**Technical assessment for**

**Afforestation**

Sector: Land Use

Agency Level: Land Manager

Keywords: Biosequestration, Biomass Crops

AUGUST 2019

**Prepared by:**

Ryan Hottle, Senior Fellow

Urmila Malvadkar, Research Fellow

Johnnie Chamberlin, Junior Fellow

Ariani Wartenberg, Research Fellow



27 GATE 5 RD., SAUSALITO, CA 94965 [info@drawdown.org](mailto:info@drawdown.org) [www.drawdown.org](http://www.drawdown.org)

Table of Contents

[List of Figures 4](#_Toc18443073)

[List of Tables 4](#_Toc18443074)

[Executive Summary 5](#_Toc18443075)

[1. Literature Review 6](#_Toc18443076)

[1.1. State of the Practice 6](#_Toc18443077)

[1.2. Adoption Path 9](#_Toc18443078)

[1.2.1 Current Adoption 9](#_Toc18443079)

[1.2.2 Trends to Accelerate Adoption 9](#_Toc18443080)

[1.2.3 Barriers to Adoption 11](#_Toc18443081)

[1.2.4 Adoption Potential 12](#_Toc18443082)

[1.3 Advantages and disadvantages of Forest plantations 12](#_Toc18443083)

[1.3.1 Similar Solutions 12](#_Toc18443084)

[1.3.2 Arguments for Adoption 13](#_Toc18443085)

[1.3.3 Additional Benefits and Burdens 14](#_Toc18443086)

[2 Methodology 16](#_Toc18443087)

[2.1 Introduction 16](#_Toc18443088)

[2.2 Data Sources 16](#_Toc18443089)

[2.3 Total Available Land 17](#_Toc18443090)

[2.4 Adoption Scenarios 18](#_Toc18443091)

[2.4.1 Reference Case / Current Adoption 19](#_Toc18443092)

[Project Drawdown Scenarios 19](#_Toc18443093)

[2.5 Inputs 20](#_Toc18443094)

[2.5.1 Climate Inputs 20](#_Toc18443095)

[2.5.2 Financial Inputs 21](#_Toc18443096)

[2.6 Assumptions 22](#_Toc18443097)

[2.7 Integration 23](#_Toc18443098)

[2.8 Limitations/Further Development 26](#_Toc18443099)

[3 Results 27](#_Toc18443100)

[3.2 Adoption 27](#_Toc18443101)

[3.3 Climate Impacts 29](#_Toc18443102)

[3.4 Financial Impacts 30](#_Toc18443103)

[4 Discussion 33](#_Toc18443104)

[4.2 Limitations 34](#_Toc18443105)

[4.3 Benchmarks 34](#_Toc18443106)

[5 References 36](#_Toc18443107)

[6 Glossary 41](#_Toc18443108)

# List of Figures

[Figure 3.1 World Annual Adoption 2020-2050 in Mha (a) and as a percentage of TLA (b). 28](#_Toc18443109)

[Figure 3.2 World Annual Greenhouse Gas Emissions Reduction 30](#_Toc18443110)

[Figure 3.3 Net Profit Margin Increase 32](#_Toc18443111)

# List of Tables

[Table 1.1: Average Annual Growth Rate in Planted Forest (FAO 2015) 9](#_Toc18443153)

[Table 1.2: Land Use Solutions Comparison: Economic Impacts 14](#_Toc18443154)

[Table 1.3: Land Use Solutions Comparison: Social and Climate Impacts 15](#_Toc18443155)

[Table 2.1 Climate Inputs 20](#_Toc18443156)

[Table 2.2 Financial Inputs for Conventional Practice (Grazing on Degraded Lands) 22](#_Toc18443157)

[Table 3.1 World Adoption of the Solution 27](#_Toc18443158)

[Table 3.2 Climate Impacts 29](#_Toc18443159)

[Table 3.3 Impacts on Atmospheric Concentrations of CO2-eq 29](#_Toc18443160)

[Table 3.4 Financial Impacts 31](#_Toc18443161)

[Table 4.1: Benchmarks 35](#_Toc18443162)

# Executive Summary

Climate mitigation literature often fails to differentiate between *afforestation* and other "afforestation" systems such as *bamboo* and *perennial biomass*, grouping these systems together. Project Drawdown defines *afforestation* as productive tree plantations established through afforestation, e.g. on previously non-forested land (which includes abandoned or degraded pasture- or cropland or other marginal land).

This solution has the potential to provide alternatives to deforestation for the logging industry and to contribute to carbon sequestration and restoration of degraded land. It has been widely promoted as a land-based mitigation strategy due in part to its high carbon sequestration rates in soils and above- and belowground tree biomass. Drawdown's forest plantations scenarios are more modest than others existing in current literature. This is because under Drawdown modeling hierarchy, other tree-focused solutions with high sequestration rates are given higher priority, including agroforestry, forest restoration, and tree cropping approaches. Drawdown also models *bamboo* and *perennial biomass* independently. Nonetheless, forest plantations are of critical importance for mitigation, building material, and restoration of degraded lands.

In Drawdown’s Agroecological Zone model *afforestation* is established on degraded grazing land, much of which was formerly forested. The current extent of afforested forest plantations systems is estimated at 291 million hectares globally. Future adoption potential was modeled based on FAO data and IPCC and regional projections and is constrained principally by high establishment costs and the necessity for suitable climatic conditions. Adoption is determined at the farmer- or landowner-level, and impacts were modeled for C sequestration, establishment and operational costs and profitability, based on case-study data from peer reviewed literature.

Under the projected *Plausible* Scenario, total adoption is 88 million hectares in 2050. The sequestration impact of this scenario is 19.1 Gt CO2 eq. by 2050. Cumulative first cost is US $83.45 billion, with a net profit margin of US$725.87 billion. Under the *Drawdown* Scenario, total adoption is 130 million hectares in 2050. The sequestration impact under this scenario is 28.4 Gt of CO2 eq. by 2050. Cumulative first cost is US $123.77 billion, with net profit margin of US$1,116.62 billion. Under the *Optimum* Scenario, projected total adoption is 153 million hectares in 2050. The sequestration impact under this scenario is 37 Gt of CO2 eq. by 2050. Cumulative first cost is US $151.02 billion, with net profit margin of US$1,456.60 billion.

# Literature Review

Afforestation is a tree-based production systems established in forest plantations; these can take extremely varied and diverse forms and can be applied across a range of climates and at different scales. Increased recognition of their many environmental and economic benefits, particularly in the context of climate change and deforestation, coupled with improved national or regional incentive mechanisms, is likely to significantly increase future adoption rates of this solution at the farmer / landowner agency level.

## State of the Practice

According to the FAO’s most recent Global Forest Resource Assessment, global forest area has increased by about 291 million hectares between 1990-2010 due to afforestation expansion (FAO, 2010). The FAO’s definition of afforestation refers to the establishment of commercial forests, agroforests or forest conservation areas on previously non-forested land, and thus includes *afforestation.* Drawdown defines *afforestation* as productive plantations established through afforestation, e.g. on previously non-forested land (which includes abandoned or degraded pasture- or cropland or other marginal land).

Afforestation includes both monocultures and mixed stands and can consist of native or non-native species; they are established to provide industrial timber, fiber and pulp products. Establishment requires the preparation of previously non-forested land, and the procurement and planting of tree seedlings. While about 10% of commercial plantations yield biofuel or non-timber forest products (FAO, 2010; Lamb, Erskine, & Parrotta, 2005), these are excluded from Project Drawdown’s definition to avoid overlap with the *perennial biomass* solution, which focuses on biofuel crops (Drawdown 2016). Some of the most common species groups found in current forest plantations are: *Acacia* spp., *Eucalyptus* spp., *Pinus* spp., and *Tectona* spp., along with other coniferous and broadleaf species.

Global afforestation, which includes establishment of new forest plantations, has been predicted to expand at an average annual rate of 1.9 - 3.6 Mha through 2030 (Lambin & Meyfroidt, 2011; Paquette & Messier, 2009) . Most current documented afforestation areas are concentrated in boreal and temperate regions (FAO, 2016), although expansion in tropical regions is also increasing through increased participation in multilateral programs like the NY Declaration of Forests or the Bonn Challenge. To date, China has the highest global growth rate in afforestation since 1990, due to extensive investments for ambitious initiatives, for instance the “Grain for Green” program (Dunne, 2018) .

Through the application of sustainable forest management practices, forest plantations have the potential to store significantly more carbon than pastures, croplands, or grasslands. Management practices that can encourage biomass growth and carbon sequestration include maintaining partial forest cover, planting directly after harvest to reduce carbon loss, selecting fast-growing tree species, practicing selective cutting rather than clear cutting, using targeted fertilizer application, etc. Other practices like thinning have more nuanced benefits: while they may reduce carbon storage potentials, they have also been shown to improve plantation productivity through increased average tree sizes (Thornley & Cannell, 2000).

The relative importance of economic priorities and ecological concerns can drive the location of forest plantation establishment: selection of suitable areas for planting is essential to not only promote higher production levels but also to ensure ecological stability. In areas with unsuitable climates for tree-growth, tree establishment might lead to water-stresses. In such areas, grasslands are more likely to establish than forests, particularly on already degraded, depleted or compacted soils. In suitable climates with sufficient rainfall, however, establishment of forest plantations on degraded land might contribute to soil restoration by reducing the risk of erosion, boosting soil carbon and improving water quality.

***Carbon Sequestration and Lifetime Carbon Stock Benefits***

Reported carbon uptake by afforested tree plantations established on degraded crop- or range-land varies widely, ranging from 0.5 – 11.4 tC/ha/yr in existing literature (Nosetto, Jobbágy, & Paruelo, 2006; Smith, 2014).Case studies in the literature illustrate that carbon sequestration potential of forest plantations systems can be highly variable and depends on a number of factors, including previous land use and current management practices (e.g. Luyssaert et al., 2008; Martin, Newton, & Bullock, 2013). Accurately estimating carbon stocks and sequestration remains challenging, and the science is still evolving.

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. The Drawdown model does not account for existing carbon stocks but rather focuses on annual sequestration rates in soils and vegetation biomass.

***Variables and Uncertainties in Carbon Sequestration Calculations***

Within afforested forest plantations established in different regions and climates, carbon sequestration rates over time are influenced by many factors. One significant factor is potential 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). (Gibbs, Brown, Niles, & Foley, 2007) moreover describe different ways of measuring carbon stock: biome averages, estimations from tree surveys, and technological measurements. Even within a biome, biomass can vary greatly. Nevertheless, 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. Tree survey methods use allometric equations to estimate above-ground and below-ground biomass. However, particularly in the diverse tropics, tree surveys may not produce an accurate measurement of overall biomass, as allometric relationships vary by species and are not available for all species, and as there may be significant variation even between individual trees of a single species. Lastly, technological methods using optical, radar, and laser sensors may be uncertain, expensive, or inappropriate for one or more land and forest types.

In addition, carbon sequestration rates are based on broad assumptions regarding the fate of harvested timber. In reality, the fate of carbon from plantation products is highly variable: it can be reemitted quickly into the atmosphere if biomass is burned or decomposed or can alternatively be sequestered for the medium- to long-term in durable wood-based products (construction materials, flooring, furniture, wood pulp for paper or cardboard, etc). Accurate life-cycle assessments for these different options are still being developed.

***Economics Benefits***

Afforestation costs and profits vary greatly depending on location and policies - even within a country or region. For instance, establishment costs depend on whether the existing landowner is afforesting their own land or if land must be purchased for a forest plantations project. Profits for timber plantations depend on species, location, management, and use of harvested material. While management and maintenance costs are typically incurred every year, income from harvests occurs less regularly, generally when plantations are thinned or during final harvest (Cubbage et al., 2007) . Average annual net profits similarly range widely and are significantly impacted by government subsidies or leasing of plantation lands for hunting, as both types of interventions can provide additional and/or more regular sources of income for plantation owners (Cubbage et al., 2007; Mengak, 2009).

## Adoption Path

Current adoption of afforestation is estimated at about 291 Mha. This figure is likely to increase due to the practice’s rapidly increasing recognition and integration into strategies to address deforestation and land degradation developed by international organization such as the IPCC, the FAO or the UN, and by a growing number of national governments. Increased recognition of the tangible benefits of the practice remains limited by a lack of data, and increased adoption remains hampered by economic challenges such as high risks of loss and long-term payoffs, which are exacerbated by the current lack of relevant policies and incentive schemes. Nevertheless, countries like China and India have successful pioneered innovative approaches to increase afforestation through forest plantations, and other countries are likely to follow suit in the next.

### Current Adoption

According to the (FAO, 2010), the global area of afforestation has increased by about 291 Mha between 1990-2010, nearly doubling in the boreal region over this time period. Drawdown assumes that this reported afforestation activity mostly took the form of *afforestation* establishment. Average annual growth rates of new forest plantations have fluctuated in the last decades (Table 1), and various interpretations of these fluctuations and other global trends and agreements are reflected in Drawdown’s future adoption scenarios for this solution. Both economic forces and government policies have contributed to the increase in afforested forest plantations this is likely to continue impacting forest plantations trends going forward.

Table .**: Average Annual Growth Rate in Planted Forest (FAO 2015)**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Time Period** | **1990 - 2015** | **1990 - 2000** | **2000 - 2010** | **2010 – 2015** |
| **Avg. Growth Rate (Mha/yr)** | 4.2 | 3.6 | 5.3 | 3.2 |

### Trends to Accelerate Adoption

Successful and long-term conversion of suitable degraded or marginal land to afforestation requires strong support and cooperation from local stakeholders (Agyeman et al., 2003) . Landowners and communities are more likely to support forest plantations projects that provide tangible benefits such as commercial wood production or ecosystem services (Schneider, Pohnan, & others, 2012) . Peer-pressure from local landholder groups as well as access to knowledge about sustainable forestry management practices can also increase of individual landowner’s likelihood of forest plantation establishment (Schirmer & Bull, 2014).

Afforestation has gained traction on the international stage, and afforestation practices like forest plantations have been identified as a potential strategy to address deforestation and land degradation by the IPCC, the FAO or the UN. As a response, several countries have included the practice in their national programs, recognizing its potential for carbon sequestration and other environmental benefits as well for economic growth. The United States, Australia, and United Kingdom currently offer tax incentives for forest plantation establishment, although the effectiveness of such programs has been questioned (Jacobson, Michael G., Greene, John L., Straka, Thomas J., Daniels, Steven E., & Kilgore, Michael A., 2009). India and China have had ambitious national afforestation projects, which focus largely on forest plantation establishment as part of efforts to reduce desertification, provide flood control, and provide forest resources (Huang, Liu, Shao, & Xu, 2012; Ravindranath, Somashekhar, & Murthy, 2008; Rudel, 2009) and provide incentives through subsidies and other types of government-funded compensation schemes (Uchida, Xu, & Rozelle, 2005). Similarly, as a response to the Bonn Challenge, the AFR100 and 20x20 initiatives have resulted in afforestation and forest plantation pledges from numerous countries in Latin American and Sub-Saharan Africa.

Another type of approach is that of “carbon offset” or “carbon credit” mechanisms, through which actors (from individual to national scales) offset carbon emissions by financing carbon sequestration elsewhere, often through forest plantations projects. To this end, the Kyoto Protocol instituted the Clean Development Mechanism (CDM) which allows industrialized nations to finance forest plantations and other carbon sequestration projects in developing countries to reach their emission reduction target. As payment for forest plantations projects is often cheaper than energy reduction, many countries participated in the scheme and the CDM has provided an important source of funds for forest plantations in recent years.

There are additional incentive mechanisms that can contribute to increased adoption of forest plantations. For instance, sustainable forestry certification programs such Forestry Stewardship Council (FSC) and building certification programs like Leadership in Energy & Environmental (LEED) incentivize sourcing wood from sustainably managed timber plantations and are already popular globally and expanding. Developing a market for other/non-traditional forest products can also encourage the establishment of forest plantations. In the southeastern United States, plantation owners can lease their lands during hunting season, for $20+ /ha/yr and sometimes more (Mengak, 2009). In Ecuador, edible mushrooms provided much earlier financial returns than timber products; a mushroom processing plant inspired nearby communities to start timber plantations (Farley, 2010).

### Barriers to Adoption

Complex feedback loops between forest growth and climate change can complicate carbon uptake calculations. In areas well-suited for tree growth, increased atmospheric CO2 can foster biomass growth and lead to increased carbon uptake (McGrath & Lobell, 2013). However, climate change simultaneously increases the risk of disturbance and subsequent large releases of sequestered carbon through drought, warmer winters, increased fires, and increased pests (Dale et al., 2001). Forest growth can also impact water cycle regulation. For instance, afforested pasturelands in tropical regions have contributed to decreased air temperature, increased precipitation, and higher evapotranspiration (Bonan, 2008).

Planting trees in unsuitable areas, or selecting species unsuitable to local conditions, can exacerbate environmental issues, as new forest growth is highly intensive in terms of water and nutrient inputs. In arid regions, such as plains or mountains, trees planted on historical grasslands can lower the water table and cause groundwater salinization and acidification (Farley, Piñeiro, Palmer, Jobbágy, & Jackson, 2008; Jackson et al., 2005; Jobbagy & Jackson, 2004). (Cao, 2008)further documents negative environmental effects from a forest plantations project in China where non-native, high-water demand plants reduced the understory, which became vulnerable to wind erosion. The net decrease in vegetative cover and dry soils caused damaging dust storms.

In addition, many different economic challenges limit forest plantations, such as high risks of loss, high upfront costs, and the long-term payoffs. In developing countries, high inflation and uncertain profits limit forest establishment. Timber may be lost due to fire, disease, or pests, while cattle requires little time or upfront investment for a more certain return. In Panama, (Coomes, Grimard, Potvin, & Sima, 2008) found that teak plantations could bring substantial profit, that associated risks were too high for local communities. However, this can be addressed through financial incentives such as subsidies for plantation establishment or upfront cash advances for potential timber harvests.

Carbon offset mechanisms like the CDM have been particularly criticized. First, critics have challenged its complicated and expensive registration and application process can deter applying for these funds, particularly by individuals or small community groups (Thomas, Dargusch, Harrison, & Herbohn, 2010). Second, carbon offsets do not reduce absolute energy usage and does not incentivize lifestyle changes, improved industrial practices, or new technologies. Carbon offsets thus contribute to postponing the adoption of solutions that directly address excessive and unsustainable resource consumption issues at their root. Third, the issue of leakage is significant: forest plantations in one location may be matched by deforestation elsewhere. Fourth, for developing countries, committing to sequestration projects may limits future options for land use and other development. Further, poor implementation practices have harmed some local communities by denying them traditional use of forests (Boyd & others, 2009). Carbon Trade Watch, a non-profit organization that focuses on social justice, lists additional concerns about carbon offsets. They state that lack of regulation of offset markets gives unscrupulous companies the opportunity to falsely state that trees are being planted. Purchasing carbon offsets also allow companies with significantly negative environmental records to “greenwash” their practices.

### Adoption Potential

A recent study by Lal et al. (2018) estimates the current global area of land available for afforestation at about 500 Mha, which includes abandoned cropland and land degraded through erosion, chemical degradation or mining. Much of this land is in developing countries; this provides both challenges and opportunities, as forests meet basic human needs and can improve quality of life. Wood consumption dominates energy usage for much of world’s poor, with 40% of residents in developing countries using wood to cook (Cox, Crews, & Jackson, 2014). Timber plantations provide other ecosystem services, strengthening the support of communities whose livelihoods depend on the land. (Chhatre & Agrawal, 2009) found that land-tenure security can motivate communities to preserve forests. Communities with well-established communal ownership had both high rates of carbon sequestration and high forest livelihood benefits.

## Advantages and disadvantages of Forest plantations

### Similar Solutions

On appropriate lands, carbon sequestration in forests can be achieved through different pathways in addition to *afforestation* establishment: with *avoided deforestation*, land can be conserved from the get-go; alternatively, restoration or regeneration can occur through reforestation of secondary forests (*forest restoration*) or the integration of trees on agriculture/pasture lands (*agroforestry*). Compared to forest plantations, *avoided deforestation* requires less monitoring and up-front costs, protects intact ecosystems, and preserves biodiversity making it potentially more desirable from a carbon-cost perspective. However, wider implementation of forest plantations strategies might contribute to avoided deforestation if managed well and does not necessarily require a decrease in consumption levels. Global deforestation is driven both by the demand for wood products and by agricultural practices (Lambin & Meyfroidt, 2011). Tree-based solutions (*multistrata agroforestry, tree intercropping, and silvopasture*) address food-production issues while offering ecological benefits similar to those of forest plantations. *Bamboo*, which may be viewed as related to, or as a subset of, forest plantations, can contribute to the restoration of degraded lands and offers a range of benefits (including natural regeneration, food and forage production and shorter delays before harvest). An assessment of stakeholders’ priorities, in consultation with forestry experts, might help identify which of these related solutions (or combinations of them) best suits needs in a particular context.

### Arguments for Adoption

Currently existing solutions related to sustainable natural resource management are all associated with varying trade-offs between economic and ecological benefits. In the case of *afforestation,* ecological benefits can include carbon sequestration, improved air and water quality, and economic benefits include revenue from forest products (Lamb et al., 2005). Some of the more significant advantages associated with forest plantations are:

* Natural forests store more carbon than plantations or secondary forests (Chen et al., 2005; Liao, Luo, Fang, & Li, 2010). Sourcing wood from plantations dramatically reduces global harvests from natural forests (by ~26%), thus preventing deforestation and degradation and protecting the biodiversity and carbon sequestration benefits of those forests (Buongiorno & Zhu, 2014).
* While the establishment and maintenance of forest plantation might cost more than natural secondary growth, it is also associated with slightly higher carbon sequestration (Bonner, Schmidt, & Shoo, 2013). However, the high initial costs are generally met through revenues from later harvests, and the delay in compensation can be addressed through subsidies or other financial mechanisms.
* Timber plantations sequester additional carbon in durable wood products and wood can be used in place of more energy and carbon intensive materials such as concrete, steel, aluminum, and plastic, thus leading to avoided emissions.
* In addition to reducing human impacts on primary forests, tree plantations offer some habitat benefits, though less than secondary forests. Plantations can have a diverse secondary understory and can provide crucial habitat connectivity for some species (Brockerhoff et al. 2008; Lamb et al. 2005).
* Forest plantations projects can sequester carbon, help preserve biodiversity, restore degraded lands, reduce logging in primary forests, and improve the overall well-being of people who live near them. The design of forest plantations projects should be based on the demands and preferences of local people, balancing the need for sequestration with needs for food, fiber, and a healthy ecosystem.

Nevertheless, despite these advantages, the following potential negative impacts should be taken into account:

* If implemented inappropriately, forest plantations can also cause environmental degradation, through stream flow reduction, erosion, soil salinization and acidification (Cao, 2008).
* Forest plantations on marginal lands can require significant fertilizer input, often in the form of nitrogen, which can generate potent greenhouse gases (Oren et al., 2001).
* Afforestation projects do not guarantee long-term carbon sequestration due to uncertainty surrounding the risk of fire, drought, and pests. Deforestation is always possible, whether natural (through climate change) or human induced.
* Afforestation has many ecological and economic benefits in addition to carbon sequestration. However, forests take decades to establish and to fully realize many of their benefits, especially those from timber harvest. Particularly in developing countries, individuals need government or private support to understand the perhaps unfamiliar timber farming, minimize risks, and provide initial funding. Research and education into appropriate species and management techniques can reduce the risk of environmental degradation from tree-planting.

### 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, afforestation increases commercial biomass production but has inferior ecosystem services when compared to ecosystem protection and restoration solutions.

Table .: 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 |
| 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 .: 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 |

# Methodology

## 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:

1. Sequestration of carbon dioxide from the atmosphere into plant biomass and soil; and
2. 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]](#footnote-1)) is what constituted the results.

Drawdown’s *afforestation* solution models future adoption on marginal, degraded, or abandoned lands, in particular unproductive pasture or agricultural land under thermal-moisture regimes that could support trees. Current adoption is estimated at about 290 million hectares (FAO 2015). While forest plantations systems are most prevalent in boreal or temperate regions, they are also found in the tropics.

*Agency Level*

The land manager 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.

## Data Sources

Data for the model was drawn from a review of 45 peer-reviewed publication as well as from grey literature (e.g government reports and university financial resources for farmers) and public sector sources (e.g. FAO & USDA publications).

One of major challenges with establishing global values for forest plantations 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 is that forest plantations are often lumped together with other afforestation solutions (e.g. agroforestry, bamboo and/or biomass for biofuel plantations). Nevertheless, wherever possible, data specific to forest plantations established through afforestation was used in the model.

## 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 silvopasture is modeled specifically on degraded, abandoned, and marginal crop- and grassland globally suitable for forest plantations.

In terms of future projections, global-level studies do not consistently differentiate between general afforestation and forest plantations in their estimates. We therefore use existing estimates for afforestation expansion, which have been determined by different authors through use of varying methods, models, and carbon rental rate assumptions. (Zomer, Trabucco, Coe, & Place, 2009) estimate 749 Mha available in the developing world, while (van Minnen, Strengers, Eickhout, Swart, & Leemans, 2008)(Sohngen & Mendelsohn, 2003)arrive at a total maximum potential of 2750 Mha. When examining economic feasibility, (Sohngen & Mendelsohn, 2003) estimated 488 Mha of afforestation potential, implying that additional policies may still be needed to incentivize afforestation to allow it to reach its global carbon sequestration potential.

Drawdown’s maximum area allocated to afforestation is 582 million hectares. This value is lower than estimates given in the literature, as it is both based on this existing data regarding available and suitable marginal and degraded grassland area, 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.

## 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 afforested forest plantations is based on both linear projections of current global data (FAO, 2010) for afforestation/planted forests, and on model projection from recent literature (Evans, 2009; Kreidenweis et al., 2016). Project Drawdown’s model assumes that afforestation/planted forest growth rates are applicable to forest plantation expansion. Details are given below:

1. ***Custom adoption scenario one:*** In this scenario, future afforested forest plantation area is projected based on available country-level data for afforestation/planted forest available for the years 1990, 2000, 2005, and 2010 from the FAO's Forest Resource Assessment 2015 report (FAO, 2010). Country-level data was aggregated for Drawdown regions and interpolated to determine forest plantation area for 2014. The resulting regional growth rates from 1990 – 2014 were used to project future adoption using a linear trend.
2. ***Custom adoption scenario two:*** The maximum annual afforested planted forest growth rates between 1990 – 2000, 2000 – 2005, 2005 – 2010 and 2010 – 2014 were determined for each Drawdown region based on historical data from 1990 – 2010 (FAO, 2010) and interpolations for 2014. The global maximum annual afforestation growth rate of 0.57 Mha/year reported for the Asia region. In this scenario, this same growth-rate was used to project future adoption for Asia using a linear trend; for other regions half of this rate was applied.
3. ***Custom adoption scenario three:*** The maximum annual afforested planted forest growth rates between 1990 – 2000, 2000 – 2005, 2005 – 2010 and 2010 – 2014 were determined for each Drawdown region based on historical data from 1990 – 2010 (FAO, 2010) and interpolations for 2014. The global maximum annual afforestation growth rate of 0.57 Mha/year reported for the Asia region. In this scenario, this same growth-rate was used to project future adoption for all regions using a linear trend.
4. ***Custom adoption scenario four:*** This projection of future adoption of afforested forest plantations is based on (Kreidenweis et al., 2016)'s "global afforestation" scenario, which assumes 1614 Mha total afforested area by 2050. We calculated the proportion of this projection based on current total land allocated to drawdown biomass crops and the TLA set for afforested forest plantation.
5. ***Custom adoption scenario five:*** This projection of future adoption of afforested forest plantations is based on (Kreidenweis et al., 2016)'s "no boreal afforestation" scenario, which assumes 1351 Mha total afforested area by 2050. We calculated the proportion of this projection based on current total land allocated to drawdown biomass crops and the TLA set for afforested forest plantation.
6. ***Custom adoption scenario six:*** Projections of future adoption of afforested forest plantations are based on the total predicted area of planted forest in 2030 (344.5 Mha), as reported by (Evans, 2009). The predictions are made according to two scenarios (Scenario 2: "Business as Usual" and Scenario 3: "Higher Productivity") described in Table 5.2 of the publication.

### Reference Case / Current Adoption

Current adoption of *afforestation* is estimated at 290 million hectares based on FAO’s most recent Global Forest Resources Assessment (FAO 2015).

### 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, and future growth of the solution is estimated based on the “average of all” custom adoption scenarios as listed above.

#### Drawdown Scenario – For the drawdown scenario, an ambitious approach is adopted, and future growth of the solution is estimated based on the “high of all” custom adoption scenarios as listed above.

#### Optimum Scenario – For the optimum scenario, custom adoption scenario that is giving maximum growth based on the existing prognostication is considered, which is represented by the “custom scenario five” where future adoption is projected based on the high estimates of (Kreidenweis et al., 2016).

## Inputs

### Climate Inputs

Sequestration rates of *Afforestation*are set at 3.3 tons of carbon per hectare per year. This is the result of meta-analysis of 29 data points from 10 sources.

***Table 2.1 Climate Inputs***

|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| --- | --- | --- | --- | --- | --- |
| C sequestration | *tC/ha/yr* | 1.1 – 5.5 | 3.3 | 29 | 10 |

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[[2]](#footnote-2).

*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 multistrata agroforestry) 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.

*End of Life Emissions for Perennial Cropping Systems*

Carbon is sequestered annually in plants of perennial crops, including biomass and timber crops. Much or all of this carbon is lost at the end of life of these crops. It is assumed that remaining biomass is burned and soil is greatly disturbed at the end of the productive life of these crops. The Drawdown model assumes that all soil carbon gains are lost at this time, and that 90% of aboveground carbon biomass is lost due to burning, with 10% of aboveground biomass retained as residue which becomes soil carbon upon decomposition (Marvinney, Kendall, & Brodt, 2014). However, for afforestation it is assumed that the carbon stored in the form of biomass will not be burnt after the timber harvest, so, in the calculation of emission at the time of harvest, amount of carbon stored in the biomass is subtracted from the total amount of carbon sequestered in the entire life span of the timber plant.

### Financial Inputs

The present solution*,* *afforestation,* is allocated on degraded land area (forest, grassland, and cropland). Project Drawdown’s *afforestation* model assumes marginal conventional use of this degraded land areas, principally for grazing. In the absence of sufficient financial data sources documenting the implementation of grazing practices on degraded land, Drawdown’s *afforestation* 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. This calculation is based on Project Drawdown's AEZ values.

For *afforestation* activities, first costs are estimated at US$668.57 per hectare.  Results are based on meta-analysis of 27 data points from 6 sources. Net profit per hectare is US$460.22 per year (13 data points from 5 sources), compared to US$143.54 per year for the conventional practice (10 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 (Afforestation)***

|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| --- | --- | --- | --- | --- | --- |
| First costs (Solution) | *US$2014/ha* | $410.54 - $926.60 | $668.57 | 27 | 6 |
| Net profit (Solution) | *US$2014/ha* | $2.18 - $248.18 | $123.37 | 19 | 6 |
| Operating Cost (Solution) | *US$2014/ha* | $86.15 - $1,101.77 | $594.96 | 16 | 3 |

## 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](http://www.drawdown.org). Beyond these core assumptions, there are other important assumptions made for the modeling of this specific solution. These are detailed below.

Beyond these core assumptions, there are other important assumptions made for the modeling of this specific solution. These are detailed below.

**Assumption 1:** Emissions from forest plantations established through afforestation are equivalent to emissions from the pre-existing land use.

**Assumption 2:** Forest plantations will not reach carbon saturation by 2050.

**Assumption 3:** Forest plantations will not be harvested before 2050.

**Assumption 4:** Forest plantations areas are managed according to sustainable forest management practices.

**Assumption 5:** Project Drawdown models assume that the "planted forest area" (FAO 2015) used to determine current adoption of forest plantations is equivalent to new forest area established through afforestation activities. This assumption is made due to a lack of data breaking down previous land-use of planted forest and method of establishment, and to similar lack of data about the proportions of land-uses established through afforestation activities. If such data becomes available, Drawdown recommends reviewing estimates. In reality, "planted forest" as reported in FAO (and other) documentation may likely also be established through regeneration, so Drawdown estimates might not be accurate.

**Assumption 6:**Similarly, Drawdown assumes that financial and C sequestration data relevant to “afforestation” can be applied to this solution, as afforestation activities mostly consist of planting forests for commercial timber/paper pulp harvest. While these activities might also include agroforestry, bamboo forest or biomass for biofuel plantations, Drawdown assumes that this does not significantly affect calculation for this solution.

**Assumption 7:** 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 proportion of total global grassland area (3514 Mha) that is already degraded (979 Mha), i.e. 27.85%. This calculation is based on Project Drawdown's AEZ values.

## Integration

The complete Project Drawdown integration documentation (will be available at [www.drawdown.org](http://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.

*Afforestation* 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.

Adoption of *afforestation* is included in the yield model because new adoption occurs on degraded grassland, which displaces 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* andagroforestry 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.

## Limitations/Further Development

Drawdown figures for current adoption are based on estimates of afforestation and planted forest reported by the FAO (FAO, 2010). While the majority of afforestation activities consist in establishing forest plantation systems as defined by Drawdown, the term also includes several other land-uses such as bamboo plantations or agroforestry. Currently, it remains difficult to distinguish between these land-uses.

Drawdown’s approach is further limited by data limitations in the current literature, particularly regarding carbon sequestration impacts and financial variables. Extrapolating sequestration rates from the few areas represented in the literature to all forest plantations 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.

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 forest plantations’ drawdown capacity given current knowledge.

# Results

## 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 405.04 million hectares in 2050, representing 85 percent of the total suitable land. Of this, 114.58 million hectares are adopted from 2020-2050.

Total adoption in the *Drawdown* Scenario is 476.77 million hectares in 2050, representing 95 percent of the total suitable land. Of this, 186.31 million hectares are adopted from 2020-2050.

Total adoption in the *Optimum* Scenario is 476.77 million hectares in 2050, representing 100 percent of the total suitable land. Of this, 186.31 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** |
| Afforestation | Mha | 290.46 | 114.58 | 186.31 | 186.31 |
| % Total Land Available | 50% | 70% | 82% | 82% |

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

## 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 22.32, 43.63, and 44.69 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 CO2 Sequestered** | **Total Additional CO2 Sequestered** | **Total Atmospheric CO2-eq Reduction** | **Emissions Reduction in 2030** | **Emissions Reduction in 2050** |
| --- | --- | --- | --- | --- | --- | --- | --- |
| *(Gt CO2-eq/yr.)* | *Gt CO2-eq/yr. (2020-2050)* | *(Gt CO2-eq/yr.)* | *Gt CO2-eq/yr. (2020-2050)* | Gt CO2-eq (2020-2050) | (Gt CO2-eq/year) | *(Gt CO2-eq/year)* |
| ***Plausible*** | -0.40 | -4.81 | 1.34 | 27.13 | 22.32 | 0.69 | 0.93 |
| ***Drawdown*** | -0.92 | -11.01 | 2.13 | 54.63 | 43.63 | 1.63 | 1.21 |
| ***Optimum*** | -1.02 | -11.92 | 2.12 | 56.61 | 44.69 | 1.78 | 1.10 |

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 CO2-eq (2050)* | *PPM CO2-eq change from 2049-2050* |
| **Plausible** | 1.83 | 0.07 |
| **Drawdown** | 3.49 | 0.07 |
| **Optimum** | 3.54 | 0.06 |

***Figure 3.2 World Annual Greenhouse Gas Emissions Reduction***

Note that the negative value in the later phase shows the emissions associated with the end of life of the afforested plantation and there is no new adoption.

## 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$ 101.00 billion. Marginal first cost is the same as cumulative first cost. Net operating savings are US$-80.52

billion, and the net profit margin and lifetime profit margin are US$1320.09 billion and US$2355.92 respectively. Lifetime cashflow savings NPV is US$-39.69.

For the *Drawdown* Scenario, the cumulative first cost of adoption is US$185.04 billion. Marginal first cost is the same as cumulative first cost. Net operating savings are US$-270.58 billion, and the net profit margin and lifetime profit margin are US$2673.06 and US$4371.21 respectively. Lifetime cashflow savings NPV is US$-111.49.

For the *Optimum* Scenario, the cumulative first cost of adoption is US$191.67 billion. Marginal first cost is the same as cumulative first cost. Net operating savings are US$-291.24 billion, and the net profit margin and lifetime profit margin are US$2772.53 and US$4543.82 billion respectively. Lifetime cashflow savings NPV is US$-122.51.

***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** | 101.00 | 101.00 | -80.52 | 1320.09 | 2355.92 | -39.69 |
| **Drawdown** | 185.04 | 185.04 | -270.58 | 2673.06 | 4371.21 | -111.49 |
| **Optimum** | 191.67 | 191.67 | -291.24 | 2772.53 | 4543.82 | -122.51 |

***Figure 3.3 Net Profit Margin Increase***

# Discussion

Results presented in this report suggest that afforestation systems are a form of land-use with a high potential to not only sequester carbon, but also contribute to soil regeneration and economic revitalization in marginal or degraded areas. Afforestation is well recognized as a strategy to address climate change by many governments and international organizations, and there is therefore high potential for increased adoption of forest plantations in the coming decades. Nevertheless, several factors should be considered in relation to Drawdown model results.

First, the climate impacts generated by our model are significantly lower than those of other sources including the IPCC. This likely reflects both the variety of land-uses that can be established through afforestation, as well as the multiple mitigation options available for the finite amount of degraded land available (agroforestry-related solutions, biomass production solutions, *forest restoration*, etc.), both of which contribute to restrict the total area available for forest plantations.

Second, variable harvest cycles of forest plantations are difficult to accurately model. On the one hand, assumptions regarding long harvest cycles may lead to overestimation of the solution’s mitigation potential. While final plantation harvests may lead to significant emissions, they are not reflected in this model as forest plantation life-cycles are currently projected to end after 2050, i.e. outside of the scope of Drawdown’s projections. On the other hand, long harvest cycles are also associated with delayed profits and suggest that forest plantations are an expensive mitigation option with no financial return. While Drawdown assumes full harvest only at the end of plantation life-cycles, in reality, some trees are harvested throughout a plantation life-cycle through continuous thinning. Additionally, some species are harvested on much shorter rotations than others.

Finally, not all afforested plantations are used for timber, and data about the proportions of final products from forest plantations on regional or global scales are currently not available. Similarly, studies documenting the amount of carbon stored in final products from commercial forest plantations remain scarce. This data would provide valuable information about the amount of carbon that stays stored in biomass (e.g. in timber furniture, construction materials, cardboard, etc.) and allow for more accurate estimates of this solution’s carbon sequestration potential. Note that for this reason, this solution also connects with other Drawdown solutions such as *Building with Wood*, *Recycled Paper*, and *Clean Cookstoves*.

While accurate data reflecting the complexity of harvest cycles and of related financial and ecological consequences is currently still lacking, future reiterations of this model might be improved through the inclusion of such data as it becomes available.

## Limitations

This study could be improved with additional, more accurate data points on financials and C sequestration parameters, as well as more accurate data on current and projected adoption which focus on forest plantations rather than general afforestation activities. Another limitation is the use of a single sequestration rate across all climates. In addition the current version of the model does not account for albedo impacts at temperate and boreal latitudes. It would additionally be desirable to model the impacts of timber replacing carbon and steel in construction, as these materials are emissions-intensive.

## Benchmarks

The IPCC provides a benchmark of 4.0 gigatons of carbon dioxide-equivalent per year in 2030 from afforestation, given a price of $100 per ton of carbon dioxide (Netz et al., 2007). A recent study by Lal et al. (2018) estimates about 500 Mha of degraded and abandoned land available for afforestation activities, and further estimates a technical mitigation impact of 4.0 – 9.1 Gt CO2 eq. on this land. The Drawdown model, which limits the adoption of afforested plantations on degraded and marginal grassland not allocated to other land-use solutions, shows 0.69-1.78 gigatons of carbon dioxide-equivalent per year in 2030 from *afforestation*. These impacts are lower than the benchmarks presented here – this might be explained by broader definitions of afforestation in both presented sources, which may include other systems other than forest plantations. The combined impact of Drawdown’s three dedicated perennial biomass solutions (*afforestation*, *bamboo* and *perennial biomass*) is 1.10-2.76 gigatons of carbon dioxide-equivalent per year in 2030. Additionally, as mentioned above, Project Drawdown models projects significantly lower adoption than several others due to higher prioritization of other land uses. Ultimately, Project Drawdown’s estimates are more conservative than other existing benchmarks, which implies that potential impacts of the solution might be higher than projected here.

Table .: **Benchmarks**

| **Source and Scenario** | **New Adoption in Mha** | **Mitigation Impact (i.e. Gt CO2-eq in 2030)** |
| --- | --- | --- |
| Netz (2007) | n/a | 4.0 |
| Lal (2018) technical potential | 500 | 4.0 – 9.1 |
| Project Drawdown – Plausible Scenario (PDS1) | 352.07 | 0.69 |
| Project Drawdown – Drawdown Scenario (PDS2) | 435.98 | 1.63 |
| Project Drawdown – Optimum Scenario (PDS3) | 449.31 | 1.78 |
| Drawdown combined dedicated perennial biomass solutions | 1073 | 1.10-2.76 |

In conclusion, afforestation establishment is already practiced on a wide scale and represents an important high-carbon land use. It produces products of critical importance and can help reduce pressure on intact forests. Though not a "silver bullet," it is an essential component of land-based mitigation efforts.

# References

Agyeman, V. K., Marfo, K. A., Kasanga, K. R., Danso, E., Asare, A. B., Yeboah, O. M., & Agyeman, F. (2003). Revising the taungya plantation system: new revenue-sharing proposals from Ghana. *Unasylva*, *54*(1), 40–43.

Bonan, G. B. (2008). Forests and climate change: forcings, feedbacks, and the climate benefits of forests. *Science*, *320*(5882), 1444–1449.

Bonner, M. T., Schmidt, S., & Shoo, L. P. (2013). A meta-analytical global comparison of aboveground biomass accumulation between tropical secondary forests and monoculture plantations. *Forest Ecology and Management*, *291*, 73–86.

Boyd, E., & others. (2009). Governing the Clean Development Mechanism: global rhetoric versus local realities in carbon sequestration projects. *Environment and Planning. A*, *41*(10), 2380.

Brockerhoff, E. G., Jactel, H., Parrotta, J. A., Quine, C. P., & Sayer, J. (2008). Plantation forests and biodiversity: oxymoron or opportunity? *Biodiversity and Conservation*, *17*(5), 925–951.

Buongiorno, J., & Zhu, S. (2014). Assessing the impact of planted forests on the global forest economy. *New Zealand Journal of Forestry Science*, *44*(Suppl 1), S2. https://doi.org/10.1186/1179-5395-44-S1-S2

Cao, S. (2008). Why large-scale afforestation efforts in China have failed to solve the desertification problem. *Environmental Science & Technology*, *42*(6), 1826–1831.

Chen, G.-S., Yang, Y.-S., Xie, J.-S., Guo, J.-F., Gao, R., & Qian, W. (2005). Conversion of a natural broad-leafed evergreen forest into pure plantation forests in a subtropical area: Effects on carbon storage. *Annals of Forest Science*, *62*(7), 659–668. https://doi.org/10.1051/forest:2005073

Chhatre, A., & Agrawal, A. (2009). Trade-offs and synergies between carbon storage and livelihood benefits from forest commons. *Proceedings of the National Academy of Sciences*, *106*(42), 17667–17670. https://doi.org/10.1073/pnas.0905308106

Coomes, O. T., Grimard, F., Potvin, C., & Sima, P. (2008). The fate of the tropical forest: Carbon or cattle? *Ecological Economics*, *65*(2), 207–212.

Cox, S., Crews, T., & Jackson, W. (2014). From genetics and breeding to agronomy and ecology. *Perennial Crops for Food Security: Proceedings of the FAO Expert Workshop*, 158–168. Retrieved from https://landinstitute.org/wp-content/uploads/2014/11/PF\_FAO14\_ch12.pdf

Cubbage, F., Mac Donagh, P., Sawinski Júnior, J., Rubilar, R., Donoso, P., Ferreira, A., … Alvarez, J. (2007). Timber investment returns for selected plantations and native forests in South America and the Southern United States. *New Forests*, *33*(3), 237–255. https://doi.org/10.1007/s11056-006-9025-4

Dale, V. H., Joyce, L. A., McNulty, S., Neilson, R. P., Ayres, M. P., Flannigan, M. D., … others. (2001). Climate change and forest disturbances: climate change can affect forests by altering the frequency, intensity, duration, and timing of fire, drought, introduced species, insect and pathogen outbreaks, hurricanes, windstorms, ice storms, or landslides. *BioScience*, *51*(9), 723–734.

Dunne, D. (2018). Mapped: Where ‘afforestation’ is taking place around the world. Retrieved from CarbonBrief - Clear on Climate website: https://www.carbonbrief.org/mapped-where-afforestation-is-taking-place-around-the-world?utm\_source=NEW+Weekly+Briefing&utm\_campaign=86febf2fdd-Carbon\_Brief\_Weekly\_12\_10\_2018&utm\_medium=email&utm\_term=0\_b6e0a2d2ef-86febf2fdd-303546961&ct=t(Carbon\_Brief\_Weekly\_12\_10\_2018)&goal=0\_b6e0a2d2ef-86febf2fdd-303546961

Evans, J. (Ed.). (2009). *Planted forests: uses, impacts, and sustainability*. Wallingford, UK ; Cambridge, MA: Published jointly by Food and Agriculture Organization of the United Nations and Cabi Pub.

FAO. (2010). *Global forest resources assessment 2015: How are the world’s forests changing?* Food and Agriculture Organization of the United Nations.

FAO. (2016). Global Forest Resources Assessment 2015. How are the World’s Forests Changing? (Second edition) - a-i4793e.pdf. Retrieved October 26, 2016, from http://www.fao.org/3/a-i4793e.pdf

Farley, K. A. (2010). Pathways to forest transition: Local case studies from the Ecuadorian Andes. *Journal of Latin American Geography*, *9*(2), 7–26.

Farley, K. A., Piñeiro, G., Palmer, S. M., Jobbágy, E. G., & Jackson, R. B. (2008). Stream acidification and base cation losses with grassland afforestation. *Water Resources Research*, *44*(7). Retrieved from http://onlinelibrary.wiley.com/doi/10.1029/2007WR006659/full

Gibbs, H. K., Brown, S., Niles, J. O., & Foley, J. A. (2007). Monitoring and estimating tropical forest carbon stocks: making REDD a reality. *Environmental Research Letters*, *2*(4), 045023.

Huang, L., Liu, J., Shao, Q., & Xu, X. (2012). Carbon sequestration by forestation across China: past, present, and future. *Renewable and Sustainable Energy Reviews*, *16*(2), 1291–1299.

Jackson, R. B., Jobbágy, E. G., Avissar, R., Roy, S. B., Barrett, D. J., Cook, C. W., … Murray, B. C. (2005). Trading water for carbon with biological carbon sequestration. *Science*, *310*(5756), 1944–1947.

Jacobson, Michael G., Greene, John L., Straka, Thomas J., Daniels, Steven E., & Kilgore, Michael A. (2009). Influence and Effectiveness of Financial Incentive Programs in Promoting Sustainable Forestry in the South. *Southern Journal of Applied Forestry*, *33*(1), 35–41.

Jobbagy, E. G., & Jackson, R. B. (2004). Groundwater use and salinization with grassland afforestation. *Global Change Biology*, *10*(8), 1299–1312.

Kreidenweis, U., Humpenöder, F., Stevanović, M., Bodirsky, B. L., Kriegler, E., Lotze-Campen, H., & Popp, A. (2016). Afforestation to mitigate climate change: impacts on food prices under consideration of albedo effects. *Environmental Research Letters*, *11*(8), 085001. https://doi.org/10.1088/1748-9326/11/8/085001

Lal, R., Smith, P., Jungkunst, H. F., Mitsch, W. J., Lehmann, J., Nair, P. K. R., … Ravindranath, N. H. (2018). The carbon sequestration potential of terrestrial ecosystems. *Journal of Soil and Water Conservation*, *73*(6), 145A-152A. https://doi.org/10.2489/jswc.73.6.145A

Lamb, D., Erskine, P. D., & Parrotta, J. A. (2005). Restoration of Degraded Tropical Forest Landscapes. *Science*, *310*(5754), 1628–1632. https://doi.org/10.1126/science.1111773

Lambin, E. F., & Meyfroidt, P. (2011). Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences*, *108*(9), 3465–3472.

Liao, C., Luo, Y., Fang, C., & Li, B. (2010). Ecosystem Carbon Stock Influenced by Plantation Practice: Implications for Planting Forests as a Measure of Climate Change Mitigation. *PLoS ONE*, *5*(5), e10867. https://doi.org/10.1371/journal.pone.0010867

Luyssaert, S., Schulze, E.-D., Börner, A., Knohl, A., Hessenmöller, D., Law, B. E., … Grace, J. (2008). Old-growth forests as global carbon sinks. *Nature*, *455*(7210), 213–215. https://doi.org/10.1038/nature07276

Martin, P. A., Newton, A. C., & Bullock, J. M. (2013). Carbon pools recover more quickly than plant biodiversity in tropical secondary forests. *Proc. R. Soc. B*, *280*(1773), 20132236. https://doi.org/10.1098/rspb.2013.2236

McGrath, J. M., & Lobell, D. B. (2013). Regional disparities in the CO2 fertilization effect and implications for crop yields. *Environmental Research Letters*, *8*(1), 014054.

Mengak, M. (2009). Growing Loblolly Pine With Wildlife Food Plots, Hunting Lease Assumptions And Liability Issues. Retrieved October 31, 2016, from http://www2.hcmuaf.edu.vn/data/nmduc/2008\_forest%20proceedings(1).pdf

Netz, B., Davidson, O., Bosch, P., Dave, R., Meyer, L., & others. (2007). Climate change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Summary for Policymakers. *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Summary for Policymakers.*

Nosetto, M. D., Jobbágy, E. G., & Paruelo, J. M. (2006). Carbon sequestration in semi-arid rangelands: comparison of Pinus ponderosa plantations and grazing exclusion in NW Patagonia. *Journal of Arid Environments*, *67*(1), 142–156.

Oren, R., Ellsworth, D. S., Johnsen, K. H., Phillips, N., Ewers, B. E., Maier, C., … others. (2001). Soil fertility limits carbon sequestration by forest ecosystems in a CO2-enriched atmosphere. *Nature*, *411*(6836), 469–472.

Paquette, A., & Messier, C. (2009). The role of plantations in managing the world’s forests in the Anthropocene. *Frontiers in Ecology and the Environment*, *8*(1), 27–34.

Ravindranath, N. H., Somashekhar, B. S., & Murthy, I. K. (2008). Forest conservation, afforestation and reforestation in India: implications for forest carbon stocks. *Current Science*, *95*(2), 216–222.

Rudel, T. K. (2009). Tree farms: driving forces and regional patterns in the global expansion of forest plantations. *Land Use Policy*, *26*(3), 545–550.

Schirmer, J., & Bull, L. (2014). Assessing the likelihood of widespread landholder adoption of afforestation and reforestation projects. *Global Environmental Change*, *24*, 306–320.

Schneider, T., Pohnan, E., & others. (2012). Assessing Rainforestation: the social and ecological effects of smallholder-based native species reforestation in the Philippines. *Tropical Resources: Bulletin of the Yale Tropical Resources Institute*, *31*, 78–85.

Smith, P. (2014). *Climate Change 2014 Mitigation of Climate Change: Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. https://doi.org/10.1017/CBO9781107415416

Sohngen, B., & Mendelsohn, R. (2003). An optimal control model of forest carbon sequestration. *American Journal of Agricultural Economics*, *85*(2), 448–457.

Thomas, S., Dargusch, P., Harrison, S., & Herbohn, J. (2010). Why are there so few afforestation and reforestation Clean Development Mechanism projects? *Land Use Policy*, *27*(3), 880–887.

Thornley, J. H. M., & Cannell, M. G. R. (2000). Managing forests for wood yield and carbon storage: a theoretical study. *Tree Physiology*, *20*(7), 477–484. https://doi.org/10.1093/treephys/20.7.477

Uchida, E., Xu, J., & Rozelle, S. (2005). Grain for Green: Cost-Effectiveness and Sustainability of China’s Conservation Set-Aside Program. *Land Economics*, *81*(2), 247–264. https://doi.org/10.3368/le.81.2.247

van Minnen, J. G., Strengers, B. J., Eickhout, B., Swart, R. J., & Leemans, R. (2008). Quantifying the effectiveness of climate change mitigation through forest plantations and carbon sequestration with an integrated land-use model. *Carbon Balance and Management*, *3*(3), 1–20.

Zomer, R. J., Trabucco, A., Coe, R., & Place, F. (2009). *Trees on Farm: Analysis of Global Extent and Geographic Patterns of Agroforestry* (No. ICRAF Working Paper no. 89). Retrieved from World Agroforestry Centre website: http://www.worldagroforestry.org/sites/default/files/WP89\_text\_only.pdf

# 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 CO2 (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 CO2e/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

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. [↑](#footnote-ref-1)
2. 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. [↑](#footnote-ref-2)