**Technical assessment for**

**Tropical Forest Restoration**

Sector: Land Use

Agency Level: Government

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# Executive Summary

Project Drawdown defines tropical forests as: the restoration and protection of tropical-climate forests. This solution replaces degraded forest. Tropical forest regrowth is often rapid, and results in impressive rates of carbon sequestration. The tropical forests solution models natural regeneration of tropical forests on degraded lands. This has the benefit of being a low-cost strategy. It is assumed that forest regrowth will be legally protected so that it will not be cleared or degraded again. Restoring degraded and deforested tropical lands to sequester carbon is widely considered to offer substantial climate change mitigation opportunities, if conducted at large spatial scales. Despite this assertion estimates of how much carbon could be sequestered from the atmosphere as a result of large-scale restoration are largely lacking, furthermore, the international community has pledged to restore 350 million hectares of degraded forest land by 2030, meaning that quantifying carbon storage over large spatial scales is very timely .

Undertaking restoration in the tropics by enabling natural regeneration of abandoned agricultural lands allows for sequestration of carbon, however, natural regeneration also offers additional co-benefits which make it an appealing option for restoration, these include; biodiversity conservation, watershed protection, soil protection, and resilience to pests and disease.

Out of a total land area available for the solution of 304 million hectares, the current solution adoption assumed to be 0. Starting from this adoption value nine custom PDS adoption scenarios were developed for this solution which were combined to produce the *Plausible*, *Drawdown* and *Optimum* scenarios.

In the *Plausible* Scenario, 176.06 million hectares come under protection totaling 58% of total land area in 2014. Climate impact is 61.23 gigatons of carbon dioxide equivalent.

In the *Drawdown* Scenario, 238.80 million hectares come under protection totaling 79% of total land area in 2014. Climate impact is 89.05 gigatons of carbon dioxide equivalent.

In the *Optimum* Scenario, 255.26 million hectares come under protection totaling 84% of total land area in 2014. Climate impact is 105.61 gigatons of carbon dioxide equivalent.

Financials are not modeled.

# Literature Review

## State of Forest Protection

Project Drawdown defines tropical forests as: the restoration and protection of tropical-climate forests. This solution replaces degraded forest. Approximately 11.3 million ha (Mha) yr-1 of tropical forest were lost between 2000 and 2010 ([Achard *et al.*, 2014](#_ENREF_1), [FAO, 2010](#_ENREF_34), [Hansen *et al.*, 2013](#_ENREF_45), [Pan *et al.*, 2011](#_ENREF_71)), and a further 9 Mha of degraded forest exist in the tropics ([FAO, 2010](#_ENREF_34), [ITTO, 2002](#_ENREF_54)); defined as a reduction in stocking volume within a forest leading to a reduction in aboveground biomass (AGB) and ecosystem services ([FAO, 2000](#_ENREF_33)). The tropical carbon flux from deforestation and forest degradation is estimated to be 1.2 Gt C yr-1 (1 Gt = 109 tonnes; Grace *et al*., 2014) , which is predominantly driven by timber extraction and agricultural expansion ([Geist & Lambin, 2002](#_ENREF_39)). Specifically the conversion of forest to pastures for cattle ranching and soya (*Glycine max*) plantations in South America, the extraction of timber for fuel wood in Africa ([Fisher, 2010](#_ENREF_36)) and the conversion of forest to palm oil (*Elaeis guineensis*) plantations in Southeast Asia ([Miettinen *et al.*, 2012](#_ENREF_67)).

Areas of deforested and degraded tropical land are often abandoned for a number of reasons. For example, in areas cleared for agricultural crop production, depletion of soil nutrients over successive growing seasons can lead to reductions in crop yield, forcing cultivators to move on to new areas ([Benayas *et al.*, 2007](#_ENREF_8)). In the case of selectively logged forest, areas are abandoned immediately to allow the forest to recover, until timber species grow to a merchantable size and an area can be re-logged. Repeated logging eventually leads to diminished returns ([Putz *et al.*, 2012](#_ENREF_76)), meaning logging efforts are moved elsewhere and the remaining severely degraded forest is abandoned.

Such areas of abandoned land are able to naturally regenerate ([Poorter *et al.*, 2016](#_ENREF_74)), following the processes of secondary succession, eventually resembling old growth forest if given a sufficient amount of time ([Guariguata & Ostertag, 2001](#_ENREF_44), [Martin *et al.*, 2013](#_ENREF_65)). Estimates suggest that naturally regenerating tropical lands currently sequester approximately 1.6 Gt C yr-1 globally ([Grace *et al.*, 2014](#_ENREF_42), [Pan *et al.*, 2011](#_ENREF_71)). However, natural regeneration on abandoned land can often be very slow or halted altogether in severely degraded lands in a process termed arrested succession. A number of different factors can lead to arrested succession the most common of which is fire. Degraded tropical forests are particularly susceptible to fire ([Cochrane, 2003](#_ENREF_20)), and fire can lead to a positive feedback mechanism, whereby areas that have been burnt once are liable to repeated burnings ([Cochrane *et al.*, 1999](#_ENREF_21)). Poor seed dispersal in highly fragmented landscapes ([Cubiña & Aide, 2001](#_ENREF_23)), and a limited soil seed bank ([Guariguata & Ostertag, 2001](#_ENREF_44)) in abandoned land can limit regeneration of native seedlings. Soils in abandoned land can also be severely degraded, cultivation can deplete soils of nutrients ([Uhl *et al.*, 1982](#_ENREF_87)), reducing nutrient availability for seedlings, and heavy machinery used for logging can lead to soil compaction, increasing soil penetration resistance ([Hattori *et al.*, 2013](#_ENREF_46)). Finally, the spread of invasive species in abandoned land can also lead to arrested succession. Disturbed areas are more susceptible to invasion by exotic species ([Lonsdale, 1999](#_ENREF_61)) due to increased resource availability in the form of light, alongside climate conditions, which are more favorable to heliotropic, invasive species as opposed to native forest specialist species ([Van Kleunen *et al.*, 2010](#_ENREF_90)). The combination of these factors acting simultaneously, can limit natural regeneration in abandoned land. Therefore active management interventions to restore tropical forest ecosystems may be necessary overcome arrested succession.

By allowing disturbed tropical lands to naturally regenerate following abandonment or undertaking active management interventions to enable regeneration when necessary, means the ecosystem structure and function can be restored ([Chazdon, 2008](#_ENREF_17), [Lamb *et al.*, 2005](#_ENREF_59)), which provides numerous ecosystem services including; carbon sequestration, biodiversity protection, soil protection, watershed protection, resilience to fires, resilience to pest and diseases and production of non-timber forest products ([NTFPs; Locatelli *et al.*, 2015](#_ENREF_60)). Here the carbon sequestration and biodiversity benefits are considered in detail.

*Carbon Sequestration*

Approximately 50% of a tree’s mass is carbon ([Thomas & Martin, 2012](#_ENREF_83)), therefore restoring areas with a low carbon density, such as abandoned agricultural land, allows for carbon to be sequestered within the terrestrial biome ([e.g. Poorter *et al.*, 2016](#_ENREF_74)). If forest restoration is conducted over a large enough spatial scale then it could help mitigate the effects of climate change ([Bellassen & Luyssaert, 2014](#_ENREF_7), [Canadell & Raupach, 2008](#_ENREF_13), [Houghton *et al.*, 2015](#_ENREF_51)).

Many past studies have quantified carbon sequestration following a change in land-use across the tropics (e.g. [Alves *et al.*, 1997](#_ENREF_2), [Hughes *et al.*, 1999](#_ENREF_52), [Saldarriaga *et al.*, 1988](#_ENREF_79), [Uhl *et al.*, 1988](#_ENREF_86)). There have also been successful syntheses of research findings, which estimate regional or pan-tropical rate of carbon sequestration in naturally regenerating forests (e.g. [Bonner *et al.*, 2013](#_ENREF_11), [Poorter *et al.*, 2016](#_ENREF_74), [Ziegler *et al.*, 2012](#_ENREF_93)). A recent study by [Poorter *et al.* (2016](#_ENREF_74)) estimated a carbon sequestration rate of 3.1 t C ha-1 yr-1 within neotropical secondary forests recovering on abandoned agricultural land, and predicted it would take a median of 66 years for secondary forest to recover 90% of old-growth forest carbon stocks. In a pan-tropical study by [Bonner *et al.* (2013](#_ENREF_11)) a carbon sequestration rate of 3.7 t C ha-1 yr-1 in secondary forests recovering following agricultural use was estimated for the first 18 years of recovery.

Rates of carbon sequestration have also been estimated within actively restored sites. For example, [Wheeler *et al.* (2016](#_ENREF_92)) estimated a carbon sequestration rate of 1.9 t C ha-1 yr-1 in abandoned agricultural lands in Uganda, which had been planted with native tree species over 18 years. Another study by [Preece *et al.* (2012](#_ENREF_75)), conducted in Australia, estimated carbon sequestration rates of 5.7 t C ha-1 yr-1 in restoration plantings following agriculture use. The large variation in carbon sequestration rates between these studies likely reflects the differences in land use history and restoration methods used. However, there is a real paucity of studies, which have estimated carbon sequestration within actively restored forest, and to date, there are no studies that have synthesized current literature, such as seen for naturally regenerating forest. For this reason analysis in this report considers only carbon sequestration within naturally regenerating forest, as the scarcity of data from actively restored sites limits the accuracy of results.

However, if conducted over a large spatial scale tropical forest restoration has the potential to sequester large quantities of carbon from the atmosphere. A recent study by [Chazdon *et al.* (2016](#_ENREF_18)) estimated that if all of the 2.4 Mha of neotropical secondary forest were left to naturally regenerate then a total of 8.5 Gt C would be sequestered over the next 40 years, furthermore they estimated that a further 2 Gt C could be sequestered if 40% of the current pasture area (0.5 Mha) were abandoned and allowed to naturally regenerate. Another study by [Arora and Montenegro (2011](#_ENREF_3)) estimated that if 50% of the tropical land area currently under cultivation (270 Mha) were to afforested then approximately 50 Gt C would be sequestered between 2011 and 2100, at a rate of approximately 0.6 Gt C yr-1, providing a reduction in global temperatures of 0.16 ˚C. Such studies show the large carbon storage potential of tropical forest restoration at a regional or pan-tropical scale, which could offer valuable climate change mitigation possibilities.

*Biodiversity*

Whilst deforestation and forest degradation in the tropics is often detrimental for biodiversity, leading to: decreased species richness, decreased species abundance and altered species composition ([Barlow *et al.*, 2007](#_ENREF_6), [Gibson *et al.*, 2011](#_ENREF_40)), degraded or naturally regenerating forests can nevertheless still retain relatively high biodiversity (e.g. [Dent & Wright, 2009](#_ENREF_26), [Edwards *et al.*, 2011](#_ENREF_31), [Gilroy *et al.*, 2014](#_ENREF_41)). For example, a study by [Berry *et al.* (2010](#_ENREF_9)) which assessed the species richness of nine taxa in logged forest in Borneo, found that declines in species richness following logging were on average less that 10%, showing the high value of degraded forest for biodiversity.

Similarly, benefits to biodiversity have also been observed in actively restored forest, with restoration estimated to enhanced biodiversity by 15% to 84% in comparison to degraded ecosystems ([Crouzeilles *et al.*, 2016](#_ENREF_22)). The species richness of birds, in forests restored after selective logging, were shown to be approaching that of primary forest just 15 years after planting with native species in Borneo ([Edwards *et al.*, 2009](#_ENREF_30)). Research such as this suggests that enabling natural regeneration or undertaking forest restoration in the tropics could help safeguard biodiversity.

However, the greatest benefits of forest restoration for biodiversity could be seen if restoration were conducted over large spatial scales, in a way that increases connectivity between forest fragments, allowing for the dispersal of species throughout the landscape. Targeted large-scale restoration could help increase connectivity through the creation of corridors between forest fragments or buffer zones around smaller forest fragments, which could help improve the dispersal ability of species and prevent populations becoming isolated from one another ([Lamb, 2010](#_ENREF_58)). Improving the dispersal ability of species, through the creation of corridors, could also help species be more resilient to climate change by enabling species to shift their distribution in response to changing conditions ([Hodgson *et al.*, 2009](#_ENREF_49)).

*Why Tropical Forests?*

In addition to the ecosystem services described above, restoration of tropical forest offers greater climate change mitigation benefits in comparison to temperate and boreal forest because tropical forest have a high carbon density estimated at approximately 100 t C ha-1 ([Avitabile *et al.*, 2016](#_ENREF_4), [Baccini *et al.*, 2012](#_ENREF_5), [FAO, 2011](#_ENREF_35), [Saatchi *et al.*, 2011](#_ENREF_78)). Tropical forests have higher above ground net primary productivity (NPP), of between 12 and 15 t C ha-1 yr-1 ([del Aguila-Pasquel *et al.*, 2014](#_ENREF_25), [Kho *et al.*, 2013](#_ENREF_55), [Malhi, 2012](#_ENREF_63)), compared to temperate and boreal forest estimated at between 6 to 9 t C ha-1 yr-1 and 4 to 5 t C ha-1 yr-1 respectively ([Luyssaert *et al.*, 2007](#_ENREF_62), [Malhi *et al.*, 1999](#_ENREF_64)). Tropical forest also offer temperature benefits that are up to three times greater than those observed in temperate and boreal forests, ([Arora & Montenegro, 2011](#_ENREF_3)). This is because, forest which appear darker than open land, especially where snow is lying, such as in boreal and northern temperate forests, reduces surface albedo, exerting positive radiative forcing effects. The positive forcing effects of afforestation in high latitude regions could outweigh the negative forcing effects of carbon sequestration, thereby causing a net increase in temperature ([Betts, 2000](#_ENREF_10)).

## Adoption Path

### Current Adoption

Current adoption of *tropical forest restoration* is set to 0 in the absence of relevant data.

### Trends to Accelerate Adoption

The recent signing of the Paris Agreement states an ambition to keep global temperatures well below 2˚C above pre-industrial levels ([UNFCCC, 2015](#_ENREF_89)), and to achieve net zero greenhouse gas (GHG) emissions in the second half of this century ([UNFCCC, 2015](#_ENREF_89)), by balancing sources and sinks of GHG emissions ([Tian *et al.*, 2016](#_ENREF_84)). Furthermore, the agreement states that parties should strive to enhance sinks of GHGs, specifically mentioning the role of forest. The inclusion of forest in the Paris Agreement, alongside other international initiatives on forest protection and enhancement has meant that forest restoration has been gaining prominence within the international policy arena ([Suding *et al.*, 2015](#_ENREF_81)). Numerous restoration initiatives have been established over the past few years (see Table 1), most notably the New York declaration on forest, which builds on the BONN challenge ([The BONN Challenge, 2016](#_ENREF_82)), aiming to restore 350 million ha of forest by 2030 ([UNFCCC, 2014](#_ENREF_88)), and the Aichi biodiversity target 15 of the Convention on Biological Diversity, which aims to restore 15% of degraded ecosystems by 2020 ([CBD, 2013](#_ENREF_16)). Together these initiatives set ambitious targets for forest restoration, which alongside the Paris Agreement increase likelihood of major new forest restoration projects commencing across the tropics.

Table 1.1: International forest restoration initiatives and commitments.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Initiative (Organisation)** | **Details** | **Location** | **Commitment** | **Implementation deadline** |
| The BONN Challenge (IUCN) |  | Global | 150 Mha | 2020 |
| New York Declaration on Forests (UNFCCC) | Extends the BONN Challenge pledging an additional 200 Mha | Global | 200 Mha | 2030 |
| Initiative 20x20  (World Resource Institute) |  | Latin America | 20 Mha | 2020 |
| AFR100  (World Resource Institute) |  | Africa | 100 Mha | 2030 |
| Plant a Billion Trees Programme  (The Nature Conservancy) |  | Brazil, USA, China | 1 Billion trees | 2025 |
| Billion Trees Campaign (UNEP) |  | Global | 14 Billion trees | On-going |
| The Great green Wall  (African Union) | Combating desertification in 20 African countries | Sahara & Sahel | |  |
| Aichi Biodiversity Target 15 (Convention on Biological Diversity) | Restore 15% of degraded ecosystems | Global |  | 2020 |

The World Resource Institute (WRI) and the International Union for the Conservation of Nature (IUCN) recently estimated that there were approximately two billion ha (Bha) of land suitable for restoration globally ([Minnemeyer *et al.*, 2011](#_ENREF_68)). They suggested that 0.5 Bha would be suitable for wide-scale restoration, defines as restoration to closed canopy forest in areas with low human impact (<10 people per km2), whilst the remaining 1.5 Bha would be suitable for mosaic restoration, defined as restoration that integrates forest landscapes with agroforestry and small settlements, in areas with moderate human pressure (10-100 people per km2). A further 0.2 Bha may be suitable for restoration, but due to their extremely remote location (predominantly in Northern boreal regions) restoration work was unlikely ([Minnemeyer *et al.*, 2011](#_ENREF_68)). The majority of land suitable for restoration was located in the tropics (Figure 1), with approximately 298 Mha suitable for wide-scale restoration and 1112 Mha suitable for mosaic restoration. To date a total of 266 Mha of land have been committed to restoration globally under various different schemes including the BONN challenge and as intended nationally determined contributions (INDCs) under the Paris agreement. Of these commitments 93% (248 Mha) are located in the tropics (See Appendix 1 for breakdown of commitments by country). The large areas of land suitable for restoration coupled with large areas of land committed to restoration in the tropics suggests that the use of forest restoration for climate change mitigation is widely accepted and the tropics offer particularly good opportunities for forest restoration. However, the total climate change mitigation potential from restoration in the tropics is still poorly quantified.

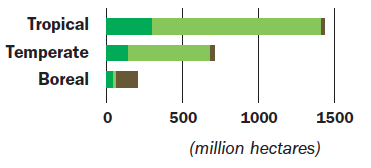


Figure 1: Area of land suitable for restoration taken from [Minnemeyer et al. (2011](#_ENREF_68)). Dark green = wide-scale restoration, light green = mosaic restoration, brown = remote restoration.

## Advantages and disadvantages of Forest Protection

### Similar Solutions

*Protection Solutions*

Peatlands and mangroves are types of forests with extremely high carbon stocks. These are thus distinct subtypes of forest protection and are analyzed as separate solutions. Indigenous forest management – another separate solution – provides tenure to indigenous forest people, under whose management deforestation and degradation rates are greatly reduced. Sustainable forestry strives to maintain forest integrity while harvesting timber and other products.

Protection of non-forest ecosystems (grasslands, salt marshes, seagrass beds, ocean areas) is also important for maintaining carbon stocks.

*Restoration Solutions*

Ecosystem restoration efforts (for forests, coastal wetlands, etc.) restore healthy ecosystems on degraded land and then protect them.

### Arguments for Adoption

Across the tropics forest restoration offers excellent opportunities as a biosequestration method, due to the high rates of carbon sequestration seen within regenerating forests and the large areas of degraded or abandoned land available across the tropics. Additionally, forest restoration allows for degraded or abandoned lands to regenerate back to an intact forest state, and therefore could provide a number of additional ecosystem services.

*Carbon*

* High rates of carbon sequestration of between 3 and 4 t C ha-1 yr-1 ([Bonner *et al.*, 2013](#_ENREF_11), [Poorter *et al.*, 2016](#_ENREF_74)).
* Carbon storage in restored forest can recover back to intact forest levels, potentially within 100 years ([Martin *et al.*, 2013](#_ENREF_65), [Poorter *et al.*, 2016](#_ENREF_74)).
* Carbon sequestered in regenerating forest represents a long term store of carbon that lasts many decades ([Galbraith *et al.*, 2013](#_ENREF_38)), whereas carbon sequestered in timber plantations is re-released into the atmosphere on a 20 to 30 year rotation ([Diaz-Balteiro & Rodriguez, 2006](#_ENREF_27)).
* Reduce emissions from land use change - areas located within restoration projects are protected and unlikely to be cleared.

*Biodiversity*

* Increasing forest area & creating buffers around forest fragments helps conserve species. Species-Area relationships suggest that larger areas can support more species or larger more viable populations ([Hill *et al.*, 2011](#_ENREF_48)).
* Increase connectivity between forest fragments means 1) Species can disperse across landscape more readily reducing isolation of separate populations. 2) Improved dispersal ability allows species to adapt to climate change ([Hodgson *et al.*, 2009](#_ENREF_49)).
* Restored forests offer refugia for species, particularly forest dependent species, that may not survive in plantations or agricultural land ([Chazdon *et al.*, 2009](#_ENREF_19)).
* Naturally regenerating or restored tropical forest offers greater biodiversity benefits compared to timber plantations ([Barlow *et al.*, 2007](#_ENREF_6), [Fitzherbert *et al.*, 2008](#_ENREF_37)) and agricultural land ([Gilroy *et al.*, 2014](#_ENREF_41)).

*Resilience*

* The higher diversity of restored habitats increases ecosystem resilience to local disturbance, climate perturbations and outbreaks of diseases/pests ([Cardinale *et al.*, 2012](#_ENREF_14), [Cardinale *et al.*, 2011](#_ENREF_15), [Hooper *et al.*, 2005](#_ENREF_50)).

*Watershed protection*

* Tree cover reduces incident rainfall (i.e. more rainfall intercepted by canopy), which reduces soil saturation and surface water runoff, which are linked to flooding ([Bruijnzeel, 2004](#_ENREF_12), [Martínez & Zinck, 2004](#_ENREF_66)).
* Trees provide an increased root network, to take in water, which can reduce flooding ([Trabucco *et al.*, 2008](#_ENREF_85)).

*Soil protection*

* Extensive root networks increase soil stability, reducing the chance of landslides ([Mugagga *et al.*, 2012](#_ENREF_69)).
* Decrease surface water runoff helps reduce soil erosion into watercourse ([Ehigiator & Anyata, 2011](#_ENREF_32)), which can cause problems downriver with crop irrigation and flooding ([Douglas *et al.*, 1993](#_ENREF_29)).
* Tree cover reduces soil compaction, which can improve water infiltration ([Bruijnzeel, 2004](#_ENREF_12)) and reduce soil penetration resistance, which can cause stunted seedling growth ([Hattori *et al.*, 2013](#_ENREF_46)).
* Tree cover helps nutrient cycling in soils, litter fall from trees replenished organic matter in soils ([Lal, 2005](#_ENREF_57), [Vitousek & Sanford, 1986](#_ENREF_91)).

*Timber & non-timber forest products*

* Increased timber production - sustainable extraction could reduce pressure on primary forest, such as observed in agroforests.
* Increase production of NTFPs (food, fodder, medicinal plants, rattan etc.), in comparison to heavily degraded habitats ([Guariguata *et al.*, 2010](#_ENREF_43), [Rist *et al.*, 2012](#_ENREF_77))
* Livelihood creation via sale of NTFPs/ work within restoration areas ([Shackleton & Pandey, 2014](#_ENREF_80)).

### Additional Benefits and Burdens

Here this solution is compared with other solutions in the food production cluster for farm, ecosystem, and social impacts.

Table 1.2: Land Use Solutions Comparison: Economic Impacts

**First Cost**: Free is $0**,** Low is $1-100, Medium is $100-500, Expensive is $500+. **Net Profit Margin:** Low is $0-100/ha, Medium is $100-500, High is $500+. **Value of Ecosystem Services:** Set values for very high, high, medium, low. **Timber and Biomass Production:** Decrease indicates restriction of

|  | **First Cost $/ha** | **Net Profit $/ha** | **Value of Ecosystem Services** | **Timber and Biomass Production** |
| --- | --- | --- | --- | --- |
| Bamboo | Expensive | Medium | High | Increase |
| Forest Plantations | 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 1.3: Land Use Solutions Comparison: Social and Climate Impacts

**Carbon Stock Protected:** Low 0-500 Gt CO2-eq, Medium is 500-1000 Gt CO2-eq, high is 1000+ Gt CO2-eq.

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

|  | **Carbon Stock Protected** | **Social Justice Benefits** | **Climate Impact/ha** | **Global Adoption Potential** |
| --- | --- | --- | --- | --- |
| Bamboo | Medium | Relevant | High | Medium |
| Forest Plantations | Medium to High | 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

## 2.1 Introduction

Project Drawdown’s models are developed in Microsoft Excel using standard templates that allow easier integration with each other since integration is critical to the bottom-up approach used. The template used for this solution was the Land Model which accounts for sequestration of carbon dioxide from the atmosphere into plant biomass and soil, and 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. The 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.

*Agency Level*

Government is selected as the agency level for this solution. Though certainly other agents can, do, and should play an important role in this solution, government is the most critical player in implementation.

## 2.2 Data Sources

Key data sources include Bonn Challenge and New York Declaration, country level data was analyzed to estimate future commitments for intact forest restoration. Restored land is assumed to sequester carbon at a constant rate of 3.4 tonnes C ha-1 yr-1 (1.2 SD). This sequestration rate is a mean of seven studies, including two review studies Poorter et al. (2016) and Bonner et al. (2013). The study by Poorter et al. (2016) includes data from 26 studies conducted in the neotropics, which estimated carbon sequestration within secondary forests recovering on abandoned agricultural land. The study by Bonner et al. (2013) includes data from 23 studies from across the tropics (Latin America = 15; Southeast Asia = 7; Africa = 1), which are also recovering secondary forests following agricultural use. Of the studies conducted in Latin America there is there is very little overlap between the studies used in Poorter et al. and Bonner et al. with just four studies in common. Therefore, the rates used in this model are based on a large body of evidence from >50 studies. However, there is a strong bias towards studies from the neotropics, with seven studies from Southeast Asia and just one from Africa all in Bonner et al., this reflects the paucity of data quantifying carbon sequestration in degraded or abandoned lands in these two regions. The poor coverage of current studies in Southeast Asia and Africa suggests that further research into the rates of carbon sequestration within naturally regenerating forest in is needed in these regions

## 2.3 Total Available Land

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 of 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 total land area allocated for the *tropical forest restoration* solution is 304 million hectares.

## 2.4 Adoption Scenarios

Two different types of adoption scenarios were developed: a Reference (REF) Case which was considered the baseline, where not much changes in the world, and 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.

This model predicts potential carbon sequestration from tropical forest restoration over the next 30 years. Inputs to the model are based on the targets from New York Declaration of Forests (NYDF), which commits to reforesting 350 million hectares by 2030 ([UNFCCC, 2014](#_ENREF_88)). The commitments of the NYDF build on the BONN Challenge ([Laestadius *et al.*, 2015](#_ENREF_56)), which committed to restore 150 Mha by 2020. In line with these commitments adoption scenarios were built to project tropical forest restoration under the following two custom adoption scenarios.

* ***Custom adoption scenario one*** - 15-year Adoption (100% land area), linear increase in restored area from 0 to 350 Mha between 2015 and 2030. The 15-year adoption scenario assumes that the targets of the NYDF are met by 2030 and that no further land is restored after 2030, giving an annual adoption rate of 21.88 Mha yr-1.
* ***Custom adoption scenario two*** - 30-year Adoption (100% land area), linear increase in restored area from 0 to 350 Mha between 2015 and 2045. The 30-year adoption scenario assumes that the targets of the NYDF are not met by 2030, rather, 350 Mha are restored by 2045, giving an annual adoption rate of 11.29 Mha yr-1.

To date approximately 248 Mha of land have been committed for restoration across the tropics in 35 countries (Appendix 1). Twenty-four of these countries have indicated what type of restoration will be done and the area for each option (Table below). Of the seven restoration options available just two (natural regeneration and assisted natural regeneration) allow for recovery back to an intact forest state. Approximately 32.8% of current commitments are using natural regeneration or assisted natural regeneration; therefore, a second pair of custom adoption scenarios were also used in this model.

* ***Custom adoption scenario three -*** 15-year Adoption (32.8% Land area), linear increase in restored area from 0 to 114.8 Mha between 2015 and 2030, assuming 32.8% of land areas is restored back to intact forest.
* ***Custom adoption scenario four -*** 30-year Adoption (32.8% Land area), linear increase in restored area from 0 to 114.8 Mha between 2015 and 2045, assuming 32.8% of land areas is restored back to intact forest.

Adoption scenario 3 and 4 gives an annual adoption rate of 7.2 Mha yr-1 and 3.7 Mha yr-1, respectively. Using adoption scenarios 3 and 4 gives a more realistic estimate of carbon sequestration within restored tropical forests between 2015 and 2045, however, the results from adoption scenarios 1 and 2 are also shown for reference, to demonstrate the upper limits of carbon sequestration if all 350 Mha were to be restored.

Table 2.1: The percentage of current restoration commitments for each restoration option available under the NYDF. ± 95% CI in parentheses.

|  |  |
| --- | --- |
| Restoration Option | % of commitments |
| Planted forest/Woodlots | 44.8 (13.3) |
| Natural Regeneration a | 10.7 (9.7) |
| Assisted natural regeneration a | 22.1 (11.0) |
| Agroforestry | 20.7 (12.5) |
| Improved Fallow | 0.2 (0.5) |
| Mangrove replanting | 0.1 (0.1) |
| Watershed/erosion control | 1.3 (1.7) |

a = Restoration option allows forest to recover back to an intact forest state.

### 2.4.1 Reference Case / Current Adoption[[2]](#footnote-2)

Current adoption of *tropical forest restoration* is assumed to be 0 in the lack of sufficient information.

### 2.4.2 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 – An ambitious approach is taken for the drawdown scenario, which is represented by the “high of all” custom adoption scenarios.

#### Optimum Scenario - This scenario represents the maximum adoption of the solution, which is represented by the “Custom adoption scenario one”.

## 2.5 Inputs

### 2.5.1 Climate Inputs

Carbon sequestration value was set to 4.15 based on the meta-analysis of carbon sequestration and root to shoot ratio value of the degraded forest.

Table 2.1 Climate Inputs

|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| --- | --- | --- | --- | --- | --- |
| Biosequestration | *tC/ha/yr* | 2.23 - 4.89 | 3.56 | 11 | 9 |
| Root to shoot ratio of degraded forest | *%* | 15.8% - 29.9% | 22.9% | 6 | 6 |

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

*Modeling Saturation*

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

The Drawdown land model takes the conservative approach that all land units currently adopted for agricultural solutions (including 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 afforestation in long-term products like buildings.

### 2.5.2 Financial Inputs

It is assumed that any costs for *forest protection* (e.g. carbon payments or payment for ecosystem services) are borne at a government or NGO level. Drawdown land solutions only model costs that are incurred at the landowner or manager level.

## 2.6 Assumptions

Six overarching assumptions have been made for Project Drawdown models to enable the development and integration of individual model solutions. These are that the infrastructure required for the 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 are 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.

**Assumption 1:** Assumption 1: Carbon is sequestered at 4.15 tonnes C ha-1 yr-1 and increases linearly..

**Assumption 2:** Assumption 2: By 2045, 350 Mha of land are restored.

**Assumption 3:** Four adoption scenarios are used for modeling, using either a 15 year or 30 year adoption, assuming either 100% or 32.8% of total land area is restored to intact forest.

**Assumption 4:** Initial carbon storage in 2014 is 12 tonnes C ha-1 yr-1, this is the median of short-fallow swidden (i.e. agricultural land abandoned for <5 years) from [Ziegler *et al.* (2012](#_ENREF_93))

**Assumption 5:** Areas that are undergoing tropical forest restoration are naturally regenerating back to an intact forest state following disturbance.

1. The first costs of restoration are assumed to be $0, as natural regeneration does not require any financial outlay. All that is required is for land to be protected from future degrading activities.

## 2.7 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.

*Forest protection* is part of Drawdown’s Land Use sector. Within land use it is part of a cluster of solutions based on ecosystem protection.

***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 of a given solution. Data on global land is acquired from the 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.

Drawdown’s Agro-Ecological Zone model allocates current and projected adoption of solutions to the planet’s forest, grassland, rainfed cropland, and irrigated cropland areas. *Forest protection* was the fourth priority for use of non-degraded forest, following *peatlands*, mangrove protection (in the *coastal wetlands* solution), and *indigenous peoples’ land management* (all of these are forms of forest protection).

***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 were 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. This solution is integrated in the yield model because it is adopted on degraded grassland, which displaces grazing.

## 2.8 Limitations/Further Development

Currently a limitation of this study is the lack of financial data.

# Results

## 3.1 Adoption

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

Total adoption in the *Plausible* Scenario is 176.06 million hectares in 2050, representing 58 percent of the total suitable land in 2014. Of this, 76.06 million hectares are adopted from 2020-2050.

Total adoption in the *Drawdown* Scenario is 238.80 million hectares in 2050, representing 79 percent of the total suitable land in 2014. Of this, 238.80 million hectares are adopted from 2020-2050.

Total adoption in the *Optimum* Scenario is 255.26 million hectares in 2050, representing 84 percent of the total suitable land. Of this, 255.26 million hectares are adopted from 2020-2050.

Figure 3.2 World Annual Adoption 2020-2050 [Mha]

Table 3.1 World Adoption of the Solution

| **Solution** | **Units** | **Base Year (2014)** | **New Adoption by 2050** | | |
| --- | --- | --- | --- | --- | --- |
| **Plausible** | **Drawdown** | **Optimum** |
| Forest Protection | Mha | 0 | 176.06 | 238.80 | 255.26 |
| % Total Land Available | 0.0% | 58% | 79% | 84% |

## 3.2 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).

Emissions reduction impact is 61.23, 89.05, and 105.61 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 | 0 | 2.68 | 61.23 | 61.23 | 1.93 | 2.68 |
| ***Drawdown*** | 0 | 0 | 3.63 | 89.05 | 89.05 | 3.05 | 3.63 |
| ***Optimum*** | 0 | 0 | 3.88 | 105.61 | 105.61 | 3.88 | 3.88 |

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).

Figure 3.3 World AnnualGreenhouse Gas Emissions Reduction

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** | 5.130 | 0.186 |
| **Drawdown** | 7.422 | 0.246 |
| **Optimum** | 8.747 |  |

## 3.4 Financial Impacts

Currently financial impacts are not modeled for this solution.

# Discussion

The carbon storage estimates presented in this report are only for aboveground carbon in stems >10 cm diameter, and therefore represent the lower estimate for total carbon storage. In natural forests carbon storage in belowground and necromass pools are approximately 25% and 13% of aboveground carbon, respectively ([Deans *et al.*, 1996](#_ENREF_24), [Hertel *et al.*, 2009](#_ENREF_47), [Palace *et al.*, 2012](#_ENREF_70), [Phillips *et al.*, 2008](#_ENREF_72)), increasing total carbon storage by between 1.6 and 9 Gt C (Table 4). Furthermore, additional carbon is stored in soils, carbon storage in tropical soil is poorly quantified however, the conversion of cropland to secondary forest has been estimated to increase soil organic carbon (SOC) by approximately 50% to 32 tonnes C ha-1 ([Don *et al.*, 2011](#_ENREF_28))

Table 4.1: Carbon storage in belowground and necromass pools and total carbon storage (aboveground, belowground & necromass).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Belowground & Necromass (Gt C) | | Total C storage (Gt C) | | |
|  | Land Area to intact forest | | | |
| Adoption scenario | 100% | 32.80% | 100% | 32.80% | |
| 15 year | 9.0 | 3.0 | 41.0 | 13.5 | |
| 30 Year | 6.5 | 1.6 | 29.7 | 7.2 | |

The adoption scenario used in this model assumes that 350 Mha of land are restored in the tropics by either 2030 or 2045. This value is based on the targets of the New York declaration on forests ([UNFCCC, 2014](#_ENREF_88)). The commitments of the NYDF are global targets and therefore also include restoration in temperate and boreal regions, meaning that using 350 Mha as an upper limit for restoration may be an over estimate. However, whilst restoration is likely to occur in temperate regions, currently 93% of restoration commitments are located in the tropics (appendix 1). Furthermore, estimates from the WRI and IUCN suggest that there is approximately 298 Mha of land suitable for wide-scale restoration in the tropics, with an additional 1112 Mha suitable for mosaic restoration (Figure 1; Minnemeyer *et al*., 2011), therefore using the targets of the NYDF as an upper limit for tropical forest restoration is a suitable approach.

An initial aboveground carbon (AGC) value of 12 t C ha-1 was used in this model, taken from [Ziegler *et al.* (2012](#_ENREF_93)) as the median value for short fallow swidden land. Short fallow swidden land was defines as areas abandoned following agriculture for <5 years and therefore corresponds with areas naturally regenerating following agriculture, which is the land use type used to calculate carbon sequestration rates (e.g. [Bonner *et al.*, 2013](#_ENREF_11), [Poorter *et al.*, 2016](#_ENREF_74)). However it is unlikely that all areas restored in tropical regions will be naturally regenerating from such a low carbon density. If degraded forests were included in tropical forest restoration projects then total carbon storage would be very different. Degraded forests include forests regenerating following selective logging, which can have AGC storage of approximately 60 t C ha-1 ([Berry *et al.*, 2010](#_ENREF_9), [Pinard & Putz, 1996](#_ENREF_73)) immediately following logging. If such areas of degraded land were also included within restoration projects then total carbon storage in 2045 would be much greater due to the higher initial AGC. However, rates of carbon sequestration in degraded forest can be similar to those observed in forest naturally regenerating on abandoned agricultural land (e.g. Berry *et al*., 2010), therefore carbon sequestered between 2014 and 2045 may be similar regardless of initial land use type. The biggest differences would be observed in total carbon storage. However, this model is intended to be illustrative of the potential carbon storage from tropical forest restoration, it does not predict the locations that will undergo restoration meaning that initial AGC storage is unknown. Because of this, using a lower initial AGC of 12 t C ha-1 is considered acceptable as it does not give an overly optimistic or unrealistic predication of the carbon storage potential from tropical forest restoration over the next 30 years.

## 4.2 Limitations

This solution lacks financial assessment. Inclusion of economic impacts, e.g. costs to governments and NGOs, would be a valuable addition to future updates.

## 4.2 Benchmarks

Griscom (2017) calculates a climate impact for tropical and subtropical forest restoration of 0.95 Gt CO2-eq/yr in 2030, on 472 Mha.

Table 4.2: Benchmarks

| **Source and Scenario** | **Mitigation Impact**  **Gt CO2-eq in 2030** |
| --- | --- |
| Griscom et al. (2017) | 0.95 |
| *Plausible* Scenario | 1.93 |
| *Drawdown* Scenario | 3.05 |
| *Optimum* Scenario | 3.88 |

# 5. References

Achard F, Beuchle R, Mayaux P *et al.* (2014) Determination of tropical deforestation rates and related carbon losses from 1990 to 2010. *Global Change Biology,* **20**, 2540-2554.

Alves DS, Soares JV, Amaral S, Mello EMK, Almeida SaS, Dasilva OF, Silveira AM (1997) Biomass of primary and secondary vegetation in Rondonia, Western Brazilian Amazon. *Global Change Biology,* **3**, 451-461.

Arora VK, Montenegro A (2011) Small temperature benefits provided by realistic afforestation efforts. *Nature Geoscience,* **4**, 514-518.

Avitabile V, Herold M, Heuvelink G *et al.* (2016) An integrated pan‐tropical biomass map using multiple reference datasets. *Global Change Biology*.

Baccini A, Goetz S, Walker W *et al.* (2012) Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. *Nature Climate Change,* **2**, 182-185.

Barlow J, Gardner TA, Araujo IS *et al.* (2007) Quantifying the biodiversity value of tropical primary, secondary, and plantation forests. *Proceedings of the National Academy of Sciences,* **104**, 18555-18560.

Bellassen V, Luyssaert S (2014) Managing forests in uncertain times. *Nature,* **506**, 153-155.

Benayas JR, Martins A, Nicolau JM, Schulz JJ (2007) Abandonment of agricultural land: an overview of drivers and consequences. *CAB reviews: perspectives in agriculture, veterinary science, nutrition and natural resources,* **2**, 1-14.

Berry NJ, Phillips OL, Lewis SL *et al.* (2010) The high value of logged tropical forests: lessons from northern Borneo. *Biodiversity and Conservation,* **19**, 985-997.

Betts RA (2000) Offset of the potential carbon sink from boreal forestation by decreases in surface albedo. *Nature,* **408**, 187-190.

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

Bruijnzeel LA (2004) Hydrological functions of tropical forests: not seeing the soil for the trees? *Agriculture, Ecosystems & Environment,* **104**, 185-228.

Canadell JG, Raupach MR (2008) Managing Forests for Climate Change Mitigation. *Science,* **320**, 1456-1457.

Cardinale BJ, Duffy JE, Gonzalez A *et al.* (2012) Biodiversity loss and its impact on humanity. *Nature,* **486**, 59-67.

Cardinale BJ, Matulich KL, Hooper DU *et al.* (2011) The functional role of producer diversity in ecosystems. *American Journal of Botany,* **98**, 572-592.

Cbd (2013) Quick guides to the Aichi Biodiversity Targets. Convention on Biological Diversity.

Chazdon RL (2008) Beyond deforestation: Restoring forests and ecosystem services on degraded lands. *Science,* **320**, 1458-1460.

Chazdon RL, Broadbent EN, Rozendaal DM *et al.* (2016) Carbon sequestration potential of second-growth forest regeneration in the Latin American tropics. *Science Advances,* **2**.

Chazdon RL, Peres CA, Dent D *et al.* (2009) The Potential for Species Conservation in Tropical Secondary Forests. *Conservation Biology,* **23**, 1406-1417.

Cochrane MA (2003) Fire science for rainforests. *Nature,* **421**, 913-919.

Cochrane MA, Alencar A, Schulze MD, Souza CM, Nepstad DC, Lefebvre P, Davidson EA (1999) Positive Feedbacks in the Fire Dynamic of Closed Canopy Tropical Forests. *Science,* **284**, 1832-1835.

Crouzeilles R, Curran M, Ferreira MS, Lindenmayer DB, Grelle CE, Benayas JMR (2016) A global meta-analysis on the ecological drivers of forest restoration success. *Nature communications,* **7**.

Cubiña A, Aide TM (2001) The effect of distance from forest edge on seed rain and soil seed bank in a tropical pasture. *Biotropica,* **33**, 260-267.

Deans JD, Moran J, Grace J (1996) Biomass relationships for tree species in regenerating semi-deciduous tropical moist forest in Cameroon. *Forest Ecology and Management,* **88**, 215-225.

Del Aguila-Pasquel J, Doughty CE, Metcalfe DB *et al.* (2014) The seasonal cycle of productivity, metabolism and carbon dynamics in a wet aseasonal forest in north-west Amazonia (Iquitos, Peru). *Plant Ecology & Diversity,* **7**, 71-83.

Dent DH, Wright SJ (2009) The future of tropical species in secondary forests: A quantitative review. *Biological Conservation,* **142**, 2833-2843.

Diaz-Balteiro L, Rodriguez LCE (2006) Optimal rotations on Eucalyptus plantations including carbon sequestration—A comparison of results in Brazil and Spain. *Forest Ecology and Management,* **229**, 247-258.

Don A, Schumacher J, Freibauer A (2011) Impact of tropical land-use change on soil organic carbon stocks – a meta-analysis. *Global Change Biology,* **17**, 1658-1670.

Douglas I, Greer T, Bidin K, Spilsbury M (1993) Impacts of Rainforest Logging on River Systems and Communities in Malaysia and Kalimantan. *Global Ecology and Biogeography Letters,* **3**, 245-252.

Edwards DP, Ancell FA, Ahmad AH, Nilus R, Hamer KC (2009) The value of rehabilitating logged rainforest for birds. *Conservation Biology,* **23**, 1628-1633.

Edwards DP, Larsen TH, Docherty TDS *et al.* (2011) Degraded lands worth protecting: the biological importance of Southeast Asia's repeatedly logged forests. *Proceedings of the Royal Society B: Biological Sciences,* **278**, 82-90.

Ehigiator OA, Anyata BU (2011) Effects of land clearing techniques and tillage systems on runoff and soil erosion in a tropical rain forest in Nigeria. *Journal of Environmental Management,* **92**, 2875-2880.

Fao (2000) On definitions of forest and forest change In: *Forest Resources Assessment working paper 33.* Rome.

Fao (2010) Global Forest Resources Assessment 2010. In: *FAO Forestry paper 163.* Rome.

Fao (2011) State of the worlds forests 2011. Rome, Food and Agricultural Organization of the United Nations.

Fisher B (2010) African exception to drivers of deforestation. *Nature Geoscience,* **3**, 375-376.

Fitzherbert EB, Struebig MJ, Morel A, Danielsen F, Brühl CA, Donald PF, Phalan B (2008) How will oil palm expansion affect biodiversity? *Trends in Ecology & Evolution,* **23**, 538-545.

Galbraith D, Malhi Y, Affum-Baffoe K *et al.* (2013) Residence times of woody biomass in tropical forests. *Plant Ecology & Diversity,* **6**, 139-157.

Geist HJ, Lambin EF (2002) Proximate Causes and Underlying Driving Forces of Tropical Deforestation. *Bioscience,* **52**, 143-150.

Gibson L, Lee TM, Koh LP *et al.* (2011) Primary forests are irreplaceable for sustaining tropical biodiversity. *Nature,* **478**, 378-381.

Gilroy JJ, Woodcock P, Edwards FA *et al.* (2014) Cheap carbon and biodiversity co-benefits from forest regeneration in a hotspot of endemism. *CAB reviews: perspectives in agriculture, veterinary science, nutrition and natural resources*.

Grace J, Mitchard E, Gloor E (2014) Perturbations in the carbon budget of the tropics. *Global Change Biology,* **20**, 3238-3255.

Guariguata MR, García-Fernández C, Sheil D, Nasi R, Herrero-Jáuregui C, Cronkleton P, Ingram V (2010) Compatibility of timber and non-timber forest product management in natural tropical forests: Perspectives, challenges, and opportunities. *Forest Ecology and Management,* **259**, 237-245.

Guariguata MR, Ostertag R (2001) Neotropical secondary forest succession: changes in structural and functional characteristics. *Forest Ecology and Management,* **148**, 185-206.

Hansen MC, Potapov PV, Moore R *et al.* (2013) High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science,* **342**, 850-853.

Hattori D, Kenzo T, Irino KO, Kendawang JJ, Ninomiya I, Sakurai K (2013) Effects of soil compaction on the growth and mortality of planted dipterocarp seedlings in a logged-over tropical rainforest in Sarawak, Malaysia. *Forest Ecology and Management,* **310**, 770-776.

Hertel D, Moser G, Culmsee H, Erasmi S, Horna V, Schuldt B, Leuschner C (2009) Below- and above-ground biomass and net primary production in a paleotropical natural forest (Sulawesi, Indonesia) as compared to neotropical forests. *Forest Ecology and Management,* **258**, 1904-1912.

Hill JK, Gray MA, Khen CV, Benedick S, Tawatao N, Hamer KC (2011) Ecological impacts of tropical forest fragmentation: how consistent are patterns in species richness and nestedness? *Philosophical Transactions of the Royal Society B: Biological Sciences,* **366**, 3265-3276.

Hodgson JA, Thomas CD, Wintle BA, Moilanen A (2009) Climate change, connectivity and conservation decision making: back to basics. *Journal of Applied Ecology,* **46**, 964-969.

Hooper D, Chapin Iii F, Ewel J *et al.* (2005) Effects of biodiversity on ecosystem functioning: a consensus of current knowledge. *Ecological Monographs,* **75**, 3-35.

Houghton R, Byers B, Nassikas AA (2015) A role for tropical forests in stabilizing atmospheric CO2. *Nature Climate Change,* **5**, 1022-1023.

Hughes RF, Kauffman JB, Jaramillo VJ (1999) Biomass, carbon, and nutrient dynamics of secondary forests in a humid tropical region of Mexico. *Ecology,* **80**, 1892-1907.

Ipcc (2014) Climate Change 2014: Mitigation of Climate Change. In: *Working group III.* Intergovernmental Panel on Climate Change.

Itto (2002) ITTO guidelines for the restoration, management and rehabilitation of degraded and secondary tropical forests. In: *ITTO Policy Development Series* International Tropical Timber Organization.

Kho LK, Malhi Y, Tan SKS (2013) Annual budget and seasonal variation of aboveground and belowground net primary productivity in a lowland dipterocarp forest in Borneo. *Journal of Geophysical Research: Biogeosciences,* **118**, 1282-1296.

Laestadius L, Buckingham K, S. M, Saint-Laurent C (2015) Before Bonn and beyond: the history and future of forest landscape restoration. *Unasylva,* **245**, 11-18.

Lal R (2005) Forest soils and carbon sequestration. *Forest Ecology and Management,* **220**, 242-258.

Lamb D (2010) *Regreening the bare hills: tropical forest restoration in the Asia-Pacific region*, Springer.

Lamb D, Erskine P, Parrotta J (2005) Restoration of degraded tropical forest landscapes. *Science,* **310**, 1628-1632.

Locatelli B, Catterall CP, Imbach P *et al.* (2015) Tropical reforestation and climate change: beyond carbon. *Restoration Ecology,* **23**, 337-343.

Lonsdale WM (1999) Global patterns of plant invasions and the concept of invasibility. *Ecology,* **80**, 1522-1536.

Luyssaert S, Inglima I, Jung M *et al.* (2007) CO2 balance of boreal, temperate, and tropical forests derived from a global database. *Global Change Biology,* **13**, 2509-2537.

Malhi Y (2012) The productivity, metabolism and carbon cycle of tropical forest vegetation. *Journal of Ecology,* **100**, 65-75.

Malhi Y, Baldocchi D, Jarvis P (1999) The carbon balance of tropical, temperate and boreal forests. *Plant, Cell & Environment,* **22**, 715-740.

Martin PA, Newton AC, Bullock JM (2013) Carbon pools recover more quickly than plant biodiversity in tropical secondary forests. *Proceedings of the Royal Society B-Biological Sciences,* **280**.

Martínez L, Zinck J (2004) Temporal variation of soil compaction and deterioration of soil quality in pasture areas of Colombian Amazonia. *Soil and Tillage Research,* **75**, 3-18.

Miettinen J, Hooijer A, Shi C *et al.* (2012) Extent of industrial plantations on Southeast Asian peatlands in 2010 with analysis of historical expansion and future projections. *Global Change Biology Bioenergy,* **4**, 908-918.

Minnemeyer S, Laestadius L, Sizer N, Saint-Laurent C, Potapov PV (2011) Bonn Challenge: A World of Opportunity In: *Available at:* <http://www.forestlandscaperestoration.org/resource/bonn-challenge-world-opportunity>*.* World Resource Institute.

Mugagga F, Kakembo V, Buyinza M (2012) Land use changes on the slopes of Mount Elgon and the implications for the occurrence of landslides. *CATENA,* **90**, 39-46.

Palace M, Hurtt G, Keller M, Frolking S (2012) *A review of above ground necromass in tropical forests*, INTECH Open Access Publisher.

Pan Y, Birdsey RA, Fang J *et al.* (2011) A large and persistent carbon sink in the world’s forests. *Science,* **333**, 988-993.

Phillips OL, Lewis SL, Baker TR, Chao KJ, Higuchi N (2008) The changing Amazon forest. *Philosophical Transactions of the Royal Society B-Biological Sciences,* **363**, 1819-1827.

Pinard MA, Putz FE (1996) Retaining forest biomass by reducing logging damage. *Biotropica,* **28**, 278-295.

Poorter L, Bongers F, Aide TM *et al.* (2016) Biomass resilience of Neotropical secondary forests. *Nature,* **530**, 211-214.

Preece ND, Crowley GM, Lawes MJ, Van Oosterzee P (2012) Comparing above-ground biomass among forest types in the Wet Tropics: Small stems and plantation types matter in carbon accounting. *Forest Ecology and Management,* **264**, 228-237.

Putz FE, Zuidema PA, Synnott T *et al.* (2012) Sustaining conservation values in selectively logged tropical forests: the attained and the attainable. *Conservation Letters,* **5**, 296-303.

Rist L, Shanley P, Sunderland T, Sheil D, Ndoye O, Liswanti N, Tieguhong J (2012) The impacts of selective logging on non-timber forest products of livelihood importance. *Forest Ecology and Management,* **268**, 57-69.

Saatchi SS, Harris NL, Brown S *et al.* (2011) Benchmark map of forest carbon stocks in tropical regions across three continents. *Proceedings of the National Academy of Sciences,* **108**, 9899-9904.

Saldarriaga JG, West DC, Tharp ML, Uhl C (1988) Long-Term Chronosequence of Forest Succession in the Upper Rio Negro of Colombia and Venezuela *Journal of Ecology,* **76**, 938-958.

Shackleton CM, Pandey AK (2014) Positioning non-timber forest products on the development agenda. *Forest Policy and Economics,* **38**, 1-7.

Suding K, Higgs E, Palmer M *et al.* (2015) Committing to ecological restoration. *Science,* **348**, 638-640.

The Bonn Challenge (2016) <http://www.bonnchallenge.org/>. [accessed July 2015].

Thomas SC, Martin AR (2012) Carbon content of tree tissues: a synthesis. *Forests,* **3**, 332-352.

Tian H, Lu C, Ciais P *et al.* (2016) The terrestrial biosphere as a net source of greenhouse gases to the atmosphere. *Nature,* **531**, 225-228.

Trabucco A, Zomer RJ, Bossio DA, Van Straaten O, Verchot LV (2008) Climate change mitigation through afforestation/reforestation: A global analysis of hydrologic impacts with four case studies. *Agriculture, Ecosystems & Environment,* **126**, 81-97.

Uhl C, Buschbacher R, Serrao EaS (1988) Abandoned Pastures in Eastern Amazonia. I. Patterns of Plant Succession *Journal of Ecology,* **76**, 663-681.

Uhl C, Jordan C, Clark K, Clark H, Herrera R (1982) Ecosystem Recovery in Amazon Caatinga Forest after Cutting, Cutting and Burning, and Bulldozer Clearing Treatments. *Oikos,* **38**, 313-320.

Unfccc (2014) New York Declaration on Forest. New York, United Nations.

Unfccc (2015) The Paris Agreement. In: *Conference of the Parties 21.* Paris, United Nations Framework Convention on Climate Change.

Van Kleunen M, Weber E, Fischer M (2010) A meta-analysis of trait differences between invasive and non-invasive plant species. *Ecology Letters,* **13**, 235-245.

Vitousek PM, Sanford R (1986) Nutrient cycling in moist tropical forest. *Annual review of Ecology and Systematics*, 137-167.

Wheeler CE, Omeja PA, Chapman CA, Glipin M, Tumwesigye C, Lewis SL (2016) Carbon sequestration and biodiversity following 18years of active tropical forest restoration. *Forest Ecology and Management,* **373**, 44-55.

Ziegler AD, Phelps J, Yuen JQ *et al.* (2012) Carbon outcomes of major land-cover transitions in SE Asia: great uncertainties and REDD plus policy implications. *Global Change Biology,* **18**, 3087-3099.

Appendix 1. Restoration commitments per country

|  |  |  |
| --- | --- | --- |
| **Country** | **Area (Mha)** | **Scheme** |
| Argentina | 1.0 | BONN |
| Azerbaijan \* | 1.2 | National scheme |
| Bolivia | 6.0 | INDC |
| Brazil | 23.1 | National scheme |
| Burkina Faso | 1.2 | National scheme |
| Burundi | 2.0 | National scheme |
| Chile | 0.6 | National scheme |
| China | 40.0 | INDC |
| Columbia | 2.0 | National scheme |
| Costa Rica | 1.2 | BONN |
| Cote d'Ivoire | 2.1 | National scheme |
| DRC | 16.8 | National scheme |
| Ecuador | 0.5 | BONN |
| El Salvador | 1.0 | National scheme |
| Ethiopia | 15.0 | BONN |
| Ghana | 1.7 | National scheme |
| Guatemala | 1.2 | BONN |
| Honduras | 1.0 | BONN |
| India | 13.0 | BONN |
| Indonesia | 28.9 | National scheme |
| Kenya | 5.1 | BONN |
| Lao PDR | 7.6 | National scheme |
| Lebanon \* | 0.1 | National scheme |
| Liberia | 1.0 | BONN |
| Madagascar | 1.0 | BONN |
| Mexico | 10.5 | National scheme |
| Mozambique | 1.0 | BONN |
| Nicaragua | 2.8 | BONN |
| Niger | 3.2 | BONN |
| Nigeria | 30.0 | BONN |
| Pakistan \* | 1.8 | National scheme |
| Peru | 3.2 | BONN |
| Republic of Congo | 2.0 | BONN |
| Rwanda | 2.0 | BONN |
| Sri Lanka | 0.2 | INDC |
| Uganda | 2.9 | National scheme |
| USA \* | 15.0 | BONN |
| Vietnam | 17.3 | National scheme |
| Zambia | 0.1 | National scheme |
| **Total** | 266.2 |  |
| Tropical | 248.1 (93%) |  |
| Temperate | 18.1 (7%) |  |

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. Current adoption is defined as the amount of land area adopted by the solution in 2018. This study uses 2014 as the base year due to the availability of global adoption data for all Project Drawdown solutions evaluated. [↑](#footnote-ref-2)
3. In some cases, the low boundary is negative for a variable that can only be positive, and in these cases the lowest collected data point is used as the “low” boundary. [↑](#footnote-ref-3)