TECHNICAL ASSESSMENT FOR BAMBOO

SECTOR: LAND

AGENCY LEVEL: FARMER / LAND-OWNER

KEYWORDS: BIOSEQUESTRATION,

BIOMASS CROPS

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DRAWDOWN

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Bamboo is a general term referring to thousands of species of "giant grasses", including temperate woody bamboos, tropical woody bamboos and herbaceous bamboos. Bamboo species are known for fast growth rates and are native to a wide range of climates ranging from temperate to tropical. Bamboo sequesters carbon at a rate greater than or equal to that of many tree species. Following planting, it matures much faster than trees; after harvest it resprouts via rhizomes and does not require replanting. In fact, harvesting mature culms stimulates more rapid growth of new shoots. Bamboo has thousands of uses including building materials, paper, furniture, food, fodder, and charcoal.

Bamboo is an ideal solution for restoring degraded lands, in particular sloped lands because it has the ability to simultaneously: stabilize the soil; restore soil by rapidly boosting organic carbon levels and nutrient availability; produce large quantities of biomass with social and economic value on otherwise unproductive land; and remove carbon dioxide from the atmosphere and store carbon in soil, above and belowground biomass, and in durable products.

Bamboo currently occupies roughly 34.0 Mha of land globally, with most recent growth taking place in India and China. As part of international goals to restore and reforest degraded lands, countries have pledged to restore 5 Mha of land by 2020 using bamboo. With over 1,100 Mha of global land degraded by water erosion and international goals of restoring 350 Mha of land by 2030, bamboo can be expected to continue to see strong growth in China and India, while gaining newfound popularity in Africa, North America, and other regions of the world.

Under the projected *Plausible* Scenario, total adoption is 115.89 million hectares in 2050. The total CO2-eq reduction impact of this scenario is 9.56 Gt CO2-eq by 2050. Cumulative first cost is US $82.78 billion, with a net profit margin of US$ 961.69 billion. Under the *Drawdown* Scenario, total adoption is 208.50 million hectares in 2050. The sequestration impact under this scenario is 21.06 Gt of CO2-eq by 2050. Cumulative first cost is US $180.06 billion, with net profit margin of US$ 961.69 billion. Under the *Optimum* Scenario, projected total adoption is 277.62 million hectares in 2050. The sequestration impact under this scenario is 30.47 Gt of CO2-eq by 2050. Cumulative first cost is US $254.26 billion, with net profit margin of US$ 3059.45 billion.

1. LITERATURE REVIEW

1.1. STATE OF THE PRACTICE

Project Drawdown's definition of *bamboo* includes the thousands of species of woody giant grasses that the term generally refers to, excluding the herbaceous species. This includes both temperate bamboos and tropical woody bamboos (Nath, Lal, & Das, 2015a). There are currently approximately 34.0 Mha of bamboo forests globally, covering a wide geographic range. (Lobovikov, Schoene, & Yping, 2012). While they are often thought of as being of Asian origin, there are also native bamboos in Africa, North America, and Latin America. In fact, the outstanding timber genus *Guadua* is of South American origin (Judziewicz 1999).

Establishment requires the planting and management of locally suited bamboo species. Most bamboo species are characterized by very rapid growth rates, reaching mature size after about 4-5 months - compared to several years for most tree species. Bamboo species thrive across a variety of elevations and temperature and moisture regimes, with some species able to grow on nutrient-poor and degraded soils (Lobovikov et al., 2012; Nath et al., 2015a).

Climate impact is via carbon sequestration, in soil, belowground biomass (rhizomes), aboveground biomass (culms), and harvested biomass used in long-lived products like furniture and timber. Bamboo moreover provides a range of ecological and economic co-benefits, including a multitude of economic and other ecosystem services. One particularity of bamboo species is their high phytolith content, which is associated with increased long-term carbon storage capacity (J. Parr, Sullivan, Chen, Ye, & Zheng, 2010).

Carbon Sequestration and Lifetime Carbon Stock Benefits

Carbon sequestration refers to carbon fixed from the atmosphere over a set time-period, whereas carbon stocks refer to the amount of carbon fixed at a specific point in time. Carbon stocks accumulate both in soils (soil organic carbon, or SOC) and in above- and below-ground vegetation biomass. Various studies have found bamboo forests to have carbon densities (stocks) ranging from 75-260 t C/ha with a majority (~70%) of that carbon located belowground (X. Song et al., 2011; Yiping, Li, Buckingham, Henley, & Guomo, 2010).

Project Drawdown models currently do not account for existing carbon stocks but rather focus on annual sequestration rates in soils and vegetation biomass. Carbon sequestration rates in bamboo systems vary

significantly, depending on species, age, management practices, and local climate and soil conditions. For instance, the carbon sequestration rate for woody bamboos ranges from 6 to 13 Mg ha−1 yr−1 (Nath et al., 2015a). Table 1 below was adapted from multiple sources and shows both carbon stock and sequestration ranges for various bamboo species at different geographical locations. The sequestration rates shown were used in our model.

Activities such as the application of synthetic fertilizers and clearing of understory vegetation within bamboo forests can lead to increased carbon storage in the bamboo components. However, these practices are associated with trade-offs as they may also decrease soil carbon, soil microbial activity, overall carbon storage, and net GHG benefits (Li et al., 2015; Xu, Jiang, & Xu, 2008; Yiping et al., 2010).

Table 1.1: **Carbon Sequestration and Storage Rates for Various Bamboo Species. Adapted from** *(Nath et al., 2015a)*.

Note that these rates assume bamboo is being harvested and used in durable goods.

Bamboo species	Location	Biomass C Sequestration Rate (Mg C/ha/yr)	Soil C Stocks (Mg C/ha)	Biomass C Stocks (Mg C/ha)
Phyllostachys edulis	China	34.1 - 20.1		
Bambusa bamboos	India	24		144
Bambusa oldhamii	Mexico	16		51.5
Phyllostachys bambusoides	Japan	13		68
Bambusa pallida	India	13		160
Dendrocalamus strictus	India	13		30
Phyllostachys makinoi	Taiwan	10		50
Phyllostachys pubescens	Japan	9		69
Phyllostachys heterocycla	Taiwan	8		41
Phyllostachys pubescens	China	7		40
Bambusa bambos	India	6		121
Bambusa cacharensis, B. vulgaris & B. balcooa	India		57.3	61
Bambusa blumeana	Philippines			72
Bambusa vulgaris	Philippines			53
Gigantochloa levis	Philippines			73
Gigantochloa ater and G.verticilleta	Indonesia			37
Yushania alpina	Ethiopia			55
Guadua angustifolia	Bolivia			100

Phytoliths

Phytoliths are silica structures found in some plant tissues; they are more prevalent in grasses (including bamboo) than in trees (J. Parr et al., 2010). Phytoliths are a significant component of global biosequestration mechanisms. They are more resistant to degradation than other plant material, and phytolith-associated carbon can be stored in decaying plant material or soils for hundreds, thousands, or even millions of years, representing up to 82% of total soil carbon (J. F. Parr & Sullivan, 2005; Z. Song, Liu, Li, & Yang, 2013; Yang et al., 2015). Their carbon sequestration potential at global scales is significant: for instance, (J. Parr et al., 2010) estimate global phytolith carbon sequestration potential from grass crops, including bamboo, at 1.5 billion tons of CO_2 eq/yr, which is equivalent to about 11% of the current increase in atmospheric CO_2.

Bamboo species tend to have particularly high phytolith contents: in China, about 10% of sub-tropical bamboo biomass has been found to be composed of phytoliths, a value 4-50 times higher than in other forest ecosystems (Song et al., 2013). This is likely to significantly increase their long-term carbon sequestration potential. Currently, the annual phytolith sequestration in China is equivalent to about 0.5 Tg of CO_2 /yr. Given current trends in bamboo afforestation and reforestation, the potential maximum global phytolith carbon sequestration potential of bamboo has been estimated at 27 Tg of CO_2 /yr (Song et al., 2013).

Variables and Uncertainties in Carbon Sequestration Calculations

Within bamboo systems established in different regions and climates, carbon sequestration rates over time are influenced by many factors, including:

- There is a high potential for error or variation in terms of measurement accuracy. Carbon fluxes can be measured through atmospheric transport models or land observations – both methodologies can yield significantly different results (Netz et al., 2007). Due to current limitations in terms of available data and resources, average carbon stocks for a given biome are generally extrapolated from case study measurements or low-resolution FAO Forest inventory data and are thus highly uncertain.
- There is uncertainty in the literature about the extent to which growth in new bamboo culms sequesters new atmospheric carbon or is solely the result of internal plant reallocation of carbohydrates, essentially recycling carbon from below-ground to above-ground biomass, or from old bamboo culms to new ones. Nevertheless, the current consensus is that when properly managed,

bamboo does provide high carbon sequestration potential (Lobovikov et al., 2012; Yuen, Fung, & Ziegler, 2017).

- There is additional uncertainty in the literature about trade-offs between bamboo's CO_2 emissions and sequestration rates (Yuen et al., 2017).
- Sequestration rates are highly dependent on the end-of-life fate of harvested bamboo material. Bamboo has relatively short lifespans of 7-10 years compared to tree species, and carbon could be reemitted relatively quickly into the atmosphere if bamboo biomass is left to decompose. Nevertheless, significant amounts of biomass is sequestered in below-ground components of the plant. In addition, harvested above-ground biomass carbon can be sequestered for the medium- to long-term in durable products such as construction materials, flooring, furniture, pulp for paper or cardboard, etc. (Lobovikov et al., 2012; Yuen et al., 2017). Accurate life-cycle assessments for these different options are still being developed.

Other ecosystem benefits

Bamboo is associated with many other economic and ecological benefits and uses (see Fig. 1). In terms of ecological benefits, bamboo root systems can contribute to soil stabilization and decreased erosion (X. Song et al., 2011; Yuen et al., 2017). Bamboo can further contribute to soil restoration through increased nutrient recycling and soil structure amelioration (Christianty, Mailly, & Kimmins, 1996; Yuen et al., 2017) and can contribute to water filtration (Lobovikov et al., 2012). Bamboo also provides habitat for numerous animal species (Lobovikov et al., 2012).

Bamboo's many commercial uses include the production of construction materials, food, fiber, pulp or fuel material (Lobovikov, Ball, Guardia, & Russo, 2007; X. Song et al., 2011). Its rapid growth rate and relatively short life-span contributes to bamboo's economic viability as harvests can be less delayed than with other wood-producing species (INBAR, 2015). Bamboo is moreover associated with high yields and generates little to no harvesting and processing waste. It has been shown to yield up to six times the pulp of pine plantations (Dhamarodon 2003) and responds well to manure and fertilizer application (Lobovikov et al., 2012); intensively managed bamboo stands can produce up to 10 t/ha/year (Scurlock, Dayton, & Hames, 2000). Bamboo has been traditionally important for the paper production sector; currently, millions of hectares China and India are used to provide paper feedstock (Dhamodaran, Gnanaharan, & Pillai, 2003; Lobovikov et al., 2007).

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Many of these uses result in long-term storage of carbon being stored in durable products; depending on their disposal, some industrial bamboo products can be carbon negative (van der Lugt & Vogtlander, 2016). As mentioned above, the durability of bamboo products is critical to assumptions regarding carbon sequestration in biomass and products. Improvements in durability and popularity of bamboo-based products could increase the amount of carbon sequestered in bamboo products (X. Song et al., 2011).

Using bamboo for paper or other materials can help prevent clearing of timber and deforestation. In addition, replacing comparable products made from fossil fuels or metal with bamboo products can lead to reduced carbon dioxide emissions during manufacturing due to lower heat and energy requirements (X. Song et al., 2011). In some contexts, bamboo is used to replace materials with much higher carbon footprints such as PVC, aluminum, and concrete. Since bamboo products are often manufactured using electricity, heat, or adhesives, their environmental impacts and carbon footprints are heavily impacted by processing, electricity sources, treatments, and transportation (Zea Escamilla & Habert, 2014).

Because much harvested bamboo is used or consumed at small, local scales, accurately tracking the total value of all bamboo products and uses is difficult. Still, figures for exports and industrially manufactured goods are available: global exports of bamboo products were valued at $2.5 billion in 2000 and are thought to have grown rapidly since then (Lobovikov et al., 2007). INBAR currently estimates the annual market value of the bamboo and rattan industry at $60 billion.

1.2. ADOPTION PATH

1.2.1 Current Adoption

Bamboo occupied an estimated 34 Mha in 2010 (Du et al., 2018; FAO, 2010a; Lobovikov et al., 2012). Bamboo species are native to dozens of countries across Asia, the Americas, and Africa (Fig. 2), with production currently the greatest in India, China, Brazil, and Indonesia (Lobovikov et al., 2007). While most species are found in the tropics and sub-tropics, some species of bamboo can grow in temperate climates and are quite cold hardy (Fu, 2001; Scurlock et al., 2000). Bamboo is already grown outside its native range (for instance in Europe and the northern United States) and production in those areas is expected to increase. In China, bamboo planting and production have expanded rapidly over the last several decades as bamboo is being used for afforestation, food, air quality improvement, construction materials, combatting desertification, erosion control, windbreaks and more (Lobovikov et al., 2007; X. Song et al., 2011; Yiping et al., 2010). Global growth over the past several decades is likely to continue and even

accelerate due to recent international agreements, consumption and production trends, and an expanding understanding of bamboo's social, environmental, and economic benefits.

1.2.2   Trends to Accelerate Adoption

Many bamboo species are quite tolerant of a wide range of thermal moisture regimes. Some species of bamboo with commercial value can be grown in regions with as little as 600 mm of annual rainfall (800-1800 is more typical for bamboo) and irrigation can be used to assist cultivation in drier climates (Fu, 2001; INBAR, 2015). Several popular species of bamboo in the popular genus *Phyllostachys* are hardy to -20°C (Fu, 2001).

Reforestation, Afforestation, Land Restoration

Due to its fast growth rate, economic viability and carbon sequestration benefits, and ability to thrive in a wide range of environmental conditions, bamboo has great potential to contribute to global reforestation, afforestation, and degraded land restoration efforts. Through the Bonn Challenge and the New York Declaration on Forests, the global community set goals of restoring 150 million hectares of degraded and deforested lands by 2020 and 350 million hectares by 2030. As part of this initiative, INBAR member-states have pledged to restore 5 Mha of land using bamboo by 2020 (INBAR, 2014b).

In many countries, bamboo is a native forest type or found in native forests, so it makes sense to expect that some fraction of the projected 350 million hectares of restored lands will be occupied by bamboo species. This is especially likely given its well-documented ability to grow on degraded, deforested, eroded, steeply sloped, and industrially damaged lands where other common forest species might struggle (INBAR, 2015). Bamboo afforestation projects are already being widely implemented to restore degraded lands in Latin America, Asia, and India and China, where the area of land dedicated to bamboo has increased since the 1950s, reaching up to 29 Mha by 2015 (INBAR, 2015; X. Song et al., 2011). Preliminary outcomes of bamboo afforestation projects are promising; in India, for instance, bamboo afforestation has been shown to contribute to soil restoration through soil organic carbon and nutrient inputs (INBAR, 2014a).

Market Expansion for Bamboo Products

Increased adoption of bamboo afforestation globally - assuming no global price on carbon – would require a significant expansion of markets for bamboo products. Fortunately, bamboo has thousands of documented

uses. It can be used to substitute for a range of other emission-intensive materials such as Styrofoam and plastic plates and utensils; hardwood, linoleum, or vinyl floors; yarn and other textile fibers; or virgin timber and wood pulp used for paper and cardboard manufacturing.

To lower costs and avoid carbon emissions from shipping, commercial bamboo production could be expanded in suitable regions where it is not currently produced. Current major importers of bamboo products are the United States, European Union, Japan, and Hong Kong (Lobovikov et al., 2007). Some bamboo species can be grown in temperate parts of the United States and Europe (Fu, 2001; Scurlock et al., 2000). Increasing localized cultivation in these regions could contribute to decreased shipping-related carbon emissions, which have been shown to represent the largest environmental cost of bamboo products (van der Lugt, van den Dobbelsteen, & Janssen, 2006).

There has also been increased recognition of bamboo's potential by a variety of certification programs. The Forest Stewardship Council (FSC) now certifies bamboo and the use of bamboo, especially FSC certified and/or locally sourced bamboo, can help a building achieve LEED certification. LEED (and other green building certification programs like Living Building Challenge) are popular not just in importing regions like the United States and Europe, but also in producing countries like China, India, and Brazil.

Bamboo moreover has immense potential in Africa given that native bamboo species are already present and thriving in the region. As in China, bamboo could be used in Africa to restore degraded lands, improve air quality, and fight desertification with the added benefits of boosting local economies, food supplies, and national exports. Much of the short-term expansion of bamboo area and consumption is likely to occur in Ethiopia, Ghana, Nigeria, and Kenya since these countries have taken steps to develop national policies and expand planting and production of bamboo (INBAR, 2015).

Countries where production is currently limited often lack bamboo management expertise and policies. Promoting training and education programs in these countries could boost yields and profitability of existing bamboo operations and encourage more planting and production. In additional policies encouraging both high-value and low-value chain development for bamboo would be beneficial (INBAR, 2015). Land ownership and tenure systems can additionally impact bamboo management, productivity, incentives, and permitted uses. China has recently seen a major shift from complete state ownership of bamboo forests to significant private ownership and it should be noted that public land there can be leased to private interests who then have ownership of the bamboo (Lobovikov et al., 2007).

1.2.3   Barriers to Adoption

Despite the recognized potential of bamboo systems, there are significant hurdles limiting their implementation in current reforestation, afforestation, and land restoration efforts. Bamboo is barely mentioned in the Agriculture, Forestry and Other Land Use (AFOLU) chapter of the IPCC's Fifth Assessment Report and does not receive the same level of recognition as trees in international policy instruments, carbon mechanisms, or climate-related agreements and organizations such as the Kyoto Protocol, Marrakech Accords, or IPCC (INBAR, 2015; IPCC, 2014; Yiping et al., 2010). As a result, existing policy frameworks do not account for the potential of bamboo compared to other forest systems, constraining the potential for future adoption (Buckingham et al., 2011). For example, REDD mechanisms consider the harvesting and removal of biomass from forests to be a non-sustainable practice. This does not reflect the fact that bamboo regrows rapidly from established root systems and can be harvested regularly in a sustainable fashion (Nath, Lal, & Das, 2015b). Raising awareness about bamboo's potential as a climate-smart strategy and chaging bamboo is categorized and perceived by international organizations and in international agreements could facilitate and catalyze increased adoption of the solution.

Producing more bamboo closer to markets for bamboo products might improve the net carbon balance but could lead to competition with reforestation or agricultural solutions. For instance, large areas of the southeastern United States are currently private monocultural, even-aged, pine plantations. Given the limited habitat benefits of such plantations and their long lifecycles (30-50 years), bamboo, with its overlapping uses, much shorter harvesting period, greater pulp yields per hectare (potentially 6-10X), and no need for replanting, might be a sensible alternative in some locations (Dhamodaran et al., 2003). Unlike some other alternatives, bamboo can also be processed for paper with the same equipment used for trees. This might lead to some pushback from already established timber and wood-pulp industry. However, due to certain bamboo species' suitability to relatively degraded lands, there is potential to establish bamboo forests on otherwise unproductive lands to decrease competition with other industries.

To increase interest and expand the market for bamboo, better data on existing bamboo resources, production, and social and economic benefits is needed. This is hampered by a current lack of quantitative data about production or economic value which has contributed to general perceptions of bamboo as a low value plant, particularly in Latin America or Africa (Lobovikov et al., 2007). In addition, negative perceptions and incomplete understanding regarding the limits of bamboo's potential need to be further researched and addressed. For instance, some bamboo species are invasive or have the capacity to cause slope failures due to their dense rooting characteristics (Lobovikov et al., 2012). These and other potential

negative consequences of bamboo afforestation need to be recognized and evaluated in order to allow land-users to choose the most effective and relevant solutions in their given contexts.

1.2.4   Adoption Potential

Projections of the adoption potential of bamboo forests *as such* are quite rare, and to our knowledge this is the first study or initiative to model estimates at global scales. Increased research regarding the economic and ecological benefits of bamboo species under different climates, coupled with the development of bamboo inventories at regional or national scales, would provide valuable information that might increase the consideration and inclusion of bamboo in policy frameworks.

1.3 ADVANTAGES AND DISADVANTAGES OF FOREST PLANTATIONS

1.3.1   Similar Solutions

This solution could be viewed as related to other Drawdown solutions related to the reforestation, afforestation, and restoration of degraded lands (e.g. *forest restoration, forest plantations, perennial biomass, multistrata agroforestry, staple tree crops, silvopasture* and others), and has similar benefits in terms of soil restoration, slope stabilization and air quality improvements. Like agroforestry-related solutions, *bamboo* further contributes to food and/or fodder production as many species of bamboo produce edible shoots that are sources of protein, carbohydrates, and assorted vitamins and minerals (Chongtham, Bisht, & Haorongbam, 2011; INBAR, 2015; Singhal, Bal, Satya, Sudhakar, & Naik, 2013). Bamboo is, however, more restricted by the need for a humid climate than other biomass production solutions.

Bamboo also presents some advantages:

- It has comparatively faster growth rates and markets already exist for a wide range of bamboo products, unlike for some of the other related solutions.
- The carbon sequestration potential is similar to that of tree-based solution and presents one additional advantage: bamboo can be harvested in a way that does not significantly decrease carbon sequestration impacts as it can re-sprout without new planting. This is compounded by many bamboo species' high biomass yield per unit area and high phytolith contents.
- Bamboo can moreover be integrated with other solution (such as *multistrata agroforests*).
- Substituting bamboo charcoal for other forms of charcoal can prevent the clearing of slower growing trees. Bamboo charcoal compares favorably to charcoal from many other plants in terms of calorific value, smoke emissions, and ease of production (INBAR, 2015; Lobovikov et al., 2007).

Bamboo is also associated with some disadvantages and is perceived negatively as an invasive species in certain contexts, due to certain species' species tendency to spread rapidly (Lobovikov et al., 2007; Yuen et al., 2017). To address this, species and location suitability need to be considered carefully when establishing new bamboo forests. To date, *bamboo* has also received less attention in international and national dialogues about land-use change and climate change in comparison with more recognized tree-based solutions (Buckingham et al., 2011; Yuen et al., 2017). Consequently, existing policies and regulation mechanisms are not yet equipped to maximize bamboo's potential.

1.3.2   Arguments for Adoption

Due to particularly rapid growth rates, high capacity for carbon storage, and wide adaptability across different climates, *bamboo* has significant carbon sequestration potential. In addition, bamboo offers livelihood and economic benefits, and is already widely used across the world, both traditionally and at more industrial scales (Nath et al., 2015b).

1.3.3   Additional Benefits and Burdens

Here this solution is compared with other solutions in the biomass production cluster for farm, ecosystem, and social impacts. Like other biomass solutions, bamboo increases commercial biomass production but has inferior ecosystem services when compared to ecosystem protection and restoration solutions.

Table 1.2: Land Use Solutions Comparison: Economic Impacts

First Cost: Free is $0, Low is $1-100, Medium is $100-500, Expensive is $500+. **Net Profit Margin:** Low is $0-100/ha, Medium is $100-500, High is $500+. **Value of Ecosystem Services:** Set values for very high, high, medium, low. **Timber and Biomass Production:** Decrease indicates restriction of logging where it currently occurs; Increase indicates new commercial biomass production where it does not currently occur.

	First Cost $/ha	Net Profit $/ha	Value of Ecosystem Services	Timber and Biomass Production
Afforestation	Expensive	Medium	High	Increase
Bamboo	Expensive	Medium	High	Increase
Forest Protection	Not calculated	Not calculated	Very high	Decrease
Indigenous People's Forest Management	Not calculated	Not calculated	Very high	Decrease
Peatland Protection	Not calculated	Not calculated	Very high	Decrease

	First Cost $/ha	Net Profit $/ha	Value of Ecosystem Services	Timber and Biomass Production
Perennial Biomass	Expensive	Medium	Medium	Increase
Temperate Forest Restoration	Not calculated	Not calculated	High	n/a
Tropical Forest Restoration	Not calculated	Not calculated	High	n/a

Table 1.3: Land Use Solutions Comparison: Social and Climate Impacts

Carbon Stock Protected: Low 0-500 Gt CO2-eq, Medium is 500-1000 Gt CO2-eq, high is 1000+ Gt CO2-eq. **Ecosystem Services** is subjective based on impacts on biodiversity, water quality, etc. **Social Justice Benefits:** Is solution Targeted to disadvantaged producers like smallholders and women, Relevant to them, or Not Applicable (n/a). **Climate Impacts per Hectare:** Low 0-3.7 t CO2-eq/ha/yr (0-1tC), Medium 3.8-11.0 t CO2-eq/yr (1-3 tC), High 11.1-18.0 tCO2-eq/yr (3-5 tC), Very High 18.1 tCO2-eq/yr (5tC+). **Global Adoption Potential:** Low 0-100Mha, Medium 101-500 Mha, High 500+ Mha

	Carbon Stock Protected	Social Justice Benefits	Climate Impact/ha	Global Adoption Potential
Afforestation	Medium to High	Relevant	High	Medium
Bamboo	Medium	Relevant	High	Medium
Forest Protection	High	Relevant	Very High	Medium
Indigenous People's Forest Management	High	Targeted	Very High	Medium to High
Peatland Protection	n/a	Relevant	Very High	High
Perennial Biomass	n/a	Relevant	Low	Medium
Temperate Forest Restoration	n/a	Relevant	Medium	Low to Medium
Tropical Forest Restoration	n/a	Relevant	High	Medium

2 METHODOLOGY

2.1 INTRODUCTION

Project Drawdown's models are developed in Microsoft Excel using standard templates that allow easier integration with each other since integration is critical to the bottom-up approach used. The template used for this solution was the Land Model, which accounts for:

a) Sequestration of carbon dioxide from the atmosphere into plant biomass and soil; and
b) Reduction of emissions for a solution relative to a conventional practice.

These practices are assumed to use land of a specific type that may be shared across several solutions. Actual and maximum possible adoptions are therefore defined in terms of land area (million hectares). The adoptions of both conventional and solution were projected for each of several Drawdown scenarios from 2015 to 2060 (from a base year of 2014) and the comparison of these scenarios with a reference (for the 2020-2050 segment[1]) is what constituted the results.

In order to maximize climate, environmental, economic and social benefits, Drawdown's *bamboo* solution models future adoption on marginal, degraded, forest and grasslands, in particular sloped or eroded lands that could benefit from stabilization while boosting or maintaining economic productivity. Current adoption is estimated at about 34 million hectares, all allocated on the forest AEZs (Du et al., 2018; FAO, 2010a; Lobovikov et al., 2012).

Agency Level

The farmer or land-owner is selected as the agency level for this solution. Though certainly other agents can, do, and should play an important role in this solution, the decision-maker on the ground is the most critical player in implementation.

2.2 DATA SOURCES

Data for the model was drawn from a review of peer-reviewed journal articles and INBAR reports (which often cite peer-reviewed research and industry experts).

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[1] For most results, only the differences between scenarios, summed over 2020-2050 were presented, but for the net first cost, the position was taken that to achieve the adoptions in 2020, growth must first happen from 2015 to 2020, and that growth comes at a cost which should be accounted for, hence net first cost results represent the period 2015-2050.

One of major challenges with establishing global values for bamboo is the wide ranges of existing data values, methodologies used and variation in terms of reported numbers (e.g. for carbon sequestration, different studies reported above-ground biomass sequestration, total biomass sequestration, or biomass plus soil sequestration values). Another challenge particularly relevant to future adoption projections, bamboo afforestation projects may be lumped together with other afforestation solutions (e.g. agroforestry, forest plantations and/or biomass for biofuel plantations). Nevertheless, wherever possible, data specific to bamboo was used in the model.

2.3 TOTAL AVAILABLE LAND

Drawdown's agricultural production and land use model approach defines the Total Land Area for each solution as the area of land (in million hectares) suitable for adoption a given solution. Determining this figure for Total Land Area is a two-part process.

1. First, the technical potential is determined, based on: current land cover or land use; the suitability of climate, soils, and slopes; and degraded or non-degraded status. Relevant data on global land-use and availability is acquired from Global Agro-Ecological Zones database, developed by the Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA).

2. In the second stage, land is allocated using the Drawdown Agro-Ecological Zone model, based on priorities for each class of land. The Drawdown Land-Use Model categorizes and allocates land according to agro-ecological zones based on the following factors: thermal climate, moisture regimes, soil quality, slope, cover type, and degradation status. These characteristics influence the suitability of different practices, and solution adoption scenarios are restricted by one or more of these factors (see Section 2.7 for more details).

The total land allocated for each solution is capped at the solution's maximum adoption in the *Optimum* Scenario. Thus, Drawdown estimates of total available land are very conservative as final allocation numbers are less than those determined purely through technical potential. Drawdown new adoption potential for bamboo is modeled specifically on <u>degraded, abandoned, and marginal forest and grassland</u> globally suitable for forest plantations.

Replacing healthy *natural grassland* with perennial crops such as bamboo is undesirable for several reasons including competition for water resources with needs downstream, loss of habitat, and emissions from land us change. However, to date many grasslands have been established following clearing and degradation of

forests and other ecosystems (UNCCD, 2017). These grasslands are often referred to as *semi-natural* (Faber-Langendoen & Josse, 2010). Restoration of such areas has significant potential for carbon sequestration and ecosystem rehabilitation.

Drawdown's maximum area allocated to *bamboo* is <u>310 million hectares</u>, based on suitable marginal and degraded forest and grassland area as described above, as well as on land allocation as determined through the Drawdown Agro-Ecological Zone model. This figure is used throughout the Drawdown model for this solution.

2.4 ADOPTION SCENARIOS

Two different types of adoption scenarios were developed: 1) a Reference (REF) Case which was considered the baseline, where not much changes in the world; and 2) a set of Project Drawdown Scenarios (PDS) with varying levels of ambitious adoption of the solution. Published results show the comparison of one PDS to the REF, and therefore focus on the change to the world relative to a baseline.

Drawdown's future adoption for *bamboo* is based on data from the FAO's 2010 Forest Resource Assessment (FAO, 2010a) as well as on projections from (Z. Song et al., 2013). Details are given below:

1. *Custom adoption scenario one:* Scenario one is a low-growth scenario which projects the future adoption of bamboo based on historical regional growth reported for the 1990-2010 period in the FAO's Global Forest Resource Assessment 2010 report (FAO, 2010a).

2. *Custom adoption scenario two:* Scenario two is a medium-growth scenario projects the future adoption of bamboo based on the highest historical regional annual growth rate, based on 1990-2010 FAO data (FAO, 2010a). The highest annual growth rate was reported in the Asia region (0.0974 Mha/year). Thus, it was assumed that bamboo plantation in other regions will grow by half of the growth rate calculated in Asia (0.05 Mha/year), while bamboo plantation in Asia continues to grow with the same rate.

3. *Custom adoption scenario three:* Scenario three is a high-growth scenario which projects the future adoption of bamboo based on the highest historical regional annual growth rate, based on 1990-2010 FAO data. The highest annual growth rate was reported in the Asia region. Thus, it was assumed that bamboo plantation in other regions will grow at the same growth rate calculated in Asia (0.0974 Mha/year), while bamboo plantation in Asia continues to grow at double this rate (0.19 Mha/year).

4. *Custom adoption scenario four:* Scenario four is projects extremely high adoption rates by 2050. Considering the limited total land available for bamboo, this scenario projects a worldwide 85% adoption of bamboo plantation on available land by 2050.

5. *Custom adoption scenario five:* Scenario five projects a 3% annual increase in global bamboo forests as determined in (Z. Song et al., 2013).

2.4.1 Reference Case / Current Adoption[2]

Current adoption of *bamboo* is estimated at 34 million hectares (Du et al., 2018; FAO, 2010a; Lobovikov et al., 2012).

Project Drawdown Scenarios

Three Project Drawdown scenarios (PDS) were developed for each solution, to compare the impact of an increased adoption of the solution to a reference case scenario, being:

Plausible Scenario – A conservative approach is adopted for the plausible scenario, thus the result for this scenario comes from the "average of all" custom adoption scenarios as discussed above.

Drawdown Scenario – Drawdown scenario presents an ambition growth where the results are derives from the "high of all" custom adoption scenarios as discussed above.

Optimum Scenario – This is the most optimistic growth scenario, where the future growth of the solution is projected based on the maximum growth reported in anyone of the given five custom adoption scenarios. his scenario derives the result from the "high of all" custom adoption scenarios as discussed above.

2.5 INPUTS

2.5.1 Climate Inputs

Sequestration rate of *bamboo* systems is set at 2.03 tons of carbon per hectare per year, a low estimate based on the meta-analysis of 13 data points from 5 sources. The low-end value is considered as the solution is allocated on the degraded forest and grassland AEZs.

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[2] Current adoption is defined as the amount of land area adopted by the solution in 2018. This study uses 2014 as the base year due to the availability of global adoption data for all Project Drawdown solutions evaluated.

Table 2.1 Climate Inputs

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
C sequestration	*tC/ha/yr*	2.03-53.76	2.03	13	5

Note: Project Drawdown data set range is defined by the low and high boundaries which are respectively 1 standard deviation below and above the mean of the collected data points[3].

Modeling Saturation

Biosequestration does not have limitless potential. In most cases, there is a maximum amount of carbon that can be stored in soils and aboveground perennial biomass before they become saturated. Biosequestration continues after saturation but is offset by more or less equal emissions. In most cases soils, and biomass can return to their approximate pre-agricultural or pre-degradation levels of carbon. This takes anywhere between 10-50 years in agricultural cases, and sometimes somewhat longer in the case of ecosystems like forests. Data about saturation time is very limited.

The Drawdown land model takes the conservative approach that all land units currently adopted for agricultural solutions (including bamboo) have already achieved saturation and will not be contributing additional sequestration. New adopted land is assumed to sequester for at least 30 years before achieving saturation.

Note that there are some important exceptions to saturation. Certain ecosystems continue to sequester soil carbon for centuries, notably peatlands and coastal wetlands. Some scientists argue that tropical forests can continue to sequester carbon at a slower rate after saturation. The addition of biochar to saturated soils may be able to overcome this constraint, as does the use of biomass from bamboo or forest plantations in long-term products like buildings.

2.5.2   Financial Inputs

The present solution, *bamboo*, is allocated on degraded land area (forest and grassland). Project Drawdown's *bamboo* model assumes marginal conventional use of this degraded land areas, principally for grazing, degraded forest on the other hand assumed to be in no commercial use in the absence of valid

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[3] In some cases, the low boundary is negative for a variable that can only be positive, and in these cases the lowest collected data point is used as the "low" boundary.

information. In the absence of sufficient financial data sources documenting the implementation of grazing practices on degraded land, Drawdown's *bamboo* model uses conventional grazing data as a basis for comparison. However, in order to model decreased productivity on degraded land, financial variables for conventional grazing are weighted value based on the proportion of total global grassland area (3514 Mha) that is already degraded (772 Mha), i.e. 21.97%. This calculation is based on Project Drawdown's AEZ values.

For *bamboo*, establishment costs are estimated at US$915.36 per hectare. Results are based on meta-analysis of 10 data points from 6 sources. Net profit per hectare is US$717.06 per year (6 data points from 5 sources), compared to US$238.07 per year for the conventional practice (9 data points from 8 sources).

Table 2.2 Financial Inputs for Conventional Practice (Grazing on Degraded Lands)

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
First costs (Conventional)	*US$2014/ha*	$0	$0	n/a	n/a
Net profit (Conventional)	*US$2014/ha*	$69.49-$323.38	$154.12	18	16
Operating Cost (Conventional)	*US$2014/ha*	$28.06-$684.58	$328.42	9	8

Table 2.3 Financial Inputs for Solution (Bamboo)

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
First costs (Solution)	*US$2014/ha*	$1,620.60-$210.11	$915.36	10	6
Net profit (Solution)	*US$2014/ha*	$904.89-$529.24	$238.07	6	5
Operating Cost (Solution)	*US$2014/ha*	$373.14-$103.00	$717.06	9	8

2.6 ASSUMPTIONS

Six overarching assumptions have been made for Project Drawdown models to enable the development and integration of individual model solutions. These are that infrastructure required for solution is available and in-place, policies required are already in-place, no carbon price is modeled, all costs accrue at the level of agency modeled, improvements in technology are not modeled, and that first costs may change according

to learning. Full details of core assumptions and methodology will be available at www.drawdown.org. Beyond these core assumptions, there are other important assumptions made for the modeling of this specific solution. These are detailed below.

Assumption 1: All future adoption scenarios include in this model assume linear rather than exponential growth, which simplifies calculations and yields conservative estimates. While rapid growth in bamboo planting has taken place for decades in China and possibly elsewhere, it isn't clear if this historic trend will continue or if increases in growth were due to the introduction of discrete national policies. Drawdown scenarios do assume this growth as a baseline.

Assumption 2: Several of the scenarios used in this model assume a significant increase in bamboo adoption taking off outside of Asia, even though bamboo expansion has been relatively stagnant outside of the region historically. INBAR members in Africa and elsewhere have pledged to dramatically expand their planting and use of bamboo by 2020. Given bamboo's abilities to restore degraded lands while providing social and economic benefits, it is an ideal solution for countries struggling with degraded lands.

Assumption 3: Emissions from bamboo are assumed equal to those of the degraded cropland under conversion, though this is likely quite conservative.

Assumption 4: Project Drawdown models assume that bamboo clumps or stands are managed efficiently (e.g. ensuring sufficient water and nutrient availability and practicing appropriate thinning/harvesting) (Yuen et al., 2017) and sustainably.

Assumption 5: Future adoption of bamboo is allocated principally on degraded area and assumes marginal conventional use of this land, principally for grazing. In the absence of sufficient financial data sources documenting the implementation of grazing practices on degraded land, Drawdown's *bamboo* model uses conventional grazing data as a basis for comparison. To model decreased productivity on degraded land, financial variables for conventional grazing are weighted value based on the of total global grassland area (3514 Mha) that is already degraded (772 Mha), i.e. 21.97%. This calculation is based on Project Drawdown's AEZ values.

Assumption 6: Due to a lack of data sources which include soil carbon pools in carbon sequestration assessments for bamboo, Drawdown's current iteration of the *bamboo* model only includes values which explicitly include biomass C sequestration for above- and below-ground biomass components, making results more conservative than if all ecosystem carbon pools had been included. As the model is updated in

the future and more data points become available, sequestration rates will require being updated to better reflect additional sequestration potential in soil carbon pools.

Assumption 7: Due to a lack of accurate data documenting end-of-life cycles for bamboo products, carbon sequestration in harvested bamboo biomass is excluded from the model at present.

Assumption 8: Globally, projections for afforestation may include several land-uses, including bamboo. However, as the distinction between land-uses in afforestation pledges is not always clear, Drawdown model projections for future adoption assume that the majority of afforested area is used for planting forests for commercial timber/paper pulp harvest, and that bamboo area remains mostly separate from this category.

2.7 INTEGRATION

The complete Project Drawdown integration documentation (will be available at www.drawdown.org) details how all solution models in each sector are integrated, and how sectors are integrated to form a complete system. Those general notes are excluded from this document but should be referenced for a complete understanding of the integration process. Only key elements of the integration process that are needed to understand how this solution fits into the entire system are described here.

Bamboo is part of Drawdown's land-use sector.

The Agroecological Zone model

Drawdown's approach seeks to model integration between and within sectors and avoid double counting. Several tools were developed to assist in this effort. The Agroecological Zone (AEZ) model categorizes the world's land by: current cover (e.g. forest, grassland, cropland), thermal climate, moisture regime, soil quality, slope, and state of degradation. Both Food (supply-side) and Land Use solutions were assigned to AEZs based on suitability. Once current solution adoption was allocated for each zone (e.g. semi-arid cropland of minimal slopes), zone priorities were generated and available land was allocated for new adoption. Priorities were determined based on an evaluation of suitability, consideration of social and ecological co-benefits, mitigation impact, yield impact, etc. For example, *Indigenous peoples' land management* is given a higher priority than *forest protection* for AEZs with forest cover, in recognition of indigenous peoples' rights and livelihoods. *Multistrata agroforestry* is highly prioritized in tropical humid climates due to its high sequestration rate, food production, and highly limited climate constraints.

Each unit of land was allocated to a separate solution to avoid overlap between practices. The exception to this are *farmland irrigation*, *nutrient management*, and *women smallholders*, which can be implemented in addition to other practices. The constraint of limited available land meant that many solutions could not

reach their technical adoption potential. The AEZ model thus prevents double-counting for adoption of agricultural and land use solutions.

Drawdown's agricultural production and land use model approach defines the Total Land Area as the area of land (in million hectares) suitable for adoption a given solution. Data on global land is acquired from Global Agro-Ecological Zones database, developed by the Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA). The Drawdown Land-Use Model categorizes and allocates land according to agro-ecological zones based on the following factors: thermal climate, moisture regimes, soil quality, slope, cover type, and degradation status. These characteristics influence the suitability of different practices, and solution adoption scenarios are restricted by one or more of these factors.

Determining the total available land for a solution is a two-part process. The technical potential is based on: current land cover or land use; the suitability of climate, soils, and slopes; and on degraded or non-degraded status. In the second stage, land is allocated using the Drawdown Agro-Ecological Zone model, based on priorities for each class of land. The total land allocated for each solution is capped at the solution's maximum adoption in the *Optimum* Scenario. Thus, in most cases the total available land is less than the technical potential.

The Yield model

Drawdown's yield model calculates total annual global supply of crops and livestock products based on their area of adoption in each of the three scenarios, and global yield impacts of each solution (including both gains due to increased productivity per hectare and losses due to reduction of productive area due to adoption of non-agricultural solutions, e.g., loss of grazing area due to afforestation of grasslands). Grain surpluses in the yield model are also used to set a ceiling for the amount of crops available for use as feedstock for the *bioplastic* Materials solution.

The yield model matches demand and supply as an integrated system. Both *Reference* Scenarios showed a food deficit in the high and medium population scenarios (see *family planning* and *educating girls* solutions). This would require the clearing of forest and grassland for food production, with associated emissions from land conversion.

All three Drawdown scenarios show agricultural production sufficient to meet food demand and provide a surplus that can be used in bio-based industry, for example as feedstock for *bioplastic* production. Due to this surplus, no land clearing is necessary, resulting in impressive emissions reduction from avoided deforestation. Because population change (resulting from *educating girls* and *family planning*), *plant-rich diet*, and *reduced food waste* are the principal drivers of this effect, Drawdown allocates the resulting

reduction in emissions from land clearing to these solutions. However, as the impacts of population on yield and food demand are highly complex, we do not include avoided land conversion emissions associated with population change in the final emissions calculations for those solutions.

Bamboo is included in the yield model as new adoption takes place on degraded grassland, displacing grazing.

The Biomass Model

Drawdown's Biomass model begins with projected global biomass demand through 2060, based on FAO historical data and other sources, in categories including sawnwood, other woody biomass, and herbaceous biomass (which includes crop residues). It determines the impact of demand reduction solutions including *clean cookstoves* and *recycled paper*, resulting in an adjusted demand projection through 2060. Biomass supply reductions are modeled as well, which result from protection of forests, reducing biomass availability. Biomass supply increases are modeled through the increased adoption of solutions including *afforestation, bamboo, perennial biomass* and agroforestry solutions like *tree intercropping, silvopasture,* and *multistrata agroforestry*. Biomass availability from crop residues, *seaweed farming*, and dedicated biomass crops planted on cropland freed up by *sustainable intensification* is also modeled.

Surplus biomass is allocated to climate solutions that require biomass as feedstock. These include *biochar, biomass electricity, bioplastic, 2nd generation biofuels, building with wood, insulation, small-scale biogas,* and *district heating*. This biomass feedstock allocation was a constraint to the adoption of this solution.

2.8 LIMITATIONS/FURTHER DEVELOPMENT

Data on soil carbon sequestration of bamboo is currently scarce and there is lack of consistency in measurements in the literature regarding: i) total ecosystem carbon stocks versus detailed analyses of above- and below-ground biomass as well as soil carbon stocks and ii) biomass or carbon stocks vs. sequestration rates. This is associated with high uncertainty regarding C accumulation potentials of bamboo stands (Nath et al., 2015b; Yuen et al., 2017). In recent years, a study by (Zachariah, Sabulal, Nair, Johnson, & Kumar, 2016) has suggested that bamboo might contribute to higher C emissions than previously thought – while the majority of current literature points towards net C sequestration rather than emissions from bamboo, this point should be considered carefully as more research emerges on the subject.

It is likely that better modeling could be done in the future if improved numbers become available. Adjusting the model to use carbon store data rather than, or in addition to, annual sequestration rates might also allow to include data from broader geographical areas, and to include data for soil carbon pools. Current lack of data is exacerbated by the current lack of cohesive and uniform methods to measure biomass and C stocks in biomass for all bamboo species, which are in part due to high variation in factors such as growth

behavior, height and age - not only across the thousands of known bamboo species but also within stands of single species (Nath et al., 2015b).

There is currently very little data available regarding establishment and operational costs of bamboo plantations outside of India and China. As costs likely vary greatly by species, country, and management intensity, the inclusion of additional data for costs and profits in Africa, South America, and the United States would be valuable if this data becomes available in the future. Moreover, the full economic benefits of bamboo were not captured by the model as profit figures focused on the sale of harvested bamboo rather any finished products with added value (and benefits in terms of employment etc.). The full environmental & carbon benefits of bamboo were not captured by the model since avoided emissions from substitution of bamboo for other materials was not included. This would require quantifying how much concrete, steel, aluminum, plastic, etc. was avoided by a given amount of bamboo and then comparing LCAs for each material, and relevant data to undertake this type of calculations is currently scarce.

Data on current and future bamboo adoption is quite limited and is highly dependent on species type and age (with slightly better data for China). The term "bamboo" encompasses a large number of species that vary greatly in terms of usefulness, economic benefits, and carbon sequestration.

The general lack of reliable data about the economic and ecologic benefits of bamboo has been recognized by INBAR, which has acknowledged that most existing datasets are outdated and inaccurate at present. In order to address this, a current global assessment is underway (Ling, Christensen, Donnison, Belmonte, & Brown, n.d.) and should be reviewed and incorporated into Drawdown models upon publication.

3 RESULTS

3.2 ADOPTION

Below are shown the world adoptions of the solution in some key years of analysis in functional units and percent for the three Project Drawdown scenarios.

Total adoption in the *Plausible* Scenario is 115.89 million hectares in 2050, representing 34 percent of the total suitable land. Of this, 82.17 million hectares are adopted from 2020-2050.

Total adoption in the *Drawdown* Scenario is 208.50 million hectares in 2050, representing 62 percent of the total suitable land. Of this, 174.78 million hectares are adopted from 2020-2050.

Total adoption in the *Optimum* Scenario is 277.62 million hectares in 2050, representing 82 percent of the total suitable land. Of this, 243.90 million hectares are adopted from 2020-2050.

Table 3.1 World Adoption of the Solution

Solution	Units	Base Year (2014)	New Adoption by 2050		
			Plausible	Drawdown	Optimum
Forest plantations	Mha	34.0	82.17	174.78	243.90
	% Total Land Available	10%	34%	62%	82%

World Adoption in Mha

World Adoption - % of TLA
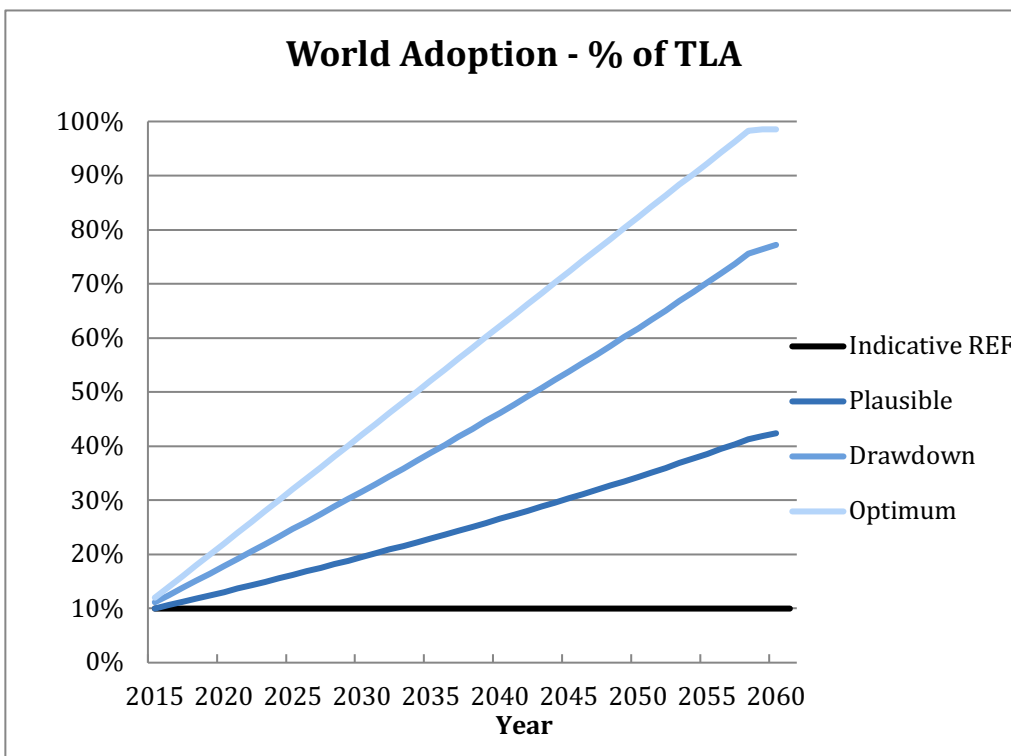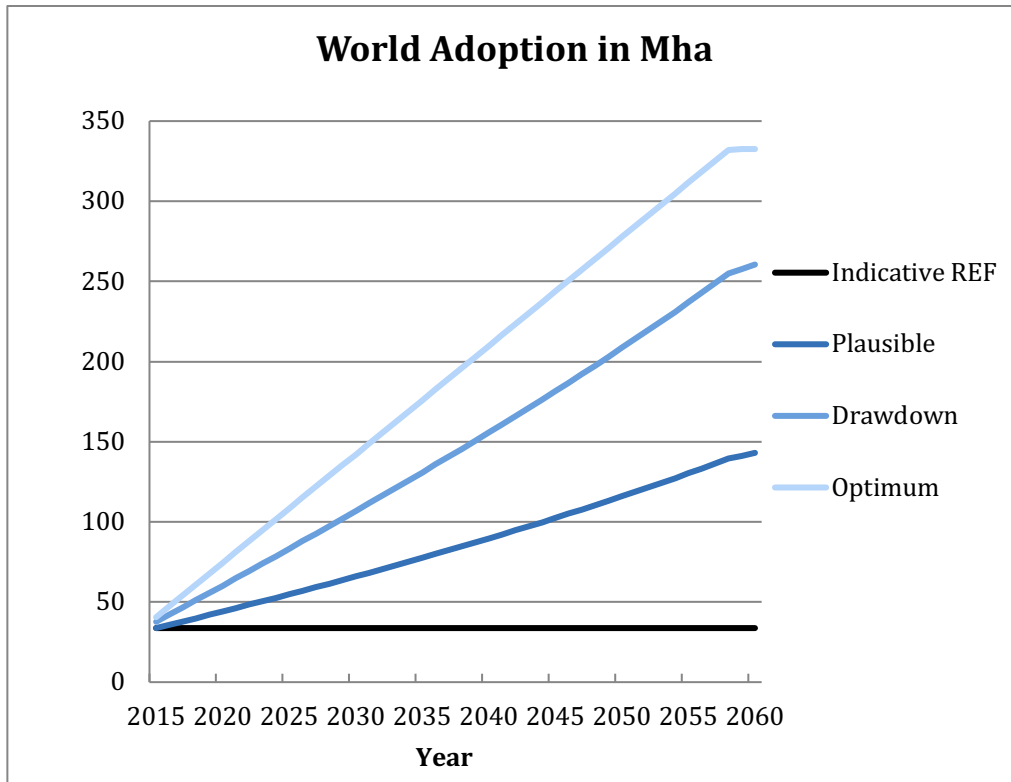
Figure 3.1 World Annual Adoption 2020-2050 in Mha (a) and as a percentage of TLA (b).

3.3 CLIMATE IMPACTS

Below are the emissions results of the analysis for each scenario which include total emissions reduction, atmospheric concentration changes, and sequestration where relevant. For a detailed explanation of each result, please see the glossary (Section 6).

Carbon sequestration impact is 9.56, 21.06, and 30.47 gigatons of carbon-dioxide equivalent in the *Plausible, Drawdown,* and *Optimum* Scenarios respectively.

Table 3.2 Climate Impacts

Scenario	Maximum Annual Emissions Reduction	Total Emissions Reduction	Max Annual CO$_2$ Sequestered	Total Additional CO$_2$ Sequestered	Total Atmospheric CO$_2$-eq Reduction	Emissions Reduction in 2030	Emissions Reduction in 2050
	(Gt CO$_2$-eq/yr.)	*Gt CO$_2$-eq/yr. (2020-2050)*	*(Gt CO$_2$-eq/yr.)*	*Gt CO$_2$-eq/yr. (2020-2050)*	Gt CO$_2$-eq (2020-2050)	*(Gt CO$_2$-eq/year)*	*(Gt CO$_2$-eq/year)*
Plausible	-0.05	-0.76	0.61	10.32	9.56	0.22	0.57
Drawdown	-0.10	-1.67	1.30	22.73	21.06	0.50	1.21
Optimum	-0.13	-2.42	1.82	32.88	30.47	0.75	1.68

The solution was integrated with all other Project Drawdown solutions and may have different emissions results from the models. This is due to adjustments caused by interactions among solutions that limit full adoption (such as by feedstock or demand limits) or that limit the full benefit of some solutions (such as reduced individual solution impact when technologies are combined).

Table 3.3 Impacts on Atmospheric Concentrations of CO2-eq

Scenario	GHG Concentration Change in 2050	GHG Concentration Rate of Change in 2050
	PPM CO$_2$-eq (2050)	*PPM CO$_2$-eq change from 2049-2050*
Plausible	0.81	0.04

Scenario	GHG Concentration Change in 2050	GHG Concentration Rate of Change in 2050
	PPM CO₂-eq (2050)	*PPM CO₂-eq change from 2049-2050*
Drawdown	1.78	0.09
Optimum	2.57	0.13
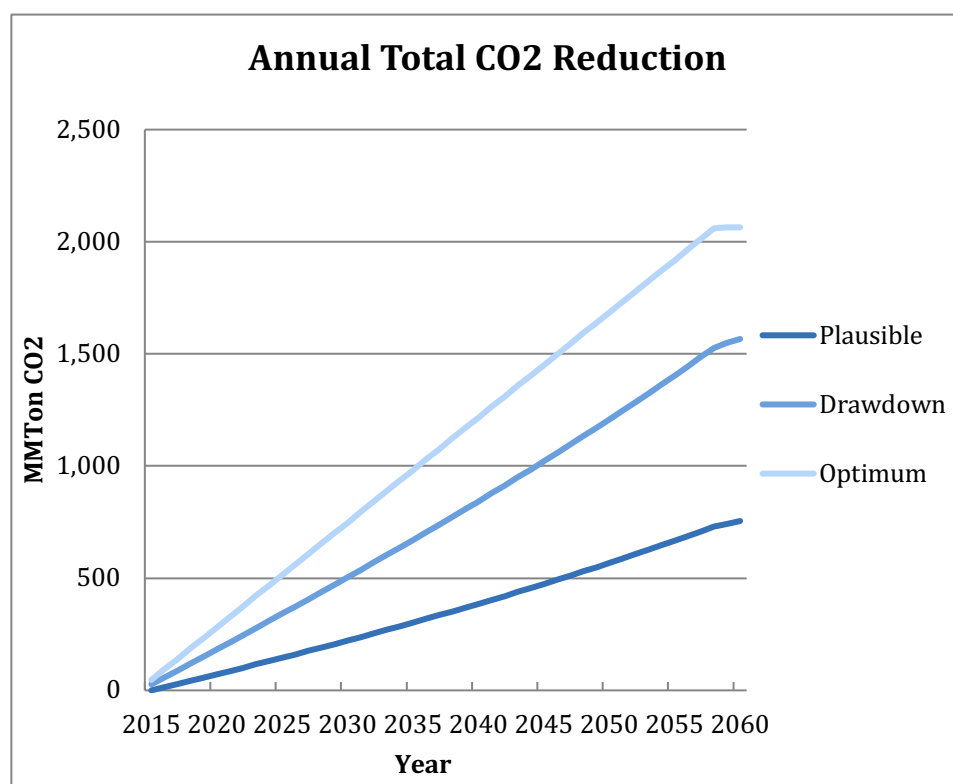
Figure 3.2 World Annual Greenhouse Gas Emissions Reduction

3.4 FINANCIAL IMPACTS

Below are the financial results of the analysis for each scenario. For a detailed explanation of each result, please see the glossary.

Note that the financial results have changed from those published in the first edition of the *Drawdown* book.

For the *Plausible* Scenario, the cumulative first cost of adoption is US$ 82.78 billion. Marginal first cost is the same as cumulative first cost. Net operating savings are US$ -101.45 billion, and the net profit margin

and lifetime profit margin are US$ 961.69 billion and US$1943.47 billion respectively. Lifetime cashflow savings NPV is US$-32.79 billion.

 For the *Drawdown* Scenario, the cumulative first cost of adoption is US$180.06 billion. Marginal first cost is the same as cumulative first cost. Net operating savings are US$-223.25 billion, and the net profit margin and lifetime profit margin are US$2116.22 billion and US$4227.30 billion respectively. Lifetime cashflow savings NPV is US$-76.29 billion.

For the *Optimum* Scenario, the cumulative first cost of adoption is US$254.26 billion. Marginal first cost is the same as cumulative first cost. Net operating savings are US$ -322.76 billion, and the net profit margin and lifetime profit margin are US$3059.45 billion and US$5976.60 billion respectively. Lifetime cashflow savings NPV is US$-112.74 billion.

Table 3.4 Financial Impacts

Scenario	Cumulative First Cost	Marginal First Cost	Net Operating Savings	Net Profit Margin	Lifetime Profit Margin	Lifetime Cashflow Savings NPV (of All Implementation Units)
	2015-2050 Billion USD	*2015-2050 Billion USD*	*2020-2050 Billion USD*	*2020-2050 Billion USD*	*2020-2050 Billion USD*	*Billion USD*
Plausible	82.78	82.78	-101.45	961.69	1943.47	-32.79
Drawdown	180.06	180.06	-223.25	2116.22	4227.30	-76.29
Optimum	254.26	254.26	-322.76	3059.45	5976.60	-112.74
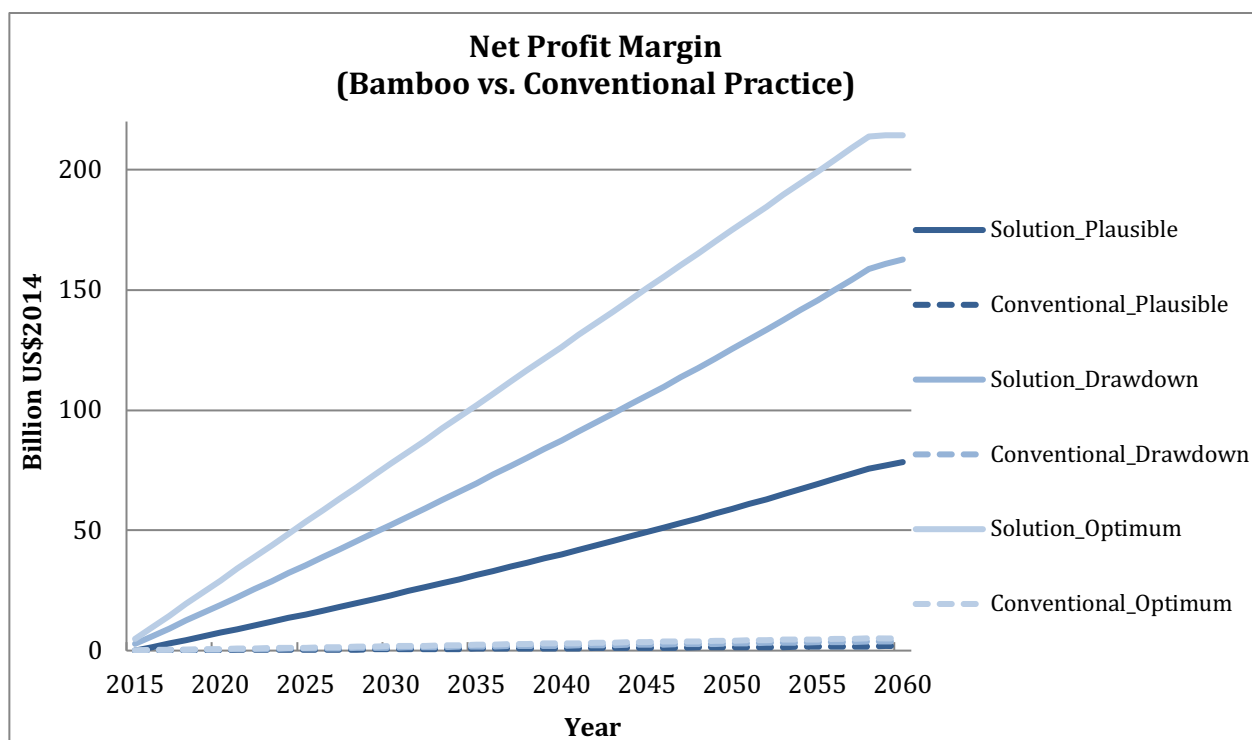
Figure 3.3 Net Profit Margin Increase

4 DISCUSSION

These results show that bamboo is a promising multifunctional mitigation solution, particularly when applied to unused or unproductive degraded lands. Particularly when applied to sloping, degraded lands, bamboo can restore land to economically and socially beneficial uses while stabilizing and improving the soil. Because it grows and matures quickly, bamboo can generate income and food in a comparatively short period of time following planting, while sequestering carbon in soil, biomass, and durable products. These products, in turn, help provide profits and incentive to plant and maintain more bamboo.

4.2 LIMITATIONS

Drawdown figures for current adoption are based on FAO data and two recent peer-reviewed publications by (FAO, 2010; Lobovikov et al. 2012; Du et al. 2018). To date, Drawdown's approach is principally limited by data limitations in the current literature, particularly for areas outside of China and India (Yuen et al., 2017). Data points documenting carbon sequestration are limited and currently do not take into account soil C pools, even though these might constitute a significant C storage component in bamboo ecosystems. Extrapolating sequestration rates from the few areas represented in the literature to all bamboo systems globally is likely inaccurate. A more accurate approach might utilize earth systems models that model carbon pools based on localized data inputs, but such an approach is computationally intense and beyond the scope of our work.

The case for bamboo would be made stronger if avoided emissions from substituting it for products with more intensive carbon LCAs were calculated. Our results would be made more accurate by including carbon impacts of establishing, maintaining, harvesting, manufacturing, and shipping related to bamboo and bamboo products.

Similarly, financial components of our model were based on a limited number of studies from a limited number of areas. Since agricultural markets are highly localized, especially in communities where producers are primarily smallholders, access to markets, input costs, and prices differ broadly.

Given these limitations, our model outcomes should not be taken as completely accurate but as being indicative of the general scale and direction of *bamboo*'s drawdown capacity given current knowledge.

4.3 BENCHMARKS

A recent study by Z. Song, Liu, Strömberg, Yang, & Zhang (2017) estimates current C sequestration in terrestrial bamboo biomes at 0.16 ± 0.9 Gt of CO_2-equivalent per year. In comparison, Drawdown's *bamboo*

model results indicate annual C sequestration rates of $0.2 - 0.75$ Gt of CO_2-equivalent per year in 2030. This range is plausible, particularly assuming some expansion of current bamboo areas by 2030.

Table 4.1 Benchmarks

Source and Scenario	Biomass Type	Total Mitigation Impact Gt $CO_{2\text{-}eq}$ in 2030
Song (2017)	Bamboo in 2017	0.07-0.23
Plausible Scenario	Bamboo in 2030	0.39
Drawdown Scenario	Bamboo in 2030	0.60
Optimum Scenario	Bamboo in 2030	0.69

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6 GLOSSARY

Adoption Scenario – the predicted annual adoption over the period 2015 to 2060, which is usually measured in **Functional Units**. A range of scenarios is programmed in the model, but the user may enter her own. Note that the assumption behind most scenarios is one of growth. If for instance a solution is one of reduced heating energy usage due to better insulation, then the solution adoption is translated into an increase in use of insulation. There are two types of adoption scenarios in use: **Reference (REF)** where global adoption remains mostly constant, and **Project Drawdown Scenarios (PDS)** which illustrate high growth of the solution.

Approximate PPM Equivalent – the reduction in atmospheric concentration of CO_2 (in **PPM**) that is expected to result if the **PDS Scenario** occurs. This assumes a discrete avoided pulse model based on the Bern Carbon Cycle model.

Average Abatement Cost – the ratio of the present value of the solution (**Net Operating Savings** minus **Marginal First Costs**) and the **Total Emissions Reduction**. This is a single value for each solution for each **PDS Scenario**, and is used to build the characteristic "*Marginal Abatement Cost*" curves when Average Abatement Cost values for each solution are ordered and graphed.

Average Annual Use – the average number of functional units that a single implementation unit typically provides in one year. This is usually a weighted average for all users according to the data available. For instance, total number of passenger-km driven by a hybrid vehicle in a year depends on country and typical number of occupants. We take global weighted averages for this input. This is used to estimate the **Replacement Time**.

Cumulative First Cost – the total **First Cost** of solution **Implementation Units** purchased in the **PDS Scenario** in the analysis period. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

Direct Emissions – emissions caused by the operation of the solution, which are typically caused over the lifetime of the solution. They should be entered into the model normalized per functional unit.

Discount Rate- the interest rate used in discounted cash flow (DCF) analysis to determine the present value of future cash flows. The discount rate in DCF analysis takes into account not just the time value of money, but also the risk or uncertainty of future cash flows; the greater the uncertainty of future cash flows, the higher the discount rate. Most importantly, the greater the discount rate, the more the future savings are devalued (which impacts the financial but not the climate impacts of the solution).

Emissions Factor– the average normalized emissions resulting from consumption of a unit of electricity across the global grid. Typical units are kg CO_2e/kWh.

First Cost- the investment cost per **Implementation Unit** which is essentially the full cost of establishing or implementing the solution. This value, measured in 2014$US, is only accurate to the extent that the cost-based analysis is accurate. The financial model assumes that the first cost is made entirely in the first year of establishment and none thereafter (that is, no amortization is included). Thus, both the first cost and operating cost are factored in the financial model for the first year of implementation, all years thereafter simply reflect the operating cost until replacement of the solution at its end of life.

Functional Unit – a measurement unit that represents the value, provided to the world, of the function that the solution performs. This depends on the solution. Therefore, LED Lighting provides petalumen-hours of light, Biomass provides tera-watt-hours of electricity and high speed rail provides billions of passenger-km of mobility.

Grid Emissions – emissions caused by use of the electricity grid in supplying power to any operation associated with a solution. They should be in the units described below each variable entry cell. Drawdown models assume that the global electric grid, even in a Reference Scenario, is slowly getting cleaner, and that emissions factors fall over time resulting in lower grid emissions for the same electricity demand.

Implementation Unit – a measurement unit that represents how the solution practice or technology will be installed/setup and priced. The implementation unit depends on the solution. For instance, implementing electric vehicles (EV) is measured according to the number of actual EV's in use, and adoption of Onshore Wind power is measured according to the total terawatts (TW) of capacity installed worldwide.

Indirect Emissions – emissions caused by the production or delivery or setup or establishment of the solution in a specified area. These are NOT caused by day to day operations or growth over time, but they should be entered into the model normalized on a per functional unit or per implementation unit basis.

Learning Rate/Learning Curve - Learning curves (sometimes called experience curves) are used to analyze a well-known and easily observed phenomenon: humans become increasingly efficient with experience. The first time a product is manufactured, or a service provided, costs are high, work is inefficient, quality is marginal, and time is wasted. As experienced is acquired, costs decline, efficiency and quality improve, and waste is reduced. The model has a tool for calculating how costs change due to learning. A 2% learning rate means that the cost of producing a *good* drops by 2% every time total production doubles.

Lifetime Capacity – this is the total average functional units that one implementation unit of the solution or conventional technology or practice can provide before replacement is needed. All technologies have an average lifetime usage potential, even considering regular maintenance. This is used to estimate the **Replacement Time**. and has a direct impact on the cost to install/acquire technologies/practices over time. E.g. solar panels generate, on average, a limited amount of electricity (in TWh) per installed capacity (in TW) before a new solar panel must be purchased. Electric vehicles can travel a limited number of passenger kilometers over its lifetime before needing to be replaced.

Lifetime Operating Savings–the operating cost in the PDS versus the REF scenarios over the lifetime of the implementation units purchased during the model period regardless of when their useful life ends.

Lifetime Cashflow NPV-the present value (PV) of the net cash flows (PDS versus REF) in each year of the model period (2015-2060). The net cash flows include net operating costs and first costs. There are two results in the model: Lifetime Cashflow NPV for a Single **Implementation Unit**, which refers to the installation of one **Implementation Unit**, and Lifetime Cashflow NPV of All Units, which refers to all **Implementation Units** installed in a particular scenario. These calculations are also available using profit inputs instead of operating costs.

Marginal First Cost – the difference between the **First Cost** of all units (solution and conventional) installed in the **PDS Scenario** and the **First Cost** of all units installed in the **REF Scenario** during the analysis period. No discounting is performed. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

Net Annual Functional Units (NAFU) – the adoption in the PDS minus the adoption in the REF in each year of analysis. In the model, this represents the additional annual functional demand captured either by the solution in the **PDS Scenario** or the conventional in the **REF Scenario**.

Net Annual Implementation Units (NAIU) – the number of **Implementation Units** of the solution that are needed in the PDS to supply the **Net Annual Functional Units (NAFU).** This equals the adoption in the PDS minus the adoption in the REF in each year of analysis divided by the average annual use.

Net Operating Savings – The undiscounted difference between the operating cost of all units (solution and conventional) in the **PDS Scenario** minus that of all units in the **REF Scenario**.

Operating Costs – the average cost to ensure operation of an activity (conventional or solution) which is measured in 2014$US/**Functional Unit**. This is needed to estimate how much it would cost to achieve the adoption projected when compared to the **REF Case**. Note that this excludes **First Costs** for implementing the solution.

Payback Period – the number of years required to pay all the **First Costs** of the solution using **Net Operating Savings**. There are four specific metrics each with one of **Marginal First Costs** or **First Costs** of the solution only combined with either discounted or non-discounted values. All four are in the model. Additionally, the four outputs are calculated using the increased profit estimation instead of **Net Operating Savings**.

PDS/ Project Drawdown Scenario – this is the high growth scenario for adoption of the solution

PPB/ Parts per Billion – a measure of concentration for atmospheric gases. 10 million PPB = 1%.

PPM/ Parts per Million – a measure of concentration for atmospheric gases. 10 thousand PPM = 1%.

REF/ Reference Scenario – this is the low growth scenario for adoption of the solution against which all **PDS scenarios** are compared.

Regrets solution has a positive impact on overall carbon emissions being therefore considered in some scenarios; however, the social and environmental costs could be harmful and high.

Replacement Time- the length of time in years, from installation/acquisition/setup of the solution through usage until a new installation/acquisition/setup is required to replace the earlier one. This is calculated as the ratio of **Lifetime Capacity** and the **Average Annual Use**.

TAM/ Total Addressable Market – represents the total potential market of functional demand provided by the technologies and practices under investigation, adjusting for estimated economic and population growth. For this solutions sector, it represents world and regional total addressable markets for electricity generation technologies in which the solutions are considered.

Total Emissions Reduction – the sum of grid, fuel, indirect, and other direct emissions reductions over the analysis period. The emissions reduction of each of these is the difference between the emissions that would have resulted in the **REF Scenario** (from both solution and conventional) and the emissions that would result in the **PDS Scenario**. These may also be considered as "emissions avoided" as they may have occurred in the REF Scenario, but not in the PDS Scenario.

Transition solutions are considered till better technologies and less impactful are more cost effective and mature.

TWh/ Terawatt-hour – A unit of energy equal to 1 billion kilowatt-hours