Green Building & Construction Economics
https://ojs.wiserpub.com/index.php/GBCE/

Research Article

Bamboo Bridges: A Nature-based Solution

Kang Rong[1], Anders Ekeland[1,2*], Changzhuan Shao[3], Yan Zhang[1], Shuyi Shangguan[4]

[1]Northwest University, Xi'an, China
[2]Statistics Norway, Oslo, Norway
[3]School of Architecture, The Chinese University of Hong Kong, Hong Kong, China
[4]China National Heavy Machinery Research Institute Co. Ltd., Xi'an, China
E-mail: anders.ekeland@ssb.no

Received: 29 December 2021; **Revised:** 1 March 2022; **Accepted:** 14 April 2022

Abstract: Given the urgency of reducing greenhouse gas emissions, developing countries are unable to develop their infrastructure, including small houses and bridges, using the same carbon dioxide (CO_2) emission "heavy" technologies as the "West" has used. Using the case of two bamboo bridge projects in China, we argue that a nature-based solution (NBS), like bamboo and wood, means considerably fewer CO_2 emissions compared to a similar bridge made of concrete and/or steel, and therefore should become the norm for small bridges worldwide. Another important aspect of a bamboo bridge is how this technology, an NBS based on local materials and knowledge, situates itself in the local community compared to a concrete or steel bridge. Creating local, or at least non-urban employment by using bamboo and using local knowledge about bamboo construction in combination with help from public scientific institutions means less dependence on high-tech capital equipment and high-level engineering expertise, which are scarce and/or expensive in developing countries. The fact that a bamboo bridge can perform cultural and social functions to a greater extent than a concrete bridge, resulting in the local community becoming more engaged in the bridge's construction and maintenance, can be an important additional factor in convincing the local community to choose a bamboo bridge, given that global warming is, by its very nature, an issue much more remote from everyday life in small rural communities.

***Keywords*:** nature-based solution (NBS), bamboo bridge, co-benefits, green building materials

1. Introduction

Bamboo grows naturally in both tropical and sub-tropical climates in Asia, Latin America, and Africa. In these regions, bamboo is widely used because of its rapid growth and multifunctional utility in different fields. From a sustainability point of view, bamboo can become a major nature-based solution (NBS), especially as a building material, having significantly fewer carbon dioxide (CO_2) emissions than steel and concrete. The world's highest all-wood building, soaring 85 meters into the sky, was completed in March 2019. This building was made from glued wood. While bamboo canes have been used for thousands of years, the use of laminated bamboo is still in its early stages. Small bamboo bridges, which are far easier to build than laminated wood skyscrapers, will be the subject of this paper. We shall not, however, discuss the usage of laminated bamboo or the combination of canes and laminated bamboo as the "floor" of a bamboo bridge, for example. If laminated bamboo can be made as durable as glued wood, it will most likely be used in similar skyscrapers. However, that discussion is beyond the scope of this article (see [1]).

DOI: https://doi.org/10.37256/gbce.3120221307

Bamboo has been used by humans since ancient times, but the connection to modern scientific engineering and international forest regulation is relatively new. The International Bamboo and Rattan Organization (INBAR) was established in 1997 to promote the use of bamboo. INBAR is a scientific community for both natural and social scientists, which is a huge repository of bamboo-related material, such as articles, reports, patents, and experts. INBAR is also working to change the regulatory regime related to bamboo. Since bamboo is not a tree and is not grown in the "West", the regulatory regime developed around "Western" and rainforest conservation and certification does not fit the characteristics of bamboo well. Certification by the Forest Stewardship Council is a very important part of this regulatory regime, although present regulations do not support the usage of bamboo [2-4].

Only a few publications about bamboo bridges can be found on the INBAR website, which includes non-academic papers and other sources. When searching the Reuters Web of Science Core collection for the phrases "bamboo" and "bridge" in titles, abstracts, and keywords, there are only a few articles about pedestrian bamboo bridges. This is a clear indication that the bamboo bridge remains a niche phenomenon in society and among the international scientific community. There is probably a larger literature in non-English languages, since there are several examples of recently built bamboo bridges in Columbia [5] and the Philippines [6].

2. The case study of "One-heart" bamboo bridges

2.1 *"One-heart" bridge project in Yubei District of Chongqing*

In this paper, we focus on two bamboo bridges of the type "One-heart" bridge that were part of a project with the same name, the Yi Xin Qiao project, based on the One University One Village (1U1V) Rural Sustainable Development Assistance Program. The program was initially prepared and launched by professors at the Chinese University of Hong Kong (CUHK) in 2014 with the idea of gathering professional knowledge and manpower from higher education institutions to help improve the environment and livelihood of one village strategically, systemically, and sustainably [7].

As the initiator of the program, Dr. Wan Li, illustrated in an interview two years ago [8]: "*What we are doing now is to promote endogenous development in rural areas. While advocating this science-based low-tech construction strategy, we are not only to build houses, but also to explore local resources, academically and physically, in order to facilitate the sustainable development in the rural areas by encouraging traditional craftsmen, using local materials, and celebrating vernacular architectural topologies. This is the social issue we respond to, as well as the social responsibility we choose to take*".

In our case, the two bridges were jointly completed by CUHK, Tsinghua University (THU), Chongqing Jiaotong University (CQJTU), and Chongqing University (CQU). So far, two bridges have been built in Yubei District, Chongqing Municipality. The first bridge was built in Xiaowu Village, and the second in Dujia Village (Figure 1). The two villages are two of the 17 villages in the Xinglong Town area of the Yubei District. The Jialing River is a big river in the Yangtze River system, flowing through Yubei District. According to the 2017 Yubei District National Economy and Social Development Statistics Report [9], the district's population was 1.63 million, with 350,000 people living in rural areas.

Figure 1. Another example of a simple bamboo bridge in the mountain area of Dujia Village in Xinglong Town, Yubei District, Chongqing Municipality. This bridge was completed in March 2019

The two villages, like many mountainous rural regions in the southwest part of China, face risks originating from frequent floods. Xiaowu and Qishan villages are mainly inhabited by Han Chinese. These two villages have 725 households each, with a population of around 2,000 people. Without a bridge, the villagers relied on a row of stones placed in the river bed to cross the river. During the rainy season, starting at the end of April every year and ending in October, the water level can rise to around one to 1.5 meters above the normal level.

As shown in Figure 2, most bridges in mountainous regions are very simple and crude. In some places, there is no real bridge; people just put slate or bamboo rafts on the river as a connecting path. But in the rainy season, such crossings are dangerous, so better bridges are clearly needed.

Figure 2. Example of a simple bamboo bridge in the mountain area of Aidong Village in Lüchun County, Honghe Prefecture, Yunnan Province. The construction was completed in July 2018

2.2 *Bamboo bridges in the villages of Xiaowu and Dujia*

The first bamboo bridge was built in Xiaowu Village. This bridge was designed in a scientific research lab, and the bamboo was precut and assembled into bigger parts. Figure 3 shows how the parts were transported to the field and assembled there. Figure 4 shows the interior of the bridge, which is around three meters wide.

Figure 3. Precutting and assembling of the bamboo bridge at Dujia

Figure 4. The interior of the bamboo bridge in Xiaowu Village

On April 26, 2019, the bamboo bridge project in Dujia Village was granted a Jury's Award by the Royal Institution of Chartered Surveyors (RICS) Awards China in the category of sustainability development. This bridge has a length of 21 meters and a width of three meters. The key research questions for this project are, of course, "How many years will the bridge last?", "What kind of maintenance is needed?", and "Who can do the maintenance?". We have not found any clear answers to such questions in the academic literature. This is expected, given that only real-life experiences can provide sufficiently solid responses and lead to further research and development of bamboo bridge technology. Bamboo has a long history, therefore there is a lot of general knowledge about the pros and cons of bamboo in various applications.

2.3 *The pros and cons of bamboo*

There are approximately over 1,000 species of bamboo in the world. In China, there are over 500 different species of bamboo [10]. Bamboo is found primarily in central and southern China, where it can form entire forests. China's bamboo forests cover about 5% of the country's total forest area. The widely available bamboo is both decorative and practical when the poles are made into products utilized in homes and businesses all over the world, such as furniture, construction materials, and other crafts. In Hong Kong, for example, the use of bamboo as scaffolding is impressive [11].

Bamboo has the advantage of being easy to bend and hard to break. Bamboo is also a natural composite material with a natural structure that resembles fiber-reinforced composites. Compared to trees, it grows very fast. A tree takes roughly 30 years to reach a sufficient height. However, bamboo takes only three to five years to be tall and big enough. Some species of bamboo exhibit compressive strengths that are equivalent to, if not superior to, those of concrete and steel. Bamboo is an ideal natural construction material due to its weight-to-strength ratio and the minimal processing required to capitalize on its strength. They have a round or nearly round cross section and are usually hollow, with rigid cross-walls strategically placed to prevent any collapse when bent. The strong hard tissues with great tensile strength are localized along the culm walls' surface. They can function most effectively in this position, providing mechanical strength as well as making a firm, resistant shell [12].

The bamboo bridge in our case is made of a widely available bamboo known as Mao bamboo or Moso bamboo. According to China's 9th National Forest Resources Inventory [13], bamboo forests cover 6.41 million hectares, or 2.94% of the country's total forest area. The Moso bamboo forest covers 4.68 million hectares, accounting for 72.96% of the entire bamboo forest area. As a result, Moso bamboo is extensively available in southern China. Moso bamboo has a three to five-year development cycle. It has a short space between the knots and can grow to a height of eight to 10 meters, with a diameter of around 10 centimeters. After chopping off the parts that are too thin, around six to seven meters of bamboo are suitable for usage.

2.4 *The limitations of bamboo*

No construction material has ideal characteristics for all purposes. As nails and screws can fracture bamboo cane, it has traditionally been held together in a variety of methods. Bamboo's limited length and conical shape make it challenging to create wide spans. Bamboo as a plant is a giant grass that contains a lot of starch that is attractive to worms. Direct contact with humid soil, for example, can cause bamboo to decay, just as it might with wood when it's submerged in water. Bamboo is also less industrial than steel or steel-reinforced concrete because of its non-standard thickness and shape [14].

There are traditional techniques applied to preserve the bamboo, for example, using chemical preservatives, but that can create unexpected environmental hazards. Therefore, to meet the objective of eco-friendly, cost-effective, and sustainable development, innovative ideas for dealing with the issue have to be considered and explored in the future.

Some efforts have been made to overcome the limitations of bamboo. One of the traditional and effective methods is heat treatment. The general heat treatment is that the material is heated in a certain medium, maintained at a certain temperature, and then gradually cooled. At the end of the temperature-change treatment, the surface or internal structure of the material, along with its chemical composition, are changed, thereby improving its performance. When bamboo material is continuously treated in a heated environment for a certain period of time, its hemicellulose is degraded; the hydroxyl group in the cell wall and the hygroscopicity are reduced, so that the dimensional stability and resistance to biological breakage are improved. After the heat treatment, the change in the chemical composition of the bamboo material will also change its color.

Heat treatment has been widely used in the wood industry. Although bamboo and wood have similar chemical compositions, the structure of bamboo is quite different from that of wood. Therefore, the methods of wood modification cannot be directly applied to bamboo [14]. However, in a recent experiment done by Tang et al. [14], tung oil heat treatment was found to be a promising approach for not only enhancing hydrophobic properties and dimension but also significantly increasing fungi resistance [14]. Nonetheless, there is insufficient experimentation to determine whether this is the most green and effective way of producing durable bamboo materials. However, bamboo's potential as an environmentally friendly material is no doubt a bright prospect.

2.5 *The technology behind the bamboo bridge*

Although the most important technology used in the construction of bamboo bridges is simple (see Figure 5), it represents a breaking point, shifting the usage of bamboo from making small things to bigger products, including infrastructure such as wide-span bridges.

Figure 5. Method for joining bamboo culms

While bamboo poles were traditionally lashed together with cord or rope, they can now be processed into laminated boards, beams, and sheet goods. In our case, we combined the traditional way of building a bridge with some simple steel parts like pegs, dowels, screw bolts, angle irons, and others (see Figure 5).

2.6 *The cultural aspects of the bamboo bridge*

The designers also considered cultural elements when building the two bamboo bridges, although in the very beginning, ideas about possible cultural aspects of the bridges emerged as a result of brainstorming to solve the bridge's maintenance cost problem.

Following the construction of the first bridge, local residents naturally inquired about the bridge's durability. In the future, the bridge will require repainting from time to time. Although paint is not expensive, it still costs money. To address the issue of maintenance funding, it was decided that the bridge should be used as an "open temple" (see Figure 6). As a result, the bridge was transformed into a place of worship, with god statues placed near the bridge's roof.

Figure 6. The first bamboo bridge as an "open temple"

When building the second "One-heart" bridge (Figure 7), cultural elements were considered in advance. The center part of the bridge was designed to become a gathering place that could be used as a school site to introduce bamboo-related culture or other topics in the future.

Figure 7. The second bamboo bridge as a gathering site

3. Technical issues related to the bamboo bridge

In the project, the tests primarily conducted included not only compression tests but also elastic modulus and shear tests. The primary reason compression tests were conducted is because the bridges constructed are arching bridges. The arch will bear the majority of the load and stress, while the joint component of the structure will be compressed. The arch is utilized because, while bamboo's tensile performance is good (approximately twice the compression), it cannot effectively transmit tensile force at the joint (relative to compression) because the tensile joint is not easy to construct. All tests were carried out in accordance with [15].

At present, all of the bridges in villages are designed exclusively for pedestrians and bicycles, not for automobiles, so the dynamic load of heavy vehicles on these bridges is irrelevant. Due to the absence of heavy cars on the bridge, the danger of earthquakes to pedestrians and cyclists has not been considered a major issue. Since bamboo is an elastic material, it has natural energy shock-wave dissipation. Recent reports on bamboo and earthquakes proved that bamboo is resilient to dynamic loads such as earthquakes and strong wind gusts [16].

Due to the mild climate in which both of the above-mentioned bamboo bridges are located, winter temperatures seldom fall below zero, and frost and extended periods of cold weather are not an issue. Bamboo, in many ways, has the same physical properties as wood and should be able to withstand temperatures well below zero degrees Celsius. Given the diversity of bamboo species, some of which grow in locations prone to snow and below-freezing temperatures, one should be able to find bamboo with the technical attributes required for practically any climate where humans live. For more details on this topic, see [17].

The standard thickness of these bridges is typically around 1 centimeter. Normal air humidity varies by location. For example, the equilibrium moisture content is 15% in Chongqing, which is the location of the second bridge and a representative village in Southern China, and 12% in Beijing, or Northern China. This paper details the chemical composition of bamboo [18].

The joining of the bamboo parts is, in this case, mostly done with bolts. Local reinforcement is critical in this context. For instance, we begin by grouting the joint section, which connects the two bamboo parts. Next, a half-meter-long thin steel pipe (the length of two to three bamboo sections) is inserted at the arch foot, thereby completing the grouting within the range.

Fire is, of course, always an issue. The risk of fire is mitigated in these bamboo bridge projects by taking preventative steps, such as avoiding elements that easily catch fire on the bridge. Bamboo itself can't prevent fire for the time being, but it does not easily catch fire in an open-air structure such as a bridge, where it is extremely difficult to generate enough heat to self-ignite the bamboo. For more discussion on bamboo and fire protection, see [19].

4. Is the bamboo bridge an example of an NBS?

According to the European Union (EU) [20,21], NBS refers to solutions that are inspired and supported by nature that are cost-effective while also providing environmental, social, and economic benefits, including increased resilience.

According to the 2015 Global Forest Resources Assessment [22]: "*Improved use of less energy-intensive construction materials, such as wood and bamboo, will continue to contribute to reductions in greenhouse gas emissions when they substitute for energy-intensive materials, such as iron and concrete*".

The main criteria for designating the "One-heart" bamboo bridge as an NBS are that bamboo is environmentally friendly, helps society adapt to climate change, and conserves raw materials [23,24].

4.1 *Environmental benefits*

Bamboo bridges benefit the local population by reducing flood risk. The benefits of bamboo bridges are primarily due to the characteristics of bamboo. Bamboo is widely available and is increasingly being used in modern life due to its environmental benefits. In comparison to many other plants, bamboo matures quickly and is easy to cultivate. Numerous species can thrive on slightly acidic soils deficient in nutrients. Relative to traditional infrastructure, bamboo is more environmentally friendly, produces less pollution, and is less expensive. Research shows that bamboo absorbs more CO_2 than any other plant and produces 35% more oxygen than trees [25].

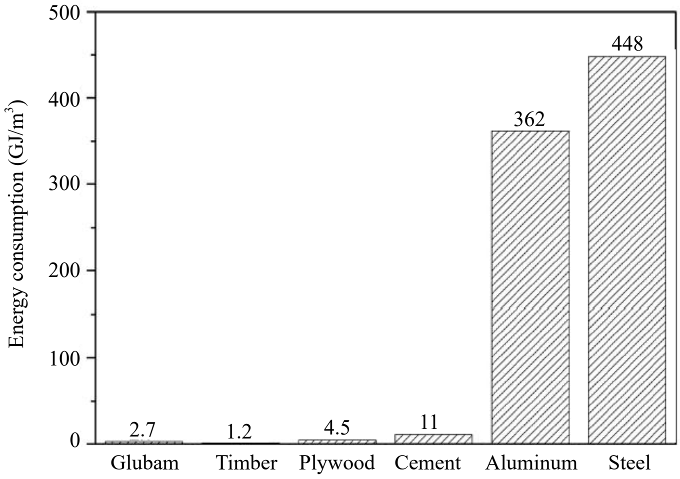

Figure 8. Energy consumption of various construction materials [26]

Figure 8 shows that wood, bamboo, and cement consume significantly less energy per cubic meter, which is a measure of the amount of energy consumed by the various materials used to construct a pedestrian bridge. It is important to note that cement consumes around ten times the energy of timber and four times the energy of glubam (laminated bamboo). Non-laminated bamboo is likely to be even more energy efficient than timber, as it may be used almost entirely in its natural state.

Even more important is the CO_2 emissions. As shown in Figure 9, wood and bamboo-based components actually produce negative emissions. It is self-evident that negative emissions, namely, carbon capture and storage, are required, and that employing wood and bamboo instead of cement and steel can contribute significantly to carbon capture and storage, i.e., negative emissions.

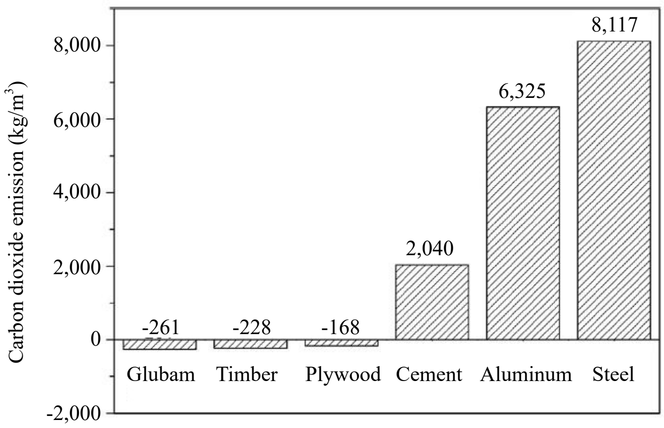

Figure 9. Carbon dioxide emission of various construction materials [26]

Previous studies also discussed the potential of bamboo as a building material in western countries, showing the importance of transportation costs in comparison to other costs [27,28].

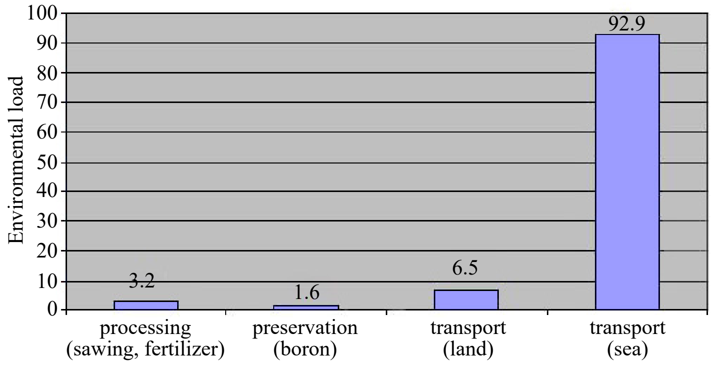

Figure 10. Environmental load of various stages of the production process [27]

The environmental load of one kilogram of bamboo culm is depicted in Figure 10, which includes transportation to the Netherlands and several stages of the production process. The unit of measurement is milli points (mPts), which corresponds to a euro 0.001 environmental cost [27].

Although this study was conducted in 2006 [27], there is still no tax on international shipping fuel and only very moderate taxes on land transport in some countries. Carbon taxes on transport are needed in order to internalize the climate and environmental costs of land and sea transport. Significant taxes on land and sea transport will only be implemented, for example, when the EU, or another significant group of nations, imposes a common high internal carbon tax, resulting in the establishment of an international carbon price due to the need for a carbon border tax. The EU is discussing such a carbon border tax as a key component of the "Fit for 55" plan.

4.2 *Social benefits*

NBS can bring about benefits in terms of health and quality of life. In this instance, the bamboo bridges reduce casualties and provide a good location for gathering, reading, and sharing knowledge, all of which have positive impacts on the lives of local residents. In the summer, because the river flows beneath the bridge, locals place bedding on the bridge's floor to make use of the river's cooling effect. As expressed by Changyong Du, a farmer from Dujia Village [29]: "*Now it is more convenient, and every day I walk over this bridge. And being more convenient is only one merit. Since it is the biggest bamboo bridge with the widest span, it has attracted people to visit it and take pictures here*".

The polarization of living conditions between urban and rural areas is a well-known feature of the Chinese economy. On the other hand, like many places in the world, urban development and rural under-development have made people migrate to cities. In the cities, people hope to enjoy the comforts of modern city life, such as public transportation, better education, improved medical care, and others. Meanwhile, rural areas continue to have a sizable population. Even in the highly urbanized districts of China, the rural population remains substantial. A significant "stylized-fact" is that in many rural places, the village population is consisting disproportionately of elderly and children, as the majority of adults have relocated to urban areas to work.

4.3 *Economic benefits*

A bamboo bridge can bring about many economic benefits. To begin with, it conserves raw materials. Utilizing bamboo immediately contributes to the reduction of wood consumption. According to the field studies conducted by our co-author, Changzhuan Shao, in Mojiang County of Yunnan Province (population 360,000) and Pengshui County of Sichuan Province (population 800,000), the demand for simple bamboo bridges in Mojiang County is estimated to be around 100 bridges and close to 300 bridges in Pengshui County. The data shows that the demand for convenient bridges is much higher than expected. If the potential demand for bridges is around 400, then the manufacture of bamboo bridges can benefit from large economies of scale, resulting in a much lower price for this kind of bamboo bridge.

Additionally, NBS may provide economic benefits, such as increased tourism. Although there are now only two bamboo bridges, they have drawn visitors from other parts of the region.

4.4 *Research and education benefits*

Further research into these bamboo bridges is important. These bamboo bridges offer good cases for the research community as examples of NBS in real life. Small-scale bamboo bridges may lead to research on wide-span bamboo bridges and structures, which can be applied in both rural and urban situations, even globally. What's more, the bamboo bridges offer a chance for people to learn more about traditional construction techniques. In ancient China, Mortise-Tenon connections were widely used in construction, especially in furniture making. In fact, in the process of building the bamboo bridges, some top-skilled craftsmen joined the team to teach the traditional techniques.

5. Discussion

5.1 *The principles of NBS exemplified by the bamboo bridges*

NBS needs to be aesthetically appealing to the locals. This is the first lesson suggested by the research based on 15 cases of NBS's experiments across 11 European cities [30]. As shown by the bamboo bridge, infrastructure can contribute in more domains than just technical functionality; it can be designed and built with an understanding of the local culture, especially the local aesthetical preferences.

In many countries, conventional wisdom holds that planting trees is the key method of afforestation and an important part of climate policy. However, it has the risk of compromising long-term carbon storage, human adaptation, and efforts to preserve biodiversity [31]. Hence, as demonstrated by the "One-heart" bamboo bridge, it is critical to emphasize the diversity and integrity of natural ecosystems while also benefiting the local community. The bamboo bridge shows two types of substitution. First of all, bamboo can replace wood to a much larger extent. This will increase the supply of wood for use in contexts where bamboo cannot be substituted for wood, making it easier to meet China's high demand for wood in non-substitution situations. China consumes about 500 million cubic meters of wood per year, half of which is imported. Therefore, greater use of domestic bamboo would have several economic and ecological benefits. For instance, creating more employment in China's bamboo-growing regions. Additionally, bamboo can be used in place of concrete and steel. Although grey infrastructure is more cost-effective, it is significantly less attractive than bamboo or wood. While China is carrying out the policy of "building beautiful countryside", it is clear that buildings with local flavor and constructed using locally sourced materials are significantly more attractive.

Technological improvements can make bamboo a stronger construction material, allowing it to be used for a wider variety of construction purposes. The bamboo bridge was constructed using a combination of traditional and modern techniques and technology. Combining traditional and academic technology and methods is unquestionably the way to overcome or mitigate bamboo's well-known limitations.

As shown by the bamboo bridge case, NBS means applying an integrated, systemic approach. A bamboo bridge demonstrates that bamboo is useful for more than just retail products and food; it can be integrated into community life, directly improving people's communication and indirectly contributing to the local people's cultural life. In order to realize its full potential, all relevant stakeholders should be involved. In the case of the bamboo bridge, stakeholders include those who use it as a bridge and as an "open temple", as well as designers, builders, craftsmen, and tourists who visit the bridge and surrounding villages.

At the same time, NBS must be able to learn, improve, and adapt to the changing needs of society while enhancing the ecological benefits to society. The "One-heart" bamboo bridge project shows that even with fairly limited technological innovation, there is still a need for politically stimulated investment in the early stages. The possibility of its application in other places and over a long period of time may decrease the cost through the effect of knowledge sharing. In our case, the bridge gained research funding, which covered the expense of treating bamboo to make it stronger and repel worms, among other things. The more bridges are constructed, the more cost-effective production will become as a result of learning effects, creating a positive feedback loop from learning, cost reductions to greater demand as a result of lower costs and improved quality. One thing is for sure, there will be no shortage of bamboo in the foreseeable future. According to the 2015 Global Forest Resources Assessment, Country Report of China [22], the area of bamboo forest in China has shown steady growth in the last 30 years (see Figure 11). The increasing bamboo forest provides more raw materials.

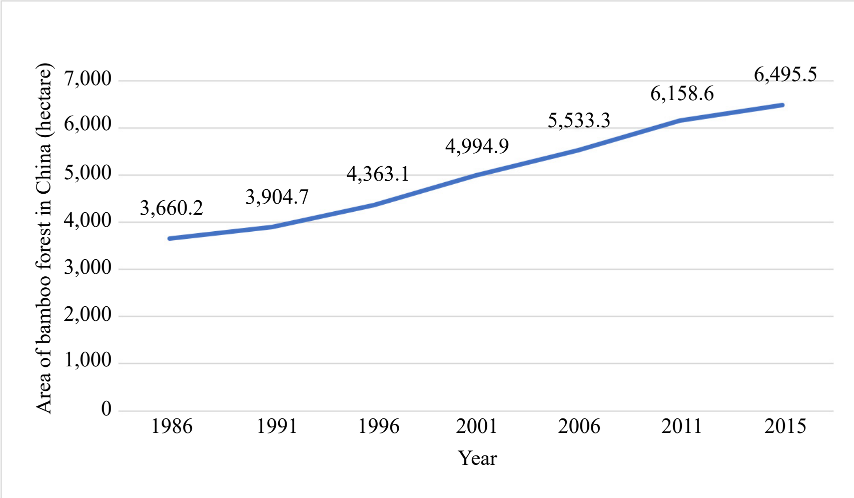

Figure 11. The area of bamboo forest in China [32]

5.2 *The path from grey to green infrastructure*

Previous research has described the strong "path dependence" of what they call "grey infrastructure", which is the concrete and asphalt-based infrastructure of modern cities, i.e., buildings and roads [33]. The study showed how thought habits and the constraints of the technology that can be used in new projects as a result of past "grey" decisions are "locking" us into an unsustainable development path. In other words, we have a strong "grey" path dependency. To get out of this "grey" path dependency and onto a path leading to the "greening" of infrastructure, four areas where change is necessary and attainable were identified:

i. Education of infrastructure professionals
ii. Institutional and cultural reform
iii. Community-empowered placemaking must include ecosystem literacy
iv. Public and private sector procurement

All four of these factors are critical in the case of bamboo in general and bamboo bridges in particular. Each of them merits an article on the status quo and what can or must be done. In addition, we believe this list is missing a crucial part of how to green the infrastructure, namely the matter of pricing. It is necessary to compare the costs of grey and green infrastructure components.

5.2.1 *The use of bamboo and the carbon price*

It is clear that if the externalities associated with fossil energy were used in the products and services of grey infrastructure, for example, through a progressive carbon tax, it would result in a very significant and steady increase in the price of all materials, products, and services with a high carbon content. As mentioned above, concrete and steel bridges have a much larger carbon footprint than bamboo bridges. A high carbon price would certainly increase the demand for bamboo as a construction material, since capturing CO_2 in bamboo and "storing" it in bridges and buildings counts as negative emissions. This may imply that bamboo would be used more extensively in areas where it is abundant and affordable now. Global demand for bamboo has the potential to grow fast, making it a substantial source of revenue for rural communities that are "poor" but bamboo-rich. A rising carbon price would, of course, have a greater impact on poor people and regions than on more affluent people and regions, but this is a question of redistribution of the carbon tax income, which is beyond the subject of this paper. As previously stated by the World Bank [34], there are numerous ways in which the revenue from a CO_2-tax might be distributed, and making the distribution progressive in order to transfer income from the rich to the poor is a purely political concern.

6. Conclusion

NBS prioritizes reducing greenhouse gas emissions as rapidly as possible while incurring the least environmental costs possible, both in the short term and especially in the long term. The fundamental idea is to use materials and processes found in non-urban nature to reduce the need for industrial production, which will inevitably result in increased emissions and energy consumption, as well as negatively influence land use and biodiversity. There are no pure technical solutions to the dual issues of global warming and biodiversity loss. All technologies exist within a social context and will have varying effects on various social groups in terms of income distribution, employment opportunities, pollution levels, and other forms of environmental degradation. From a certain technical point of view, it might be the "first best technology" if it meets strong social resistance. For example, nuclear power in Germany. Since we need a rapid introduction of emission-reducing technologies, which mix of technologies is the best? That is a multidimensional question. Political preferences are clearly one of those dimensions. One must think about the good and bad effects on the economy, the environment, and society at the same time.

Based on these two case studies from China, we conclude that the construction of bamboo bridges is an NBS that contributes significantly to emission reduction while having a negligible impact on the ecosystem and biodiversity. When compared to concrete, wood, and steel, bamboo is a species of grass that grows quite quickly. If bamboo is not allowed to root and emit CO_2, it becomes a fairly efficient negative emission technology. Due to the widespread destruction of forest land, timber is becoming scarce as a raw material. Additionally, it takes at least two to three decades for a tree to remove the maximum quantity of CO_2 from the air. This is comparatively slow given that there must be negative emissions by 2050. However, if bamboo is used instead of wood, zero emissions could be achieved in less than ten years.

Although numerous applications of bamboo have been developed, there are many more possibilities to be explored. For instance, as shown by our bamboo bridge case, which contributes to the transition from "grey" to "green" infrastructure in small communities, especially in developing countries that are constructing a modern transportation system from "scratch" [35]. Secondly, using laminated bamboo (glubam), where the next step will be to construct larger bamboo bridges. Bamboo bridges provide various advantages, including improved public transportation and health, biodiversity conservation, and recreational activities. In short, the bamboo bridge is a good example of an NBS.

Acknowledgement

This research is funded by the China-Central Eastern European Countries Higher Joint Education Project (No. 202028). This research is also supported by the Shaanxi Key Laboratory of Carbon Neutralization.

We would like to thank one of the authors, Changzhan Shao, who is also the leading member of the "One-heart" bridge project, for providing some of the figures.

Conflict of interest

The authors declare no conflict of interest.

References

[1] Xiao Y, Zhou Q, Shan B. Design and Construction of Modern Bamboo Bridges. *Journal of Bridge Engineering*. 2010; 15(5): 533-541. Available from: doi: 10.1061/(ASCE)BE.1943-5592.0000089.

[2] Buckingham KC, Jepson P, Wu LR, Ramanuja Rao IV, Jiang S, Liese W, et al. The Potential of Bamboo is Constrained by Outmoded Policy Frames. *Ambio*. 2011; 40(5): 544-548. Available from: doi: 10.1007/s13280-011-0138-4

[3] Buckingham KC, Wu LR, Lou YP. Can't See the (Bamboo) Forest for the Trees: Examining Bamboo's Fit Within International Forestry Institutions. *Ambio*. 2014; 43(6): 770-778. Available from: doi: 10.1007/s13280-013-0466-7.

[4] Buckingham KC, Jepson P. The Legitimacy of Bamboo Certification: Unpacking the Controversy and the Implications for a “Treelike” Grass. *Society & Natural Resources*. 2015; 28(6): 575-592. Available from: doi: 10.1080/08941920.2014.945057
[5] Carmiol-Umaña V. Guadua Bamboo in Pedestrian Bridges. *Revista Tecnología en Marcha*. 2016; 29: 3-13. Available from: doi: 10.18845/tm.v29i5.2513.
[6] Luansang C, Boonmahathanakorn S, Domingo-Price ML. The Role of Community Architects in Upgrading; Reflecting on The Experience in Asia. *Environment and Urbanization*. 2012; 24(2): 497-512. Available from: doi: 10.1177/0956247812456125.
[7] Qiao YX. *One University One Village Rural Sustainable Development Assistance Program*. Available from: http://web5.arch.cuhk.edu.hk/server1/staff1/edward/www/1u1v/files/CUHK/work.html [Accessed 24th November 2021].
[8] Tian X, Wang M, Wang Y. One University One Village Program: Promoting Endogenous Development in Rural Areas Through Local Practice. *Landscape Architecture Frontiers*. 2018; 6(1): 46-52. Available from: https://link.gale.com/apps/doc/A567633805/AONE?u=anon~4f4ab7a5&sid=googleScholar&xid=99ee8071 [Accessed 26th November 2021].
[9] Chen D. (ed.) *Yubei District National Economy and Social Development Statistics Report 2021*. Rong Media Center, Yubei District. 2022. Available from: http://www.cqybq.gov.cn/ybw_content/2022-03/29/content_10327520.htm [Accessed 26th November 2021].
[10] Ruiz-Perez M, Maoyi FY, Yang XS, Belcher B. Bamboo Forestry in China: Toward Environmentally Friendly Expansion. *Journal of Forest*. 2001; 99(7): 14-20. Available from: doi: 10.1093/jof/99.7.14.
[11] Ramanathan M. Hong Kong - Bastion of Bamboo Scaffolding. *Proceedings of the Institution of Civil Engineers - Civil Engineering*. 2008; 161(4): 177-183. Available from: doi: 0.1680/cien.2008.161.4.177.
[12] McClure FA. Bamboo in the Economy of Oriental Peoples. *Economic Botany*. 1956; 10(4): 335-361. Available from: doi: 10.1007/BF02859765.
[13] State Forestry and Grassland Administration. *2014-2018 China Forest Resources Report*. Beijing: China Forestry Press; 2019. p.451.
[14] Tang T, Zhang B, Liu X, Wang W, Chen X, Fei B. Synergistic Effects of Tung Oil and Heat Treatment on Physicochemical Properties of Bamboo Materials. *Scientific Reports*. 2019; 9(1): 1-1. Available from: doi: 10.1038/s41598-019-49240-8.
[15] The International Organization for Standardization. ISO 22157:2019. *Bamboo Structures - Determination of Physical and Mechanical Properties of Bamboo Culms - Test Methods*. Geneva: ISO; 2019. Available from: https://www.iso.org/standard/65950.html [Accessed 25th November 2021].
[16] Van Drunen N, Cangás A, Rojas S, Kaminsky S. *Post-earthquake Report on Bamboo Structures and Recommendations for Reconstruction with Bamboo on the Ecuadorian Coast*. International Bamboo and Rattan Organisation (INBAR). 2016. Available from: https://www.inbar.int/resources/inbar_publications/post-earthquake-report-on-bamboo-structures-and-recommendations-for-reconstruction-with-bamboo-on-the-ecuadorian-coast/ [Accessed 25th November 2021].
[17] Wu J, Wang X, Fei B, Xu X, Lian C, Chen H. The Mechanical Properties and Thermal Conductivity of Bamboo with Freeze–thaw Treatment. *Journal of Wood Science*. 2021; 67(1): 66. Available from: doi: 10.1186/s10086-021-01998-0.
[18] Sun YL. The Chemical Composition of Bamboo. *Biology Teaching*. 2007; 32(12): 9-10. Available from: https://wenku.baidu.com/view/caaaeb0003d8ce2f00662320.html [Accessed 24th of November].
[19] Gutierrez M, Solarte A, Pope I, Maluk C, Hidalgo J, Torero JL. Fire-safe Bamboo Structures - A Methodology to Facilitate Performance-based Design. In: Xiao Y, Li Z, Liu KW. (eds.) *Modern Engineered Bamboo Structures*. Boca Raton: CRC Press; 2019. p.117-128.
[20] Kang R, Li N, Shi BB. The NBS in EU from the Perspective of Ecological Economics. *Journal of Northwest University (Social Science Edition)*. 2020; 6: 135-146. Available from: doi: 10.16152/j.cnki.xdxbsk.2020-06-015.
[21] Kang R, Shi BB, Ren BP. The Climate Change Governance Based on NBS. *Journal of Environmental Economics*. 2020; 3: 169-184. Available from: doi: 10.19511/j.cnki.jee.2020.03.010
[22] Food and Agriculture Organization of the United Nations. *Global Forest Resources Assessment 2015: How are the World’s Forests Changing?*. 2nd ed. Rome: Fao Inter Departmental Working; 2016.
[23] Davis M, Krüger I, Hinzmann M. *Coastal Protection and SUDS - Nature-Based Solutions*. European Union’s Seventh Framework Programme. Policy Brief Number: 4, 2015. Available from: https://www.ecologic.eu/sites/default/files/publication/2017/2723-recreate-pb-nature-based-solutions.pdf [Accessed 25th November 2021].
[24] Zhang Y, Kang R. Chinese Practice for “Nature-based Solutions”: The Review of “Ant Forest” Project. *Journal of Business and Economic Management*. 2020; 8(4): 090-097. Available from: doi: 10.15413/jbem.2020.0703.

[25] Van der Lugt P, ThangLong T, King C. *Carbon Sequestration and Carbon Emissions Reduction Through Bamboo Forests and Products*. Beijing: INBAR; 2018. Available from: https://repository.tudelft.nl/islandora/object/uuid:54c93ab8-5d8e-4cb7-9694-c613f5e81fab?collection=research [Accessed 29th November 2021].
[26] Xiao Y, Yang RZ, Shan B. Production, Environmental Impact and Mechanical Properties of Glubam. *Construction and Building Materials*. 2013; 44: 765-773. Available from: doi: 10.1016/j.conbuildmat.2013.03.087.
[27] Van der Lugt P, Van den Dobbelsteen AA, Janssen JJ. An Environmental, Economic and Practical Assessment of Bamboo as a Building Material for Supporting Structures. *Construction and Building Materials*. 2006; 20(9): 648-656. Available from: doi: 10.1016/j.conbuildmat.2005.02.023.
[28] Janssen JJA. Bamboo - Its Use in the Construction of Roofs and Bridges. *Appropriate Technology*. 1983; 10(2): 20-23.
[29] Changyong Du. Interviewed by: Changzhuan Shao. 18th May 2018.
[30] Frantzeskaki N. Seven Lessons for Planning Nature-based Solutions in Cities. *Environmental Science & Policy*. 2019; 93: 101-111. Available from: doi: 10.1016/j.envsci.2018.12.033.
[31] Seddon N, Turner B, Berry P, Chausson A, Girardin CAJ. Grounding Nature-based Climate Solutions in Sound Biodiversity Science. *Nature Climate Change*. 2019; 9(2): 84-87. Available from: doi: 10.1038/s41558-019-0405-0.
[32] Li Y, Feng P, Bamboo Resources in China Based on the Ninth National Forest Inventory Data. *World Bamboo and Rattan Newsletter*. 2019; 17(6): 45-48. Available from: http://www.relun.com/qikan/05b6445eed5ab9511295f5aa917d38ce.html [Accessed 28th November 2021].
[33] Davies C, Lafortezza R. Transitional Path to the Adoption of Nature-based Solutions. *Land Use Policy*. 2019; 80: 406-409. Available from: doi: 10.1016/j.landusepol.2018.09.020.
[34] Carbon Pricing Leadership Coalition Reports. *Report of the High-Level Commission on Carbon Pricing and Competitiveness*. World Bank. 2019. Available from: https://openknowledge.worldbank.org/handle/10986/32419 [Accessed 29th November 2021].
[35] Paraskeva TS, Grigoropoulos G, Dimitrakopoulos EG. Design and Experimental Verification of Easily Constructible Bamboo Footbridges for Rural Areas. *Engineering Structures*. 2017; 143: 540-548. Available from: doi: 10.1016/j.engstruct.2017.04.044.