber
Resin	Resin from *Pinus* is used in the production of cosmetics, soap, candles, adhesives, paper, wood preservatives, and decorative products
Tannin	Tannins for leather tanning are obtained from *Quercus* and *Castanea*
Tools	Shovels, axes, scythes, and hammers have wooden handles
Weapons	Handles of some sporting weapons are made from *Quercus*, *Juglans*, *Acer*, and *Diospyros*
POWER SOURCE	
Cooking	Cooking of some foods is carried out using firewood or biomass plants
Heating	Heating of some buildings is produced with firewood or biomass plants
Industry	Food and agricultural industries use energy from biomass plants
Transport	Vehicles may use biofuels

FINAL REMARKS

"Although earthworms appear to be a small and insignificant link in the chain of nature, if they were to disappear they would create a lamentable abyss. They promote vegetation, which could barely survive without them."
Gilbert White (Letters, 1770)

Sustainability is a concept on the current global agenda since *Our common future* (1987) and the Conference on Environment and Development held in Rio de Janeiro (1992). The location of this meeting reflected concerns about tropical forests and highlight the role of woodlands in both the original and modern ideas of sustainability. This concept emerged explicitly and became intertwined with silviculture during the Enlightenment, coined in *Sylvicultura oeconomica* by Carl von Carlowitz under the influence of Jean-Baptiste Colbert and John Evelyn.

These authors feared that wood scarcity could affect the naval and mining industries and, in a broader sense, shared an interest in the well-being of future generations. They handle the alleged scarcity through scientific, economic, and legal proposals implemented by the State and mainly based on conifer planting and clearcutting. Nevertheless, the motivations behind such instruments may also have pursued other purposes, including securing fiscal revenues, ensuring naval power, consolidating state control over rural populations, and demonstrating political authority through the rational ordering of nature.

Carl von Carlowitz was part of a network of resource managers rooted in the culture of the Middle Ages, during which regulations promoted a forest use based on conservation guidelines derived from customary ideas and practices. The need for forest resources from villages and small urban centres was key to these measures, which aimed to safeguard the resources and rights of those who used the ecosystem, and were subsequently adopted by the state administrations. However, silviculture and sustainability were not conceived in the modern way based on the dominant approach of the three interconnected pillars of environment, society, and economy, nor did they represent a general critique of a particular style of development.

After 300 years, sustained-yield silviculture transformed into ecological silviculture that is now a key component of the current paradigm of sustainable forest management (see note 6, Table S1 in Supplementary material). Although modern silviculture retains some foundational principles, today forests are conceived as socio-ecological systems where management is primarily focused on multiple use, ecological integrity and resilience, adaptive management, and equity through participatory decision-making. Silviculture and ecology originated independently but contemporaneously during the Enlightenment, and since then, foster a constructive cooperation in the context of woodland conservation.

Key future challenges include integrating silviculture with climate change adaptation, conserving biodiversity under mounting human pressure, enhancing ecosystem services without reducing productivity, and linking ecological theory with forest management to build resilient socio-ecological systems. More broadly, the sector must meet rising global demand while ensuring sustainability, cutting emissions, and adapting to the energy transition and circular economy. The retrospective analysis presented in this review highlights the historical causes and socioeconomic context of core scientific ideas, offering insights to better address these challenges in preserving an ecosystem essential to the biosphere and humanity.

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SUPPLEMENTARY MATERIAL

Table S1: Description of notes introduced in the main text.

NOTE	DESCRIPTION
1	*The limits to growth: a report for the Club of Rome's project on the predicament of mankind* (Meadows et al., 1972) was also particularly important for the introduction of "sustainable" into today's global political language.
2	For pedagogical purposes, a free access copy in Spanish of this text is available at the institutional repository https://rdi.uncoma.edu.ar/handle/uncomaid/19111
3	The pre-Neolithic European forest extent was 60-70% of the continent compared to the current 30-40%. In France, between 800 and 1300 the area decreased from 30 to 13 million hectares, and in England between 1700 and 1850, 25 million hectares were deforested (Rackham, 2003; Williams, 2006; Peterken, 2015).
4	The historical extent of Europe's forest cover is negatively correlated with human population size (Williams, 2006; Buckley & Mills, 2015; Kirby & Watkins, 2015).
5	The terms *Ordenación Forestal* (in Spanish; the equivalent of Forest Management) and *normal* (referred to a particular frequency distribution of size and age of a tree population) reflect current elements of the sustained-yield silviculture paradigm.
6	The most influential and interdisciplinary articulated perspectives on sustainable forest management are represented by the "Adaptive management" (Walters, 1986), the "Resilience thinking" (Walker & Salt, 2006), the "Ecosystem approach" (CBD, 2013) and the "Close-to-Nature silviculture" (O'Hara, 2016).