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Framework for assessing ecosystem services from bamboo forests

Lessons from Asia and Africa

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Abbreviations

ARIES	Artificial Intelligence for Ecosystem Services
ES	Ecosystem Services
FAO	Food and Agriculture Organization of the United Nations
InVEST	Integrated Valuation of Ecosystem Services and Trade-offs
MEA	Millennium Ecosystem Assessment
MIME	Multiscale Integrated Models of Ecosystem Services
NGOs	Nongovernmental Organizations
NTFP	Non-Timber Forest Product
TEEB	The Economics of Ecosystems and Biodiversity
TESSA	Toolkit for Ecosystem Service Site-based Assessment

1 Introduction

Bamboo is a fastest growing grass species and is an important forest type in the tropical and subtropical regions of Africa, Asia, and Central and South America (Lobovikov et al. 2007; Buckingham et al. 2014; Troy Mera and Xu 2014). Bamboo is an important non-timber forest product (NTFP) and an integral part of forestry, but it is also widespread outside the forests, including on farmlands, riverbanks, roadsides and urban areas (Lobovikov et al. 2007). Although forest areas have drastically decreased in many countries, bamboo forests have progressively increased globally (Lei 2001; Zhou et al. 2005; Buckingham et al. 2014). Bamboo forests, including both natural and planted ones, cover 31.5 million ha (FAO 2010). These bamboo forests are valuable assets which not only support poverty reduction and economic development but also contribute to environmental conservation (Effah et al. 2014; Phimmachanh et al. 2015). With this, the image of bamboo forests is quickly changing from 'poor people's trees' to high-tech industrial raw materials that can be used to replace the timber and other raw materials taken from natural and planted forests (Lobovikov et al. 2007, 2009). While raw material supply from forests is decreasing, bamboo can meet demands for raw material at a global scale.

Various goods and services provided by bamboo forests that promote human well-being are regarded as ecosystem services (ES); these provide landscape restoration, prevention of soil and sediment loss, food supply, domestic and industrial raw materials, and carbon sequestration (Zhou et al. 2005; Yiping et al. 2010; Sohel et al. 2015). Many studies show that bamboo is also important for restoration of degraded lands that play a key role in achieving recently adopted global restoration targets. Targets include the Bonn Challenge (to restore 150 million ha of degraded and deforested land by 2020), the New York Declaration on Forests (to restore 350 million ha by 2030) (Jacobs et al. 2015; Paudyal et al. 2017b; Reij and Winterbottom 2017), the Great Green Wall Initiative, Land Degradation Neutrality and Sustainable Development Goals (Wood et al. 2018).

Ecosystem services from bamboo forests have been intimately associated with human well-being since time immemorial (Bajracharya et al. 2013). In developing countries, bamboo is an important component of the rural farming system and plays a critical role in the rural economy, helping to sustain the livelihoods of rural people. Bamboo enterprises are the primary source of subsistence livelihoods and a source of economic upliftment for poor and underprivileged people (Lobovikov et al. 2009; Nath et al. 2009; Hogarth and Belcher 2013; Partey et al. 2017). Bamboo also provides numerous environmental services. For example, it protects traditional houses from strong winds, and fulfils the requirements for house construction materials and fuelwood purposes (Nath et al. 2009, 2015; Partey et al., 2017).

Besides contributing to local economies and the environment, global bamboo industries have rapidly developed in recent years and contributed more than USD 60 billion annually (INBAR 2019a), proving that bamboo forests have the potential to contribute to inclusive and green economic development at regional and global levels (Lobovikov et al. 2007; INBAR 2019a). Bamboos are the world's most traded NTFPs, and have become central to emerging economies around the globe, especially in tropical regions (INBAR 2006; Lobovikov et al. 2007). Bamboos are fast growing and a sustainable wood alternative, have a high potential for carbon sequestration and are viable resources for poverty alleviation and climate change adaptation (Lobovikov et al. 2007; Liese, 2009). Furthermore, bamboo is important for the rehabilitation of degraded land, as a timber substitute, for erosion control and watershed protection (INBAR 2006). With its fast growth rate and high annual regrowth after harvesting, bamboo forests have a high carbon stock potential (Yiping et al. 2010), especially when the harvested culms are used as durable products (Nath et al. 2009).

The ES assessment of bamboo forests can serve many purposes, including: (i) raising clarity and awareness of the relative importance of bamboo forests to policymakers, investors, environmental NGOs and local communities, (ii) improving the efficient use of limited funds by identifying where bamboo forests can achieve enormous benefits at the lowest cost, (iii) supporting new opportunities to link bamboo forests with ES markets (Gu et al. 2019), (iv) providing guidance for decision-makers in understanding user preferences and the relative value that people place on ES, (v) generating information for designing bamboo forests so as to maximize their contribution to local communities, broader society and the global environment, and (vi) showing the potentiality of bamboo plantation in the restoration of degraded land to achieve the aim of the UN Decade of Restoration (UNEP 2019). In the approach outlined here, the values ascribed to various ES are determined by the beneficiaries of the particular ES, which range from local to global markets.

Although bamboo forests provide a number of ES, statistics on the ES assessment are often poor, inconsistent and based on the different definitions, assumptions and methodology in different countries, indicating that tools and a common methodological approach are missing (Lobovikov et al. 2007); these should be easily applicable, especially in data-poor regions (Paudyal et al. 2015). To our knowledge, there is not any robust framework for assessing the ES, especially from bamboo forests. Therefore, our paper attempts to fill this gap.

In this paper, we reviewed the current assessment approaches and identified ES from bamboo forests and proposed a pragmatic yet straightforward framework for assessing ES from bamboo forests. This paper is organized into eight sections. Section 1 introduces the issues and outlines the scope of the paper. The subsequent section briefly describes the method used for this paper. Section 3 discusses the typologies of bamboo forests, revisits the concepts of ES and highlights the major ES from bamboo forests. Section 4 further compares the ES from bamboo forests with ES from the major land use and land cover types including natural forests, planted forests, grasslands and agricultural lands. Section 5 provides a framework for assessing ES from bamboo forests, and the methods and tools are presented in Section 6. Section 7 presents the case studies from Nepal, Indonesia and Ethiopia demonstrating ES from bamboo forests that give local to global benefits, and the lessons learnt. Finally, Section 8 concludes.

2 Method

2.1 Literature review

An extensive literature search was undertaken from October 2018 to March 2019 using the Scopus database, the single largest abstract and indexing database (Burnham 2006; Falagas et al. 2008; Kulkarni et al. 2009; Bar-Iilan 2018). The review focused on four areas of interest, i.e. ES assessment, ES framework, ES assessment methods/tools, and ES from bamboo forests in general with a particular focus on ES from a bamboo forest in each of the case study countries.

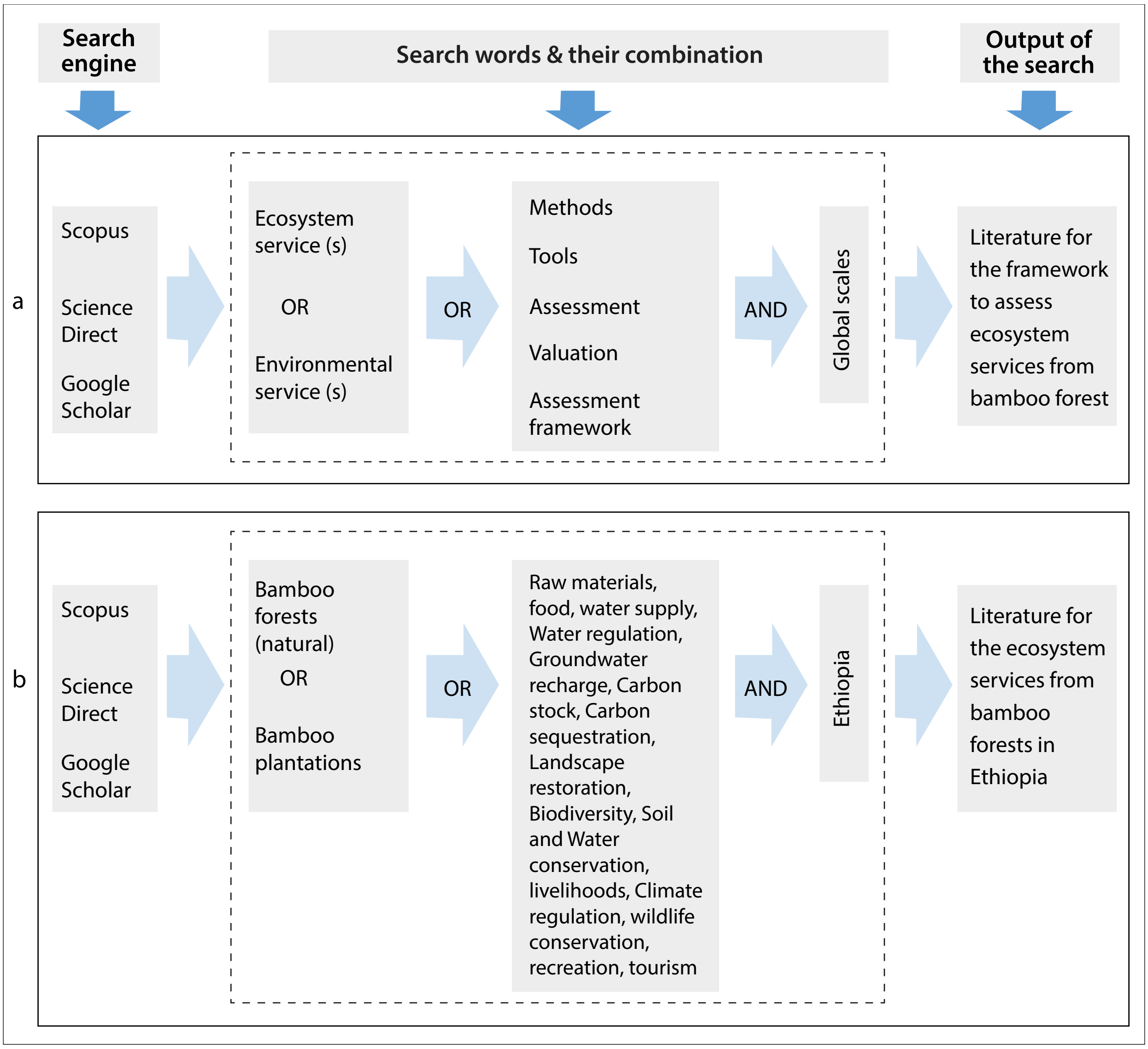

Figure 1. Procedures adopted for document search using keywords in various web-based databases. (a) Process of document search for the framework to assess ecosystem services (ES) from bamboo forests. (b) Process of searching literature-related ES from bamboo forests in Ethiopia. The process in (b) was repeated to identify ES from bamboo forests in Nepal and Indonesia.

Many combinations of keywords (Figure 1) were used to find more articles. The search first identified articles containing the words in different combinations such as (i) 'ecosystem services(s)' OR 'environmental service(s)' AND 'assessment', (ii) 'ecosystem services(s)' OR 'environmental service(s)' AND 'framework', and (iii) 'ecosystem services(s)' OR 'environmental service(s)' AND 'methods and tools' in the title, abstract and keywords to explore appropriate methods and tools and to define a potential framework for the ES assessment from bamboo forests. Further, a literature search was conducted with a combination of words 'ecosystem services(s)' OR 'environmental service(s)' AND 'bamboo forests' to find articles directly mentioning ecosystem services from bamboo forests. Other combinations of keywords were used, such as 'bamboo forests (natural) and bamboo plantations' AND 'raw materials.' These were further investigated with other items, such as subsistence livelihoods, industrial raw materials, food, water supply, water regulation, carbon sequestration, climate regulation, wildlife conservation, biodiversity, recreation, tourism and so on. Additional literature written in the English language was searched separately for Nepal, Indonesia and Ethiopia using similar search syntaxes. However, a couple of research studies written in Bhasha Indonesia were utilized for the Indonesian case and interpreted through the Indonesian experts.

To capture additional relevant information, we continued to search using databases for articles including conference proceedings, book chapters, government publications, technical reports, agency reports, student theses and synthesis papers in regard to the ES themes mentioned above and bamboo forests. We conducted a quick review of the abstracts of the retrieved articles to evaluate their relevance to the purpose of the study. Later, we evaluated these articles in detail after preparing a list of articles of interest. The aim of reviewing these articles was to glean the latest developments in ES science (assessment, method/tools and framework) as practiced in forestry and other sectors globally and to utilize this learning to develop a framework in the context of assessing ES from bamboo forests.

The most significant articles and reports related to an ES framework, bamboo forests and various ES from bamboo forests were selected, reviewed and qualitatively analyzed. For this, we utilized the 'applied thematic analysis' (ATA) approach (Guest et al. 2012) to investigate the framework for ES assessment and ES from bamboo forests from Nepal, Indonesia and Ethiopia, as applied to a study in Nepal (Paudyal et al. 2017a) and South Africa (Sitas et al. 2014). The ATA process is designed to identify and scrutinize themes from textual data in a transparent and credible way (Tuckett 2005; Guest et al. 2012). Based on the process, different themes and subthemes according to the types of ES were created through a literature search. Finally, identified ES were categorized using the TEEB (2010) classification system which covers provisioning, regulating, cultural and support services.

2.2 Inductive use of qualitative case studies

The proposed ES assessment framework was tested in three countries as case studies with aims to evaluate and improve the framework. This is, perhaps, the most popular research method that has proved effective when examining and understanding complex issues in the real world (Easton 2010; Harrison et al. 2017). Case studies can provide a great deal of mostly qualitative data (Easton 2010). Hence, the case study approach was selected to examine the state of ES from bamboo forests in three countries with contrasting landscapes, economy and culture, i.e. Ethiopia, Indonesia and Nepal. In these countries, bamboo has been linked with traditional livelihoods, culture and source of the national economy by connecting it with people from the cradle to the grave. Further, these countries are members of the International Bamboo and Rattan Organisation (INBAR) and are part of the Global Assessment of Bamboo and Rattan (INBAR 2015, 2019b; Ling et al. 2016). For this, we used peer-reviewed papers, published reports and expert opinion for qualitative assessment and ranking. In each case study, ES supply capacity from the bamboo forest was compared with different types of forest. For example, ES supply capacity of the bamboo forest was compared with the ES supply capacity of natural forest and mixed planted forest in Nepal, with mixed planted forest in Indonesia and with woodland and mixed planted forest in Ethiopia.

The authors involved in this study have substantial experience and prior knowledge of the studied countries. Feedback from other stakeholders and agencies has also been incorporated, using expert opinions sought through small workshops organized at each site for experts including women in forestry, agriculture and natural resource management. First, a list of ES from bamboo forests was presented at the workshop. Then the expert team was requested to select 10 key ES at each study site. Thereafter, the ES supply capacity of each land cover type was discussed and the present status of each ES was estimated. Opinions were scaled between 1 and 10, where 1 indicates a very low level and 10 indicates a very high level of ES supply capacity. Participants assigned a value for each ES from 1 to 10 regarding its present status. Participants were allowed to change their ratings at any time. The numerical ratings given by individuals for each ES were entered into an Excel worksheet, analyzed and presented in a radar diagram.

3 Ecosystem services from bamboo forests

3.1 Bamboo forests: Typologies

There exist a wide range of understandings, definitions, and classifications regarding bamboo forests in the literature due to a large number of bamboo species distributed in various parts of the world. Bamboos are regarded as one of the fastest-growing plants on earth (Buckingham 2014) and belong to the Gramineae family and Bambusoideae subfamily Approximately 1662 species of bamboo comprising approximately 121 genera, of which 232 (14%) have been found worldwide beyond their native ranges (Canavan et al. 2017). They can be classified into different categories and managed for various purposes depending upon the characteristics of each type of bamboo forest. Based on the flowering cycle, the bamboos are categorized into three major groups: a) annual flowering bamboos (*Indocalamus wightianus, Ochlandra* spp.); b) sporadic or irregular flowering bamboos (*Chimonobambusa* species, *Dendrocalamus hamiltonii*); and (c) gregarious flowering bamboos (*Bambusa bambos, Bambusa tulda, Dendrocalamus strictus, Thamnocalamus spathiflora*) (Yeasmin et al. 2015). Fundamentally, bamboos are classified according to three different rooting structures: (a) monopodial (diffuse or 'tree-like'); (b) sympodial (clumping), and (c) amphodial (mixed) (Jiang 2007; Buckingham et al. 2014).

Consistent with the characteristics of many other kinds of grass, bamboos grow until they flower, produce seeds and then die. These flowering bamboos are either gregarious (periodic), sporadic (irregular), or both (Shananker et al. 2004; Buckingham et al. 2014). In terms of distribution, bamboos are primarily distributed within tropical and subtropical areas, while there are limited numbers of commercially valuable species from temperate zones, and they are absent from the native flora of Europe (Buckingham et al. 2014).

Furthermore, bamboo forest can also be classified following the classification of planted forest proposed by various scientists (Baral et al. 2016; D'Amato et al. 2017) based on (a) purpose, such as integrated agroforestry at the household level or industrial use; (b) species composition, such as monoculture or mixed species; (c) management objectives such as production or protective functions; (d) intensity of management, such as intensive or low-input management; (e) ownership, such as communal, company, private or public; and (f) scope and scale of operation, such as large and contiguous, or small and fragmented. Although bamboo is classified as a grass, it is woody and tree-like (Jiang 2007; Buckingham et al. 2014), and its characteristics complement tree qualities such as broad distribution, short rotations, low capital and high labor intensity, attractive economic returns, persistent belowground carbon stores, high efficiency of conversion to commercial products, and relatively small investment (Lobovikov et al. 2009).

Bamboo forests can also be broadly categorized into natural bamboo forests and planted bamboo forests. Consequently, the potential for providing various goods and services of both types would differ, depending on the management objectives. For example, bamboo forests managed for edible shoots provide less amount of raw materials and are also likely to supply lower regulating and cultural services. As a result, benefits from these ES (provisioning, regulating and cultural) and their beneficiaries can also differ.

3.2 Revisiting the concept: Defining and classifying the ES

The ES have been defined, interpreted and classified in various ways. In assessing the ES from bamboo forests, we follow the definition and classification proposed by The Economics of

Ecosystems and Biodiversity (TEEB), which defines ES as the direct and indirect contributions of ecosystems to human well-being (TEEB 2010). This definition is also based on the definition of the ES by Millennium Ecosystem Assessment (MEA), but we have used a slight modification, especially as regards the classification of ES. For example, supporting services in MEA is replaced by habitat services, primarily to avoid any double-counting in the ES audit (Baral et al. 2016).

3.3 Major ES provided by bamboo forests

Bamboo forests provide various ES (Shinohara et al. 2014) that generate sociocultural, economic and ecological values and services to local and global stakeholders. They are socioculturally connected with forest and people (e.g. having spiritual significance for local communities), produce raw materials for economic activities with local and industrial applications (e.g. timber, housing, biofuel and crafts) and provide ecological benefits to communities both in and beyond local areas (e.g. carbon stock/sequestration).

The full suite of multiple ES provided by the bamboo forests must be recognized, quantified and valued to give a comprehensive understanding of ES from bamboo forests as all of these values illustrate direct and indirect benefits of bamboo forest ecosystems to human well-being (Table 1).

Table 1. List of ecosystem services (ES) from bamboo forests including description and indicators of each ES, unit of measurement, beneficiary and the scale of ES.

ES	Description of ES	Indicators of ES (Unit of measurement)	Beneficiary/ use	Scale of ES	References
Provisioning services					
Food provision	More than 200 species of bamboos provide food (edible and palatable shoots) from wild and cultivated areas throughout the world	• No. of species producing edible shoots • Amount of shoot production (tonnes ha^{-1} yr^{-1})	Public/Private	O-R	(Lobovikov et al. 2007; Satya et al. 2010; Chongtham et al. 2011; Choudhury et al. 2012; Troya Mera and Xu 2014; Basumatary et al. 2015; Xu et al. 2018)
Forage production	Bamboo supplies forage that is popular for local livestock development everywhere	• Amount of raw material supply (HL ha^{-1} yr^{-1} or tonnes $ha^{-1}yr^{-1}$)	Private	O-R	(Partey et al. 2017)
Timber (construction materials)	Many bamboo species provide construction timber and are used for building raw materials, modern engineered bamboo products, composite panels and boards. Engineered bamboo may well replace steel, wood and concrete in may uses	• No. timber-producing bamboo species • Amount of timber bamboo production (No. of clumps/stands per ha or tonnes $ha^{-1}yr^{-1}$)	Private	O-G	(Lobovikov et al. 2007; Chaowana 2013; Bock 2014; Zea Escamilla and Habert 2014; Yeasmin et al. 2015; Nath et al. 2018; van der Lugt et al. 2018; Ahammad et al. 2019)
Raw materials supply	Bamboo provides raw materials for various types of enterprises from traditional domestic to industrial uses such as different types of bamboo housing, flooring, crafts and fiber for pulp, paper and clothes	• No. bamboo clumps/ stands supplying raw materials • Amount of raw material supply (tonnes $ha^{-1}yr^{-1}$) • Amount of revenue earned (USD $ha^{-1}yr^{-1}$)	Public/Private	O-G	(Lobovikov et al. 2007; Gupta and Kumar 2008; Liese et al. 2015; Yeasmin et al. 2015; Sharma et al. 2016; Dai et al. 2017)

Continued to next page

Table 1. Continue

ES	Description of ES	Indicators of ES (Unit of measurement)	Beneficiary/ use	Scale of ES	References
Bioenergy	Bamboo has traditionally been used as a source of domestic energy and substitute for wood charcoal and mineral coal. Biogas and oil can also be produced from bamboo. Bioenergy can replace fossil fuel and decrease the carbon footprints	• Amount of charcoal (tonnes $ha^{-1}yr^{-1}$) • Amount of oil production (ML $ha^{-1}yr^{-1}$) • Amount of biogas production (e.g. pallets: tonnes $ha^{-1}yr^{-1}$ or electricity generated from bamboo gasification plants: KWh $ha^{-1}yr^{-1}$)	Private	O-R	(Chin et al. 2017; Ladapo et al. 2017; Sharma et al. 2018; Yusuf et al. 2018)
Medicinal resources	Traditional and indigenous medicine derived from bamboo products	• No. of species of medical value • Harvestable amount (tonnes $ha^{-1}yr^{-1}$)	Public/Private	O-G	(Lobovikov et al. 2007; Panee 2015; Yeasmin et al. 2015)
Freshwater provision	Bamboo forests contribute significantly to water source protection and helps in supplying freshwater	• Presence of water bodies such as no. of springs, ponds and streams • Amount of water yield from a particular area (ML $ha^{-1}yr^{-1}$) • No. of projects using water (e.g. watermills, drinking water, irrigation, hydropower plants)	Public/Private	O-L	(Sun et al. 2006; Liu et al. 2018)
Regulating services					
Landscape restoration	Restoration of degraded land through planting bamboo	• Total restored area (ha)	Private/Public	O-R	(Rebelo and Buckingham 2015)
Sediment retention	Bamboo forests stabilize the slope and prevent soil erosion, which improves the condition of land and controls floods and landslides. These phenomena reduce the deposition load downstream	• Rate of downstream siltation (tonnes $ha^{-1}yr^{-1}$)	Public	O-R	(Embaye 2000; Zhou et al. 2005; Tardio et al. 2017, 2018; van der Lugt et al. 2018)
Carbon sequestration	Bamboo grows faster and can sequestrate carbon from the atmosphere at a faster rate than many tree species	• Amount of carbon sequestration annually (tonnes C $ha^{-1}yr^{-1}$ or Mg $ha^{-1}yr^{-1}$) • No. of bamboo clumps/stands per ha	Public	O-G	(Liese 2009; Lobovikov et al. 2009; Song et al. 2011)
Carbon stock	Increased bamboo biomass indicates a higher amount of carbon storage	• Area of bamboo forest (No./ha) • No. of clumps/stands per ha • Amount of carbon stored (tonnes C ha^{-1})	Public	O-G	(Chen et al. 2009; Li et al. 2015; Teng et al. 2016)

ES	Description of ES	Indicators of ES (Unit of measurement)	Beneficiary/ use	Scale of ES	References
Air quality and local climate regulation	Bamboo forests filter the air and remove odors, pollutant gases (nitrogen oxides, ammonia, sulfur dioxide and ozone) and dust particles out of the air through the action of leaves and bark. Improved air quality makes the local climate better	• Total leaf area (TLA) (TLA ha^{-1}) • Amount of pollutants absorbed by the bamboo forest (No. of pollutants)	Public	O-R	(Troy Mera and Xu 2014)
Floods/ landslides control	Bamboo forests control floods and landslides by holding soil particles together through a complex network of roots and rhizomes in the field	• No. of events of landslides/flooding • Amount of soil loss (tonnes $ha^{-1}yr^{-1}$	Public	O-R	(Zhou et al. 2005; Lin et al. 2017; van der Lugt et al. 2018)
Groundwater recharge	The increased area of bamboo forests reduces the runoff rate and assists water percolation	• Water volume availability downstream (ML $ha^{-1}yr^{-1}$)	Public	O-N	(Yeasmin et al. 2015)
Water purification	Bamboo forests induce landscapes to filter out and decompose organic waste introduced into land and water and can assimilate and detoxify compounds through soil and subsoil processes	• Amount of quality/ pure water throughout the year (ML $ha^{-1}yr^{-1}$)	Private/Public	O-N	(Das and Saha 2013)
Moderation of extreme events	Bamboo forests act as a natural buffer, helping to protect against wildlife attacks, strong winds, storms, landslides and other disasters and hence reducing damaging impacts	• Number of extreme events protected against (No. yr^{-1})	Public	O-L	(FAO and INBAR 2018)
Habitat services					
Habitat provision	Bamboo forests provide suitable habitat for different species (flora & fauna)	• No. of endangered species in the forest	Public	O-N	(Coggins 2000; Linderman et al. 2005; Yeasmin et al. 2015)
Maintenance of biological diversity	Bamboo forests maintain and/or enhance biodiversity by promoting different varieties of bamboo species and providing habitat for wild animals	• No. of species, ecosystems and genetic diversity	Public	O-G	(Sharma and Nirmala 2015; Yeasmin et al. 2015)
Cultural services					
Landscape beauty	Bamboo forests create landscape beautification by preventing land degradation and enhancing landscape restoration and greenery	• Area of landscape covered by bamboo forest (area in ha) • No. of visitors appreciating the views of the landscape covered by bamboo forest	Public	O-R	(Gang 2018; van der Lugt et al. 2018)

Continued to next page

Table 1. Continue

ES	Description of ES	Indicators of ES (Unit of measurement)	Beneficiary/ use	Scale of ES	References
Recreation and ecotourism	Bamboo forests provide opportunities for ecotourism and recreational activities through the promotion of greenery and landscape beautification	• No. of recreation sites • No. of visitors per year	Public/Private	O-R	(Troy Mera and Xu 2014)
Cultural/ religious values	Bamboo materials have been used from the cradle to the grave in many countries because of religious and cultural values associated with bamboo	• No. of cultural and religious events associated with bamboo	Public	O-L	(van der Lugt et al. 2018)

Note: Ecosystem services are further classified into provisioning, regulating, cultural, and habitat services based on The Economics of Ecosystem and Biodiversity (TEEB 2010) ES categories. The scale of ES includes 'O' on-site (in situ delivery), 'L' local (offsite, 100 m to 10 km), 'R' regional (10–1000 km), 'G' global (>1000 km). Key to scale of users: 'O' – on-site users (who live within bamboo and adjoining forests and have protected and managed ES), 'L' – local users (off-site but living within the forest surroundings up to 10 km distance from the bamboo forests and who have also protected and managed bamboo for ES; 'R' – regional users (who live between 10 km and 1000 km downstream of the bamboo forests and in nearby cities, but have not contributed to resource management; 'N' – national users within a country (people living in the country of the study's landscape (Nepal) who also have not contributed to resource management); 'G' – global users (people worldwide who have not contributed to resource management, and do not know where the landscape is located). Key to measurement units: 'no.' – number; 'ML' – megaliters; 'HL' – head load (30 kg); 'tonnes' – metric tonnes (1000 kg); 'ha' – hectare; 'ha^{-1}' – per hectare; 'yr–1' – per year.

4 Bamboo forests' ES compared with major LULC types

Studies on the assessment of ES from both natural forests and planted forests (Gamfeldt et al. 2013; Hayha et al. 2015; Miura et al. 2015; Baral et al. 2016) and agricultural land (Kroeger and Casey 2007; Power 2010; Zhang et al. 2007) are well documented in the literature. However, we found no similar studies on assessing the ES of bamboo forests as such. Bamboo forests can be either stand-alone or part of both natural and planted forests, or even be on agricultural land, making the assessment of ES from these forests more complicated. The literature review indicated that bamboo forests provide the same number of ES compared to land use categories such as forests, grasslands and agricultural land.

Table 2 shows the significance of ES provided by bamboo forests by comparing the ES supply capacity of bamboo forests vis-a-vis other forest types such as natural forests, degraded natural forests, planted forests, grasslands and agricultural lands based on qualitative comparisons from the literature. The actual measurement and quantification of ES in different land use categories is required for a quantitative comparison, which takes a long time and enormous resources and is beyond the scope of this paper. Still, we believe that taking stock of major ES from bamboo forests and comparing them with other land use categories provides insight into the comparative advantage of a bamboo forest and will help in planning and managing interventions as regards bamboo forests in the future. The bamboo forest, for example, is more effective in slope stabilization, and soil erosion control compared with other land-use practices and works as a buffer against extreme events such as floods, storms and landslides (Table 2).

At a particular point of time, both natural and planted forests supply a higher amount of raw/construction materials as a provisioning service than do bamboo forests. In contrast, bamboo forests supply comparatively more biomass because bamboo has a shorter rotation (3–6 years) and a higher tree density (sometimes more than 10,000 culms per ha) than other tree species. Thus, that they can provide many times the biomass and raw materials of tree species grown either in natural or planted forests, even within a single rotation period. One study shows that a plantation of giant bamboo (*Dendrocalamus giganteus*) with 200 bamboo clumps per hectare can give an annual yield of about 2000 poles with a biomass of as much as 50 tonnes (Ramanayake 2017). Similarly, it seems to have a higher production capacity of certain provisioning services such as food provision, forage production, timber and other construction materials, bioenergy and medicinal resources than that of natural forests.

When it comes to regulating services such as landscape restoration through the processes of sediment retention, floods and landslide control, moderation of extreme events, carbon sequestration and carbon stock of the bamboo forests were found to be higher than those of natural and planted forests (Yiping et al. 2010; Yen and Lee 2011; Thokchom and Yadava 2015; Yuen et al. 2017; FAO and INBAR 2018). Similarly, bamboo forests have a higher capacity for groundwater recharge and a better local capacity to purify water than do natural forests. This is because a dense canopy with mixed and diverse vegetation types, particularly of natural forest, consume a higher amount of water than do forests with intermediate canopy cover (Ilstedt et al. 2016). However, the rate of ES supply depends on the type of bamboo forest, where natural bamboo forests have a higher capacity than do planted monoculture bamboo forests (Yiping et al. 2010). It is interesting to note that, except for natural forests, almost all of these regulating services were found to be higher in bamboo forests than in degraded forests, planted forests, grasslands and agricultural lands. As regards habitat provision, bamboo forests showed a higher capacity than planted forests and agricultural land, but lower capacity when compared with natural forests. Similarly, regarding cultural services, especially landscape beauty and ecotourism, bamboo forests had higher ES than degraded natural forests, grasslands and agricultural land.

There is a trade-off between ES from bamboo forests that depend on management objectives. For example, if a bamboo forest is managed for the shoots (food provision), they are harvested within 1–2 months, which can trigger a negative impact on the production of timber and other raw materials. This phenomenon can also cause a negative impact on many other regulating services such as carbon stocks, carbon sequestration, and sediment retention.

Table 2. Qualitative comparison of ecosystem services (ES) from bamboo forests relative to natural forests, planted forests, grasslands and agricultural lands.

Ecosystem services	Capacity of ES provision supplied by natural bamboo forests in comparison with				
	Natural forests	Degraded forests	Planted forests	Grasslands	Agricultural lands
Provisioning services					
Food provision	L	H	H	H	L
Forage production	L	L	H	L	H
Timber (construction materials)	L	H	L	H	H
Raw materials (except timber)	L	H	H	H	H
Bioenergy (biomass)	H	H	L	H	H
Freshwater provision	H	H	?	L	L
Regulating services					
Landscape restoration	H	H	H	H	H
Sediment retention	H	H	H	H	H
Carbon sequestration	H	H	H	H	H
Carbon stocks	L	H	H	H	H
Air quality and local climate regulation	L	H	?	H	H
Flood/landslide control	H	H	H	H	H
Groundwater recharge	H	L	?	H	H
Water purification	L	H	H	H	H
Moderation of extreme events	H	H	H	H	H
Habitat services					
Habitat provision	L	H	H	?	H
Maintenance of biological diversity	L	?	H	?	H
Cultural services					
Landscape beauty and recreation	L	H	L	H	H
Recreation and ecotourism	L	H	H	H	H
Cultural/religious values	H	H	H	H	H

Note: Actual provision of ES is determined by several factors including bamboo species, bamboo forest types (natural vs planted, pure vs mixed, and monopodial vs sympodial), management objectives, geographic distribution, site conditions, and management intervention. Thus, the examples given here are only indicative of identifying and comparing the ES from natural bamboo forests (mainly monopodial) in relation to other land cover categories. The tentative comparison is carried out whether the ES from the bamboo forest is higher (H), similar (S), lower (L) and difficult to define (?) than ES from other land uses. Adapted from several studies (de Groot and van der Meer 2010; Baral et al. 2013, 2014; Brockerhoff et al. 2013; Ferraz et al. 2013).

5 Framework for assessing ES from bamboo forests

A comprehensive framework is a valuable and rational tool to apply to identifying important processes (Fisher et al. 2014). Studies of the ES from bamboo forests have tended to be general, and hence, context-specific analysis is essential. However, incorporating more contextual information will often mean dealing with higher levels of complexity (Fisher et al. 2014). Thus, any framework should attempt to understand the parts of complex wholes, methodically dividing the complexity, rather than artificially simplifying it (Ostrom 2009).

As bamboo forests provide many ES beyond food and raw materials production, an improved evidence base is required for effective planning and management of ES from bamboo forests (Yiping et al. 2010; Yuen et al. 2017). Studies show that bamboo forests supply high-level ES values and are more appropriate for soil erosion control and other impacts than are natural forests (Song et al. 2011). In this context, precise ES assessment at different spatial and temporal scales is required for further investment in bamboo forests. However, there has been little focus on the assessment of ES from bamboo forests due to a lack of suitable local frameworks, methods and evaluation tools (Baral et al. 2014, 2016; Paudyal et al. 2015, 2019). To resolve the issue, a common framework for ES assessment from bamboo forests is extremely important. Such a framework can be based on various frameworks used to assess ES from other forests, e.g. planted forests (Baral et al. 2016), community forests (Paudyal et al. 2015), forest management units (Wangchuk et al. 2019) and mountain forests (Baral et al. 2017), and can be modified to fit with bamboo forests.

Figure 2 shows a proposed diagrammatic representation of the framework for the assessment of ES from bamboo forests. The framework follows an expanded explanation with examples from diverse geographies that are chosen solely for their illustrative capacity. Conceptually, the framework consists of three components: (i) bamboo ecology (silviculture and management) (Figure 2a); (ii) ES provision classified using TEEB categories (Figure 2b); and (iii) approaches to assessing ES from bamboo forests (Figure 2c). This section details each component.

The bamboo forest ecosystem forms the foundation of the framework, comprising the set of biophysical processes and structures producing ES that are altered by the silviculture and management of bamboo forests. It includes the scope of the assessment as well as identifies the objectives and process of the assessment including key questions such as underlying objectives, relevant actors, potential ES flows, adequate budget, data availability, suitable approaches and clarification of potential roles and responsibilities of different stakeholders (Rosenthal et al. 2014).

The key ES provided by bamboo forests are marked off using one of the ES classification systems and prioritized based on stakeholders' choice, management objectives and types of bamboo forests. Many studies have recognized that ecosystem benefits derived from bamboo forests could be distinguished based on the different services provided; i.e. (i) provisioning services which include tangible benefits such as raw materials, pulp, food and biomass-based energy; (ii) regulating services, which would bring benefits in the form of increased water infiltration, reduced erosion and climate regulation; (iii) habitat services that bring benefits to wildlife habitat and genetic diversity; and (iv) cultural services including recreation, ecotourism, education and spiritual experiences.

The connection between ecology and management of bamboo, ecosystem benefits and approaches and tools for assessing ES from bamboo forests need to be illustrated because ES are strongly influenced by the silviculture and management methods. Further, beneficiaries of ES are determined because ES values depend on beneficiaries who vary across local and wider scales (Paudyal et al. 2018b) while enabling both qualitative and quantitative assessments of ES sources and sinks. Further, the framework allows users to design a special approach, process and methods to suit the particular needs of local people, landscape and the predetermined objectives of the bamboo forests depending on available time, data and resources. Finally, the framework suggests that ES provision is analyzed, synthesized and communicated to relevant stakeholders in an appropriate manner that is crucial in the application of the framework in any ES assessment from bamboo forests.

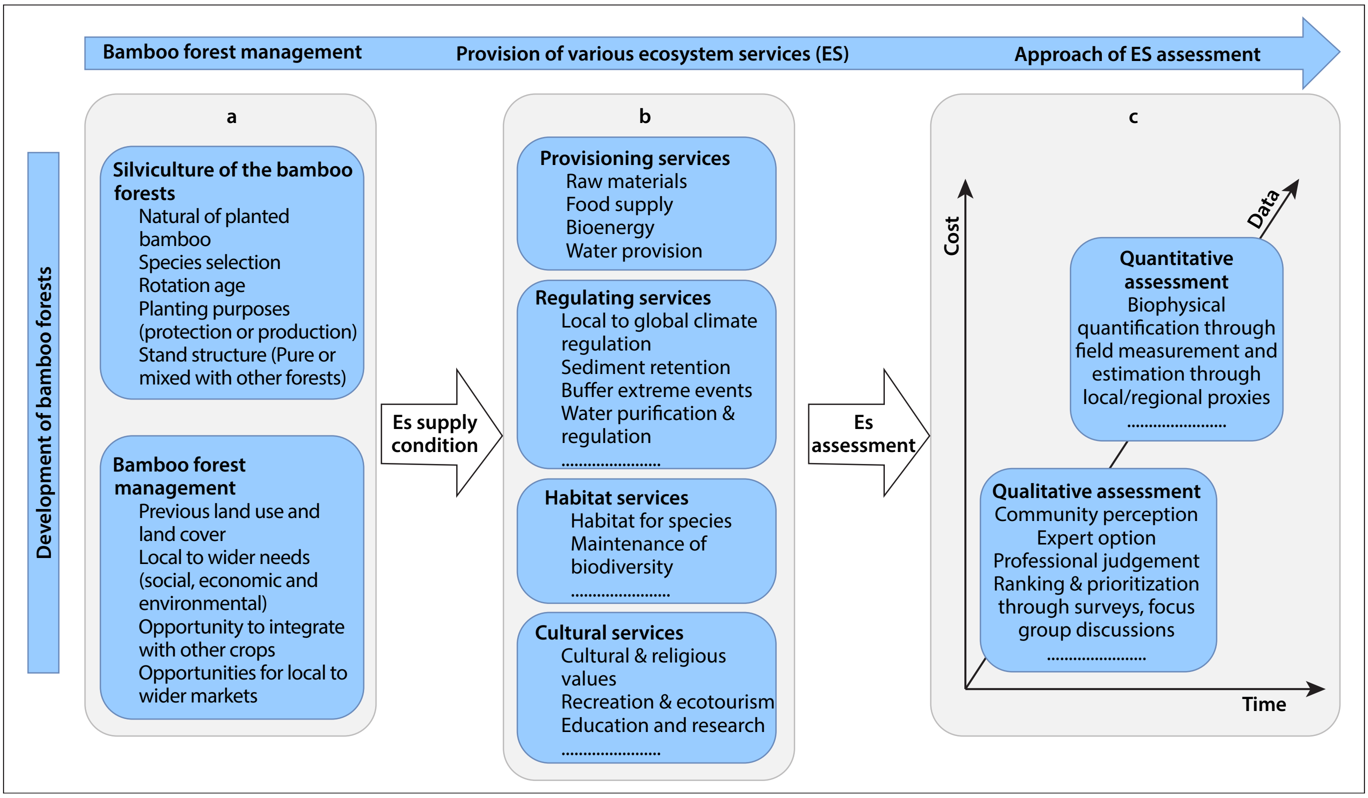

Figure 2. A framework for assessing ecosystem services (ES) from bamboo forests. The framework consists of three main components: (a) silviculture and management of bamboo forests that influence the quality of bamboo forests and supply of ES; (b) potential supply of ES based on TEEB (2010) classification system; and (c) the main approach of assessing ES from bamboo forests, which is associated with cost, time and data. The selection of approach/method and the quality assessment of ES depend on the available cost, time and data requirements for the assessment.

6 Methods and tools for assessing ES from bamboo forests

Several tools have been developed to suit various purposes and scales of assessment. These tools differ in terms of data requirements, technical knowledge and software requirement, assessment types, and whether the outputs are spatially explicit or not. For example, Baral et al. (2017) provide a non-exhaustive list of tools for assessing ES from a mountain ecosystem and categorized them into three groups: (1) stakeholder analysis, (2) market analysis, and (3) modeling analysis. These tools are equally relevant to and useful for assessing ES from bamboo forests. The stakeholder analysis includes focus group discussion, expert consultation and participatory mapping and can provide firsthand qualitative and quantitative information on the specific ES from bamboo forests (e.g. Paudyal et al. 2015; Bhatta et al. 2016; Baral et al. 2017). As the ES can vary in time and space, the stakeholder analysis is critical to identifying the ES available to the different levels of users. These users can be local, regional or global. They can specify ES benefits, such as the cultural, aesthetic, recreational, tourism, educational and cultural/religious values to these users. The stakeholders can also provide qualitative and quantitative data (at least in comparative terms) that can be used in modeling tools to determine the change in the availability of ES from bamboo forests. To enhance local knowledge of the ecosystem over time and space, the participatory mapping technique can generate spatial maps of ES from bamboo forests. However, it is crucial to triangulate information from other sources to enhance the confidence in the data quality and to reduce uncertainty.

Table 3. A comparison of tools for assessing ecosystem services (ES) from bamboo forests.

Assessment tools	Assessment type	Analysis types	Scale	Software requirement	Specialized knowledge required	Spatial mapping capacity
Toolkit for Ecosystem Service Site-based Assessment (TESSA)	Quantitative/ Qualitative	Framework and method	Site-level	No	High	No
Integrated Valuation of Ecosystem Services and Trade-offs Tool (InVEST Tool)	Quantitative	Modeling	Watershed/ Landscape/ Regional	Yes (InVEST Tool)	High	Yes
Artificial Intelligence for Ecosystem Services (ARIES)	Quantitative	Modeling	Watershed/ Landscape/ Regional	Yes (Web-based or standalone)	Low–High	Yes
Multiscale Integrated Model of Ecosystem Services (MIMES)	Quantitative	Modeling	Landscape	Yes (SMILE software)	High	Yes
Co$ting Nature	Quantitative	Modeling	Landscape	Yes (Web-based)	High	Yes
Spatial analysis tool in ArcGIS software	Quantitative/ Qualitative	Modeling	Watershed/ Landscape/ Regional	Yes (ArcGIS software)	High	Yes

Note: The user should make an informed choice of the tool for assessing ES from bamboo forests based on the scope of the assessment, scale and resources availability (software and expertise).

Source: Adapted from https://www.birdlife.org/worldwide/science/Toolkit_for_Ecosystem_Service_Site-Based_Assessment/How_TESSA_is_different_from_other_tools

The economic valuation of the ES has become a widely used approach to demonstrate the monetary values of our environment through accounting for all goods and services provided to human beings (MEA 2005; TEEB 2010; Costanza et al. 2014). This approach is considered crucial for raising awareness on the significance of the ES from the environment, and for environmental policy formulation and decision-making (Costanza et al. 2014) and also assists in assessing the trade-offs of ES under different land-use scenarios (Sharma et al. 2018). The economic valuation of ES from bamboo forests can apply the three methods used by Baral et al. (2017) to assess a mountain ecosystem. These methods include: 1) stated-preference technique, 2) revealed-preference technique, and 3) benefit transfer. However, the economic valuation of ES is challenging due to the risk of double accounting, interaction and interdependence of the ES, and the difficulties around monetizing the sociocultural and habitat values. The user should choose the best method based on the availability and reliability of the available data on disaggregated ES.

In addition, several tools for assessing ES have been developed, which can be used to evaluate ES from bamboo forests. Baral et al. (2017) listed some of the popular tools for ES assessment as: (1) Toolkit for Ecosystem Service Site-based Assessment (TESSA), (2) Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) Tool, (3) Artificial Intelligence for Ecosystem Services (ARIES), and (4) Multi-scale Integrated Models of Ecosystem Services. Table 3 compares these tools and two additional tools, i.e. Co$ting Nature and Spatial Analysis Tool in ArcGIS software for their characteristics such as assessment types, analysis types, scale, software and specialized knowledge requirement and spatial mapping capacity.

7 Case studies – Ecosystem services associated with bamboo forests

This section presents the case studies from Asia and Africa demonstrating that bamboo forests offer important ES in comparison with other forest ecosystems, and that they are crucially important (Figure 3). Among 10 locally relevant ES selected for comparison, three ES are under the provisioning services (e.g. food supply, raw materials and freshwater provision), and five from regulating services (e.g. carbon sequestration, sediment retention, flood/landslides control, protection from extreme events and water regulation). Similarly, habitat provision and cultural belief and religious values were selected. Different forest types were chosen at three sites so that the ES supply from bamboo forests could be compared. The research results from the case studies rationalize an expansion of bamboo plantations for economic, social and ecological benefits.

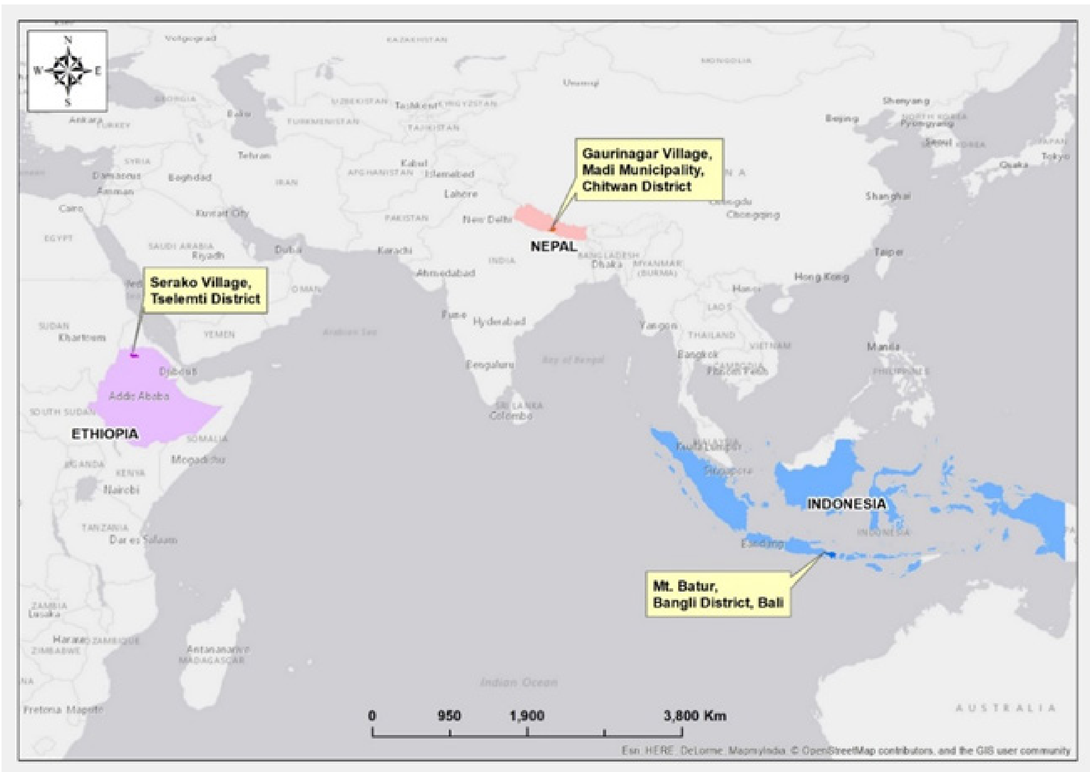

Figure 3. Location of case study sites in Nepal, Indonesia and Ethiopia.

7.1 Case 1: Gaurinagar village, Chitwan District, Nepal

Bamboo forests cover an estimated 63,000 ha in Nepal, and 60% are found in natural forests (ANSAB 2018). However, bamboo plantation practices on private land are also common in Nepal. Nepal is home to 12 genera and more than 53 species of bamboo, where seven species are endemic (ANSAB 2018). Bamboo forests with a growing stock of around 15 million m^3 supply three million culms annually, which are mostly consumed locally. For centuries, bamboos have been considered a key source of income generation and are inextricably intertwined with indigenous culture and local knowledge.

We take a case from Gaurinagar village of Madi Municipality, Chitwan (Figure 4). The village was completely inundated in 2010 due to flooding of the Rui River that washed away river banks causing significant property damage. Tonnes of silt and sand were deposited and made land unproductive. To reverse the situation, the local community planted 10,000 bamboo seedlings and created a beautiful bamboo forest (FAO and INBAR 2018). This helped the river return to its original course in Gaurinagar and stabilized the river bank and sediment retention, which rehabilitated 700 ha of land belonging to 70 households (FAO and INBAR 2018). A big chunk of natural forest (a part of the Chitwan National Park) is located at the northern side of the village on the other side of the Rui River, to which people have limited access. There is a nearby planted forest where villagers get timber, firewood and other forest products.

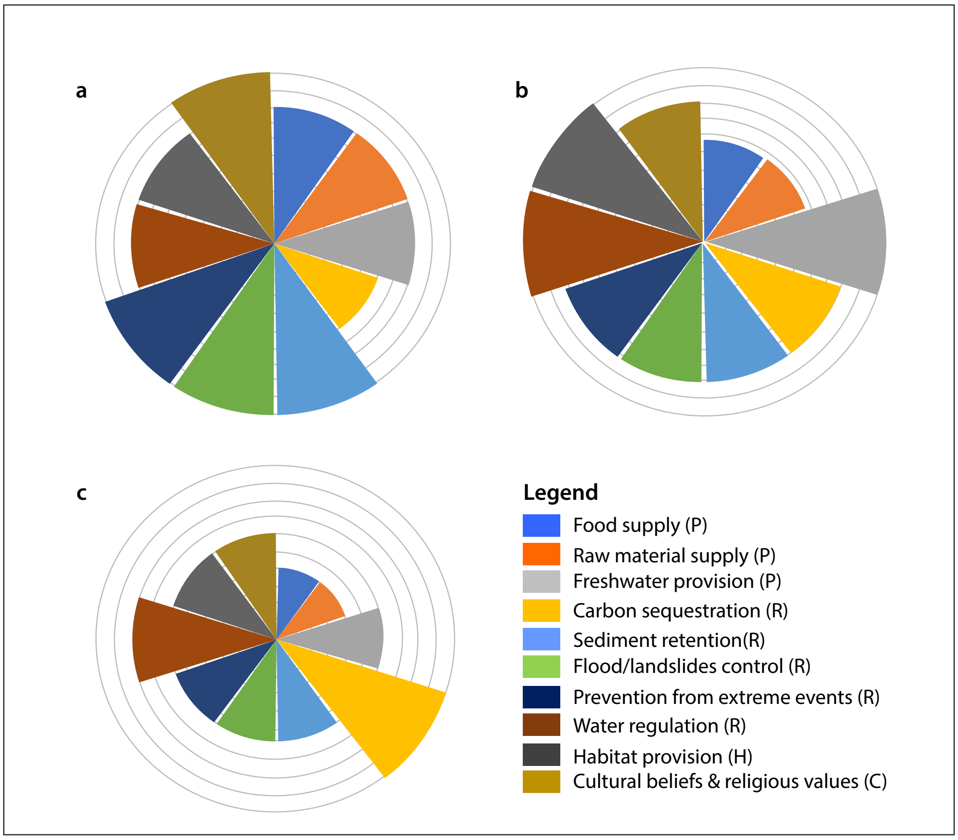

Figure 4. Comparisons of ecosystem service (ES) of various forest types in Gaurinagar assessed qualitatively. These are expressed using Likert scales of 1 to 10, where 1 (the innermost circle) represents the lowest level of ES supply, and 10 (the outermost circle) represents the highest level. (a) Bamboo forests, (b) natural forests, and (c) mixed-planted forest. Abbreviations: ‘P’– provisioning services, R – regulating services, H – habitat services, C – cultural services.

These three forest types supply different ES to the villages. While bamboos are planted to protect villages from flood and sediment, local communities also receive food, raw materials and other ES that are comparable with ES supplied by natural and planted forests. Interestingly, the bamboo has also served as wildlife fencing, a sustainable and cost-effective approach to reducing human–wildlife conflict. The bamboo forest, for instance, provides higher ES as regards sediment retention, flood control and religious and cultural values compared to other forest types. On the other hand, natural forest supplied a higher amount of ES regarding water regulation, habitat and freshwater provisions than did bamboo forest and forest plantation. The natural forest, due to its diverse species composition makes it a suitable wildlife habitat. Here, species diversity contributed to water regulation and the provision of freshwater. The bamboo forest also contributed significantly to water regulation. In contrast; the bamboo forest had a lower potential for carbon sequestration in comparison with the planted and natural forests. In line with results of many studies (e.g. Ly et al. 2012; Yuen et al. 2017), experts opined that the bamboo forest is still young and clumps are not fully grown; thus, they capture less carbon than mature bamboo and natural forests.

7.2 Case 2: Mount Batur, Bali, Indonesia

Bamboo forests cover 2.1 million ha (2% of 93.9 million ha forest land) in Indonesia and is naturally widespread in 30 provinces. Some 135 bamboo species have been recorded, and 70 of them are documented as endemic to Indonesia (Widjaja 1998; MoEF 2018). We take a case from Mt Batur located in Bangli District, Bali Province (Figure 3). The topography of the area includes mountainous, hilly, undulating and flat land and generally receives 2638 mm rainfall per year. The mountains beyond Mt. Batur contain water sources important for the coastal communities of Bali. Bamboo forests extend over about 6000 ha out of 11,536 ha of total forest area. Bamboo has been intricately linked historically with rural livelihoods for use in traditional ceremonies and livelihoods, including as food, construction, musical instrument, handicrafts, furniture and energy (Sujarwo 2018). In addition, there are plenty of Acacia and teak plantations in Mt Batur that supply various raw materials to the local people and industry (MoEF 2013). As bamboo and planted forests provide raw materials and other benefits, the comparison of ES supplies from both types of forests can provide valuable insights for forest management in Mt Batur.

Figure 5 illustrates the various types of ES from bamboo and planted forests in Mt Batur. The experts opined that bamboo forests supplied a higher amount of ES in most cases than did planted forests, except for raw materials. The study shows that planted forest provides a higher amount of construction timber (Samsudin 2016) and raw materials for the pulp and paper industries (MoEF 2013). In contrast, bamboo forest provides higher amounts of food than planted forest, in line with the findings of other studies. One study reveals that farmers receives USD 420–700 per hectare from selling shoots to the market. Freshwater provision is also high from bamboo forest due to lower consumption than in planted forest (Widiarti, 2017). Balinese culture beliefs are that old-growth bamboo forests are vital in water production (Arinasa and Peneng 2013; Sujarwo 2015). Similarly, bamboo forest regulates water efficiency better than planted forest. Corroborating these beliefs, one study indicates that bamboo forests store about 90% of rainfall, while many tree species store only 35–40% (Raka et al. 2011).

Bamboo has been used in upstream soil stabilization and is perceived to retain more soil than planted forest. Bamboo's sympodial rhizome root system is ideal for watershed protection, halting land degradation and reducing the erosion rate significantly (Mentari et al. 2018) in comparison with planted forest because planted forests cause high erosion during the harvesting period (Lathifah and Yunianto 2013). Further, this study shows that carbon sequestration capacity of both forests is very similar, and also corroborates the results of many previous studies conducted in Indonesia. For example, bamboo forests and planted forests store carbon in the range of 94–392 tCha–1 and 85–429 tCha–1, respectively (van der Lugt et al. 2018). In contrast, another study finds that bamboo clumps in Bali store about 43.67 tCha–1 (Sujarwo 2016), while fast-growing *Acacia* plantations in West Java store only about 25.4 tCha–1 (Purwitasari 2011) while slow-growing teak in Central Java stores 12–144 tCha–1 with a rotational period of up to 80 years (Lestari 2011).

In addition, bamboo in the study area of Mt. Batur has been used in upstream soil stabilization, water quality improvement, climate change and flood/landslides risk mitigation and raw materials supply for domestic use. Additionally, it also contributes to the promotion of tourism with handicrafts production and restoration of degraded land. Bamboo has been used traditionally by the Balinese community for various purposes, including livelihoods, building construction, medicine, music, and water and soil conservation.

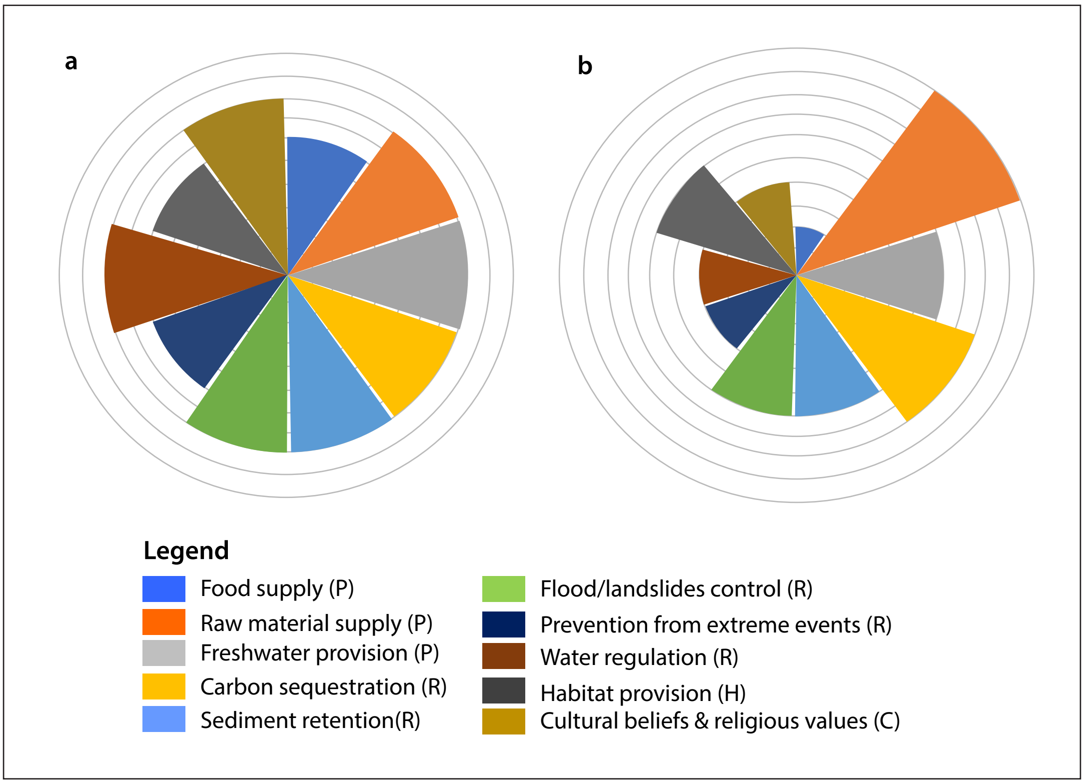

Figure 5. Key ecosystem services (ES) of bamboo and planted forests at Mt Batur assessed qualitatively. These are expressed using a Likert scale from 1 to 10, where 1 (the innermost circle) represents the lowest level, and 10 (the outermost circle) represents the highest level of ES supply: (a) bamboo forests, (b) planted forests.

Research suggests that fast-growing bamboo could provide multiple ES linked with the community's culture and traditions. Bamboo ES are valuable to Balinese tourism, which generates incentives for local government. It draws the attention of the public and private sectors with their investment in landscape restoration activities and could be linked with the payments for ecosystem services (**PES**) mechanism (e.g., Paudyal et al. 2018a).

7.1 Case 3: Sareko Tibia (village) in Northern Ethiopia

Forest in Ethiopia covers 15.7% (17.35 million ha) of the total area (NSDP 2018). Ethiopia is known for its diverse flora and fauna (Bane et al. 2007) including two indigenous bamboo species, highland bamboo *(Arundinaria alpine)* and savanna bamboo *(Oxytenanthera abyssinica)* (Embaye 2003). These two species extend over one million ha, comprising 8.2% of the total forest area of the country (Mulatu and Kindu 2016). These species grow naturally six regions and are confined to the western side of the central highlands in moist and wet lowland agro-climatic zones at 500–1600 m altitude (Bekele-Tesemma 2007; ; Tesfaye 2006; Mulatu and Kindu 2016).

The case study was conducted at *Serako* Peasant Association (Tabia), Tselemti District, North-West Tigray, Ethiopia (Figure 3), situated at 1350 m elevation above sea level (TARI 2002). The studied *Tabia* has a total area of 4710 ha with 800 ha cultivated land, and 3910 ha noncultivated land including 2130 ha of woodlands and planted forests (WARD 2014). In the past, bamboo forests were close to extinction in natural forests due to deforestation and forest degradation for agricultural expansion and the demand of fuelwood and timber in the villages. In the 1990s, more than 100 smallholders innovatively planted savanna bamboo within an agroforestry system using a rhizome offset method from the natural forest (Darcha et al. 2014), and have developed bamboo forests in the villages for multiple benefits (Figure 6). The natural forest also changed to woodland due to severe degradation. Trees were also planted at many sites to ensure land restoration and fulfill local demand for forest products.

Figure 6. Savanna bamboo planted as a homestead agroforestry system in Tselemti District.

While bamboos have been domesticated to save them from complete extinction in the natural forests, local communities also receive raw materials and other ES from bamboo. Although various forests types supplied different levels of ES, the bamboo forests supply a higher level of ES than planted forests, but less than the woodlands (Figure 7). Woodlands supply all 10 ES in a balanced way, but bamboo and planted forest supply only a few ES at higher levels. Experts state that bamboo forest is effective in controlling flood/landslides, moderating extreme events such as wind and storms, and regulating water. Corroborating our results, one study shows that the soil conservation efficiency of the bamboo forest is 99% compared with bare land (Nune et al. 2013) because bamboo forests are characterized by a complex network of rhizome–root systems which hold soil effectively, prevent soil erosion, control gullies and promote water percolation (Embaye 2003; Desalegn and Tadesse 2015). Our study also shows bamboo forest is highly preferred for fuelwood, traditional house construction and charcoal-making (but not as raw material for timber production) due to its fast-growing habit and because multiple culms in a clump can be used on degraded land (Embaye 2003; Mekonnen et al. 2014). In line with our study result, a few studies indicate that planted forest is better for raw materials, especially timber production, because of its higher timber biomass: the biomass of planted and bamboo forests is 178.8 m^3ha^{-1} and 109 m^3ha^{-1}, respectively, from the same area (Nune et al. 2013).

In contrast, woodland forests supply a higher amount of forage, that corroborates the results of other studies. Total fodder yield of woodland is more than one million tonnes, while bamboo supply is only 52,017 tonnes annually (Nune et al. 2013). Similarly, mixed-planted forests provide a higher amount of carbon stock and carbon sequestration. In line with the result, the existing study shows that the total carbon stock of planted forests is 61.52 million tonnes while bamboo forests have only 53 million tonnes from the same area (Moges et al. 2010). However, the accumulation of carbon in bamboo over a short period makes it preferable for different carbon credit projects and benefits communities' use of bamboo species in environmental rehabilitation.

In conclusion, despite the vast resource provided by bamboos in Ethiopia, the socioeconomic contribution to local livelihood improvement remains minimal because it is only used domestically. Because bamboo is a fast-growing species and adapts to the harsh environment, people prefer it. Thus, projects are likely to pay more attention at it for the rehabilitation of degraded areas, and for construction, fodder, firewood and charcoal, carbon sequestration and waste purification.

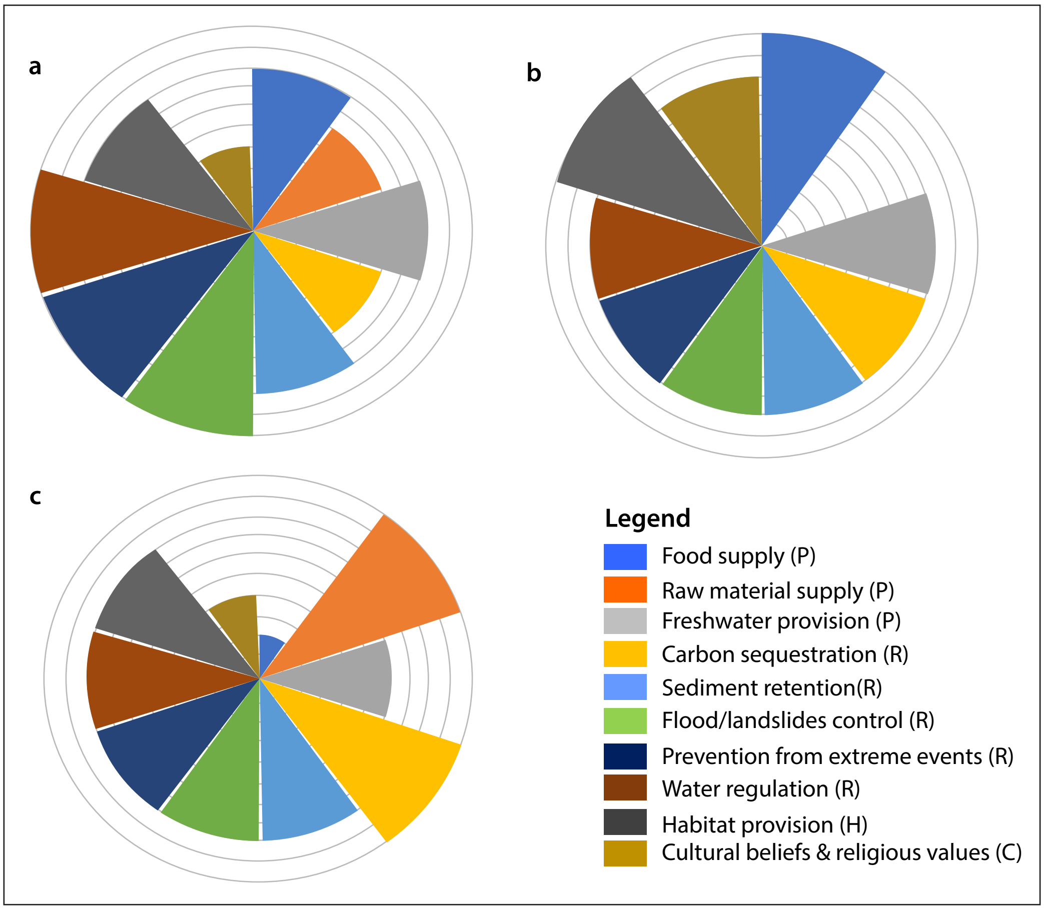

Figure 7. Comparisons of ecosystem services (ES) of various forest types in Sareko village assessed qualitatively. These are expressed using a Likert scale from 1 to 10, where 1 (the innermost ring) represents the lowest level of ES supply, and 10 (the outermost ring) represents the highest level of ES supply: (a) bamboo forests, (b) woodlands, and (c) mixed-planted forest.

7.2 Synthesis of three cases

The case studies presented above offer a wide range of similarities and differences in supplying bamboo ES from across Africa and Asia. Cases confirm that the primary purpose of bamboo plantations is for the restoration of degraded land and supplying raw materials for subsistence livelihoods at each site. However, bamboo forest has mostly unrealized potential to provide other significant ES to society at local to global scales. Although there is diversity, there are several clear findings from the case studies. The study shows that bamboo forests provide many ES besides the raw materials that other forest types supply. In general, bamboo forests offer higher amounts of ES than do degraded forest and planted forest. Only natural forest supplies some of the ES more than bamboo forests do.

In a comparison of ES from bamboo forests, soil/flood control, sediment retention, protection of village from extremes, carbon sequestration and carbon stock are considered highly preferable ES at three sites (Table 4). Similarly, improved water regulation and freshwater provision are also considered critical bamboo ES of the studied sites. In Nepal, bamboo has been planted to control floods from the Rui River and provide natural fencing to prevent wild animals entering the village from the adjoining Chitwan National Park. Forage supply is considered important in Ethiopia, while Nepal and Indonesia are highly connected culturally with bamboo forest. Research shows that bamboo has been planted for prevention from extreme events in Nepal and Ethiopia. In contrast, food supply, prevention from extreme events and habitat provision in Indonesia and carbon sequestration in Nepal are given a little priority in the management of bamboo forests.

Table 4. Capacity of ecosystem services (ES) supply of bamboo forests. These are expressed from 1 to 10 on a Likert scale, where 1 represents the lowest level of ES supply, and 10 represents the highest level of ES supply capacity.

Ecosystem services	Relative availability of ES supply capacity from bamboo forests at the case study sites		
	Gaurinagar, Nepal	Mt Batur, Bali, Indonesia	Sareko village, Northern Ethiopia
Food supply	8	6	–
Raw material supply	8	8	6
Freshwater provision	8	8	8
Carbon sequestration	6	8	6
Sediment retention	10	8	8
Flood/Landslides control	10	8	10
Prevention of extreme events	10	6	10
Water regulation	8	8	10
Habitat provision	8	6	8
Cultural beliefs and religious values	10	8	4

There are several lessons that can be drawn from these examples and are useful for assessment and valuation of bamboo ES. These cases confirm the role of the bamboo forest in providing key ES with local and global benefits. Expanding bamboo plantations can be one of the cheapest ways of reversing land degradation and is appropriate for meeting global restoration goals. At the same time, bamboo provides a variety of ES comparable with other forest types. Most importantly, bamboo is considered an alternative to forest trees globally and can provide raw material domestically and industrially at cheaper cost. This study reveals that bamboo would be a better replacement in plantation forestry (as opposed to planting other trees species) if we could not promote natural forests. Another important lesson is that bamboo is a fast-growing species and adapts to harsh environments, people prefer it and projects are likely to pay more attention at it for the rehabilitation of degraded area. It also provides benefits to the community of equally or sometimes higher value than the natural and planted forests, such as for construction materials, fodder, food, sediment retention, carbon sequestration and water regulation. Given the potential for bamboo to act as an essential carbon sink, there is a need for greater integration of bamboo into national and international policies and mechanisms aimed at managing the effects of global climate change. Bamboo is vital for landscape restoration in providing incentives for the participation of local communities.

8 Final remarks

The proposed framework helps to identify and assess ES provided by bamboo forests. The framework is divided into three components, viz. bamboo forest management, provision of various ES and approaches to ES assessment. This allows us to assess the management status of bamboo forests and qualitatively and quantitatively assess the corresponding ES. Given the significant potential of bamboo forests in providing multiple ES, the framework provides a broad outline and guidance on ES assessment from bamboo forests.

This framework may not be equally applicable to all bamboo forests in different localities and contexts. Hence, the framework requires testing across diverse geographic locations. Unlike the similar framework prepared for monoculture/planted pine forests, it involves more complexity in applying it in the field. Bamboo forests are rarely found as standalone forests; rather, they are widely distributed either in forests or on agricultural land in combination with other trees species or agricultural crops. These forests might be either planted bamboo forest or naturally grown bamboo forests. Therefore, proper care should be taken while applying the framework in the field; otherwise, it might create issues of double-counting while assessing the bamboo forests. The complexity of bamboo forests in various locations and associated ES have also been illustrated in the case studies from Nepal, Indonesia and Ethiopia in earlier sections.

While acknowledging the complexity associated with ES assessment of bamboo forests, we reiterate that the guiding framework provided here is intended to help enable users design an appropriate assessment approach that is suitable for particular situations, contexts and localities. Furthermore, this framework is also expected to serve as a basis for participatory stakeholder engagement and discussion, and to promote transparency while assessing ES and preparing a management plan for bamboo forests. Effective planning and management right from the beginning while taking into account management objectives, local needs, land-use practices, adaptive management and stakeholder engagement are key to the success of bamboo forests so that we can harness an optimum level of ES and reduce and associated negative impacts. For example, if a massive bamboo plantation is planted in a productive agriculture field, it will reduce the land available for a food crop, agriculture productivity, and consequently lead to the problem of food insecurity because agricultural land provides more food than do bamboo forests. For this, the framework is expected to guide planners and managers for the assessment and management of ES of bamboo forests both at local and broad landscape levels.

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Bamboo is well known for supporting people's livelihoods, and is widely used in landscape restoration programs while providing a wide range of ecosystem goods and services. However, while marketable goods from bamboo such as shoots for food and timber for construction, flooring and furniture are well known, the ecosystem services (ES) supply from bamboo is not, due to limited research. To date, very few studies highlight the role of bamboo forests in providing multiple ES that have local and global value. Lack of an appropriate framework and tools is considered a barrier to assessing the ES from bamboo forests. Therefore, this study attempts to develop an easy-to-apply framework to assess ES from bamboo and test them in three countries in Asia and Africa – Nepal, Indonesia and Ethiopia – in order to understand the relative supply capacity of the key ES from bamboo forests. The literature related to ES and assessment frameworks was reviewed so as to design an appropriate assessment framework for bamboo forests. This study offers an easy-to-apply framework that can be used widely. The research shows that the ES supply capacity of bamboo forests is higher than for industrial planted forest while it is lower than for the natural forests in all case study sites. The ES assessment from bamboo forests poses several challenges: defining and classifying ES, limited data, and complex relationships in trade-offs and synergies of ES that should be kept in mind while designing the framework.

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