**Technical assessment for**

**Tropical Tree Staples**

Sector: Food

Agency Level: Farmer

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# Executive Summary

Annual cropping systems are a major contributor of emissions from agriculture. The great majority of world cropland is used to produce annual staple crops like maize, wheat, potatoes, and soybeans. Annuals are not the only crops producing staple food, however – in the tropics, many *tropical staple trees* are already fully domesticated and widely grown and provide yields competitive with those of annual staple crops. These *tropical staple trees* sequester impressive carbon in soils and aboveground biomass, like any tree, while producing staple protein, fats, and carbohydrates. Their sequestration rates are much higher than any annual cropping system, though they present other tradeoffs and challenges.

One critical assumption of this study is that all projected future *tropical staple trees*adoption will take place on degraded land to avoid exacerbating forest clearing and land degradation practices currently associated with the production of staple tree crops such as avocado and oil palm. It is of great importance to note that if forest (particularly peatland) is cleared for tropical staple tree planting, this results not only in net carbon emissions but also contributes to broader environmental and social issues. Thus, for this solution, *tropical staple trees* are established on degraded or marginalized grazing land.

While the current total extent of *tropical staple tree* plantations is estimated at 50 Mha globally, all allocated on the cropland area. Future adoption was modeled on the grassland area based on historical trends derived from FAOSTAT and peer-reviewed data. To date, this solution has received little attention in the climate change mitigation literature. Future adoption, determined at the farmer-level, is constrained by high establishment costs and labor requirements. 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 147.08 million hectares in 2050. The sequestration impact of this scenario is 21.32 Gt CO2 eq. by 2050. Cumulative first cost is US$143.56 billion, with a net profit margin of US$3,095.57 billion. Under the *Drawdown* Scenario, total adoption is 166.55 million hectares in 2050. The sequestration impact under this scenario is 25.59 Gt of CO2 eq. by 2050. Cumulative first cost is US US$172.35 billion, with net profit margin of US$3,716.17 billion. Under the *Optimum* Scenario, projected total adoption is 174.25 million hectares in 2050. The sequestration impact under this scenario is 47.37 Gt of CO2 eq. by 2050. Cumulative first cost is US$275.74 billion, with net profit margin of US$7,304.76 billion.

# Literature Review

Tropical tree staple plantations include a wide range of perennial tree species that yield staple-food crops; they 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 agency level.

## State of the Practice

**Tropical Tree Staples Defined**

Most of the world’s cropland is allocated to the production of annual staples – as of 2012 they accounted for about 1.3 billion hectares of the world’s roughly 1.5 billion hectares of cropland (Wolz et al., 2018). Annual staple crops includes cereals (e.g., maize, rice, wheat), pulses (e.g., beans, peanuts, soy), oilseeds (e.g., canola, sunflower), and root crops (e.g., potatoes, cassava, taro, sweet potatoes). Staple crops provide the backbone and bulk of human food-systems as they contribute basic starch and carbohydrates as well as protein and oils for human consumption and livestock feed. The majority of existing annual cropping systems, particularly for maize and soy, are yield-intensive monocultures which contribute to significant greenhouse gas emissions, in addition to soil degradation, pollution, and other negative environmental consequences (Crews, Carton, & Olsson, 2018; Lal, 2014; Wolz et al., 2018). Although annual crops can be grown sustainably by using carbon-sequestering techniques, farmer adoption of such measures (e.g. diversification, cover cropping, reduced pesticide- and fertilizer-use, etc.) remains very low (Wolz et al., 2018).

The cultivation of perennial staple crops presents an alternative solution to the necessity of developing more sustainable staple annual food-cropping systems. *Tropical tree staples* consist of a range of perennial tree species that yield staple-food crops. Although temperate tree-staple cultivation is also a widespread practice (e.g. for olives, hazelnuts, almonds etc.), these crops are associated with high production costs, high water-use requirements and relatively low yields per hectare. As they are currently not competitive in comparison with annual staple crops they are not included in Drawdown calculations for this solution.[[1]](#footnote-1) Perennial staples can also include *perennial grains.* However, these are not yet commercially viable and are therefore covered separately as a Drawdown Coming Attraction solution.

While at commercial levels *tropical tree staple* species are currently predominantly grown in monoculture plantations, they can also be integrated with annual crops in *tree intercropping* systems or included in diverse *multistrata agroforestry* systems. However, since these strategies are included in separate Drawdown solutions, this report focuses on tropical tree staple monocultures. Their establishment requires farmers to prepare land for planting, and to procure and plant staple tree seedlings.

Tropical tree staple cultivation systems produce staple foods and have significantly higher carbon sequestration potential compared to annual cultivation systems, particularly if managed sustainably. A number of these crops are already of global importance today, particularly in the tropics, where staples like bananas and avocados are consumed daily. Today, the most widespread tropical staple tree crops are oil palm (21.1 Mha), coconut (12.1 Mha), banana (5.5 Mha), plantain (4.7 Mha), sago (6.3 Mha) and cashew (6.1 Mha). Together these major crops account for over 95% of the total global cultivation area of tropical tree staples, which approximates 58.4 Mha (Ehara, 2017; FAO, 2016) as of 2016. Other minor species include avocado, safou, coconut, brazil nuts, mesquite, enset and many others – see (Toensmeier, 2016) for a comprehensive description of common species around the world.

**Carbon Sequestration with Tropical Tree Staples**

Carbon sequestration refers to carbon fixed from the atmosphere over a set period of time. Carbon stocks, on the other hand, are a measure of total carbon accumulated in an ecosystem over the course of its lifetime, after years of carbon sequestration. The Drawdown model does not account for existing carbon stocks and all calculations include only annual sequestration rates in soils and vegetation biomass.

It is nevertheless worth exploring the differences between stocks in various farming systems as they differ widely. Carbon stocks accumulate both in soils (soil organic carbon, or SOC) and in above- and below-ground vegetation biomass (ABG and BGB). *Tropical tree staples* sequester carbon in both of these carbon pools (Nair, Nair, Mohan Kumar, & Showalter, 2010) as trees have the capacity to store high amounts of carbon in above- and below-ground biomass, particularly in comparison with essentially absent biomass stocks in annual cropping and grazing systems. Tree-based cropping systems also contribute to reduced non-CO2 greenhouse gas emissions and reduced soil degradation (as they for instance do not require tillage management after establishment), promoting long-term storage of soil carbon (Wolz et al., 2018). Combined sequestration rates for above- and below-ground carbon pools in tropical tree staple plantations in the literature range widely from 1.3 – 13.4 tC/ha/yr, as differences between tree species and management approaches can significantly impact carbon sequestration rates over time.

Project Drawdown’s calculations regarding the carbon sequestration potential of this solution are solely based on the conversion of degraded grassland to tropical tree staple crops. While the clearing of tropical forest or peatland areas for agriculture remains widespread, this is associated with net emissions of carbon, as well as a plethora of other problems (Mosnier et al., 2017; van Straaten et al., 2015). This practice is therefore excluded from all models and projections.

**Yields of Tree Staples Versus Annual Staples**

To support a shift from annual to tree-based staples, the latter must be competitive both from a financial as well as from a yield-based perspective. Today only tropical climates (here including lowland tropics, highland tropics, and subtropics) support the cultivation of various domesticated tree staple species with yields that compare favorably to annual staples in terms of their productivity per hectare (Toensmeier, 2016). See Tables 1.1 & 1.2 for a comparison of the yields of common tropical tree staple species with those of common annual crops.

Accurately comparing the per hectare yields of annual and tree-based staple crops is challenging. For purposes of this study, comparison begins by discounting inedible portions of both annual and staple crops, for example nut shells, tuber skins, banana peels etc. The yield of the edible portion is then calculated in dry weight. This provides a more reasonable basis for comparing, for example, fruits like banana which have a high water-content, with dry grains like maize. In addition, yields reporting is not standardized across existing literature and can consist of single figures, ranges, maximum values or averages. This report includes ranges and, where available, global averages. Ranges are presented for comparison only, as they are not suitable for statistical comparison. Though the data currently available is imperfect, it clearly shows that the yields of tropical tree staple crops are highly competitive with those of annual staples, and in some cases far exceed them. Section 3 of this report (Results) presents weighted average yield comparisons for common tropical perennial and annual staple crops.

Tables 1.1 & 1.2 demonstrate the competitiveness of selected common tropical tree staple crop species (both starch/carbohydrate-based and oil/protein-based), which should be prioritized for scaling-up. Note that global average yields are frequently reported to be lower than the reported range for the same crop. This illustrates the unreliability of reported ranges in existing literature.

Table 1.1:  **Yield comparison between common annual and tropical tree crops that primarily produce starch/carbohydrate staples (adapted from (Toensmeier, 2016).**

|  |  |  |  |
| --- | --- | --- | --- |
| **TROPICAL TREE STAPLE CROPS** | **Common Name** | **Yield Range (t/ha)** | **Average Yield (tons/hectare)** |
| *Metroxylon sagu* | Sago palm | 25.0 | -- |
| *Prosopis glandulosa / Prosopis pallida* | Mesquite | 1.8-49.5 | 9.0 |
| *Enset ventricosum* | Enset | 5.0 | 5.0 |
| *Musa* spp. | Banana & Plantain | 0.8-21.0 | 2.2 |
| *Artocarpus altilis* | Breadfruit | 0.9-18.0 | -- |
| *Ceratonia siliqua* | Carob | 1.7-8.3 | -- |
| *Inocarpus fagifer* | Tahitian chestnut | 0.7-4.3 | -- |
| *Artocarpus camansii* | Breadnut | -- | 3.9 |
| **Average tropical tree staple crop yields** |  |  | **5.0** |
| **ANNUAL STAPLE CROPS** | **Common Name** | **Yield Range (t/ha)** | **Average Yield (tons/hectare)** |
| *Solanum tuberosum* | Potato | 5.5-8.3 | 5.3 |
| *Zea mays* | Maize | 0.9-18 | 4.4 |
| *Manihot esculenta* | Cassava | 3.2-29.1 | 4.1 |
| *Oryza sativa* | Rice | 2.6-13. | 3.8 |
| *Ipomoea batatas* | Sweet potato | 0.6-6.4 | 3.8 |
| *Triticum aestivum* | Wheat | 2.6-7.9 | 2.7 |
| *Sorghum bicolor* | Sorghum | 2.7 | -- |
| **Average annual staple crop yields** |  |  | **4.0** |

Table 1.2: **Yield comparison between common annual and tropical tree crops that primarily produce oil/protein staples (adapted from (Toensmeier, 2016).**

|  |  |  |  |
| --- | --- | --- | --- |
| **TROPICAL TREE STAPLE CROPS** | **Common Name** | **Yield Range (t/ha)** | **Average Yield (tons/hectare)** |
| *Elaeis guineensis* | African oil palm | 13.5-34.2 | 14.5 |
| *Bertholettia excelsa* | Brazil nut | 4.4 | -- |
| *Cocos nucifera* | Coconut | 1.1-3.2 | 2.6 |
| *Macadamia integrifolia* | Macadamia | 2.2 | -- |
| *Persea americana* | Avocado | 0.2-6.0 | 1.7 |
| *Carya illinoiensis* | Pecan | 1.5 | -- |
| *Anacardium occidentale* | Cashew | 0.8-1.0 | 0.7 |
| **Average tropical tree staple crop yields** |  |  | **4.2** |
| **ANNUAL STAPLE CROPS** |  | **Yield Range (t/ha)** | **Average Yield (tons/hectare)** |
| *Glycine max* | Soybean | 0.9-4.6 | 2.1 |
| *Helianthus annuus* | Sunflower | 1.0-5.7 | 1.4 |
| *Brassica napus* | Canola | 1.9-3.8 | 1.3 |
| *Carthamnus tinctorius* | Safflower | 1.4-4.3 | -- |
| *Arachis hypogaea* | Peanut | 0.7-3.3 | 1.1 |
| *Cajanus cajan* | Annual pigeon pea | 0.9-6.8 | 0.7 |
| **Average annual staple crop yields** |  |  | **1.3** |

Though tropical staple trees yield as well or better than comparable annual staple crops (particularly for protein- and oil-yielding staples), people are often unwilling to change their diet to what can be grown sustainably in their climate, regardless of the potential climate impact. However, diet preference is less of an issue when it comes to livestock production. Roughly a third of annual cropland is used to produce livestock feed (FAO 2006) and switching to tropical tree staples to replace this is a feasible alternative. Many perennial staples have been used as livestock feed for centuries (Fukumoto, 2015), and this Drawdown solution thus aims for the “low-hanging fruit” of changing livestock diets. Nevertheless, increasing human consumption of perennial staples, and promoting market-incentives through premium prices for carbon-friendly food products, could greatly increase profitability and consequently adoption of tree staple crops.

***Environmental & Socioeconomic Benefits***

Tropical tree staples do more than provide food and contribute to carbon sequestration. Tree-based crops have much higher above- and below-ground biomass than annual crops and can thus contribute increased organic matter inputs and nutrient recycling. They require little to no tillage after establishment (Pimentel et al., 2012) as well as less application of costly inputs such as fuel, fertilizer and pesticides than annual cropping systems (Cox, Crews, & Jackson, 2014).

Tropical tree staples can provide benefits in terms of soil structure, nutrient storage and water holding capacity (Lal, 2014; Pimentel et al., 2012). Through soil improvements, tropical tree staple plantations can be effective for reduced erosion on slopes or for the restoration of degraded land (Pimentel et al., 2012). Tree-based systems also have a much higher contribution to water cycle regulation than annual or herbaceous cropping systems, for instance by recycling precipitation and transpiring water for cloud creation (Ellison et al., 2017; Leakey, 2013). Trees contribute to soil structure improvement and increased soil water storage capacity. This can lead to reduced runoff and nutrient leaching, and increased rainwater infiltration (De Leeuw, Njenga, Wagner, & Iiyama, 2014)(Pimentel et al., 2012), in turn reducing downstream flooding and recharging groundwater (De Leeuw, Njenga, Wagner, & Iiyama, 2014).

As a result, tree-based cropping systems tend to be more resilient to droughts, floods, landslides or other climate-related shocks than annual cropping systems (Schoeneberger et al., 2012). For instance, some systems have the capacity to go dormant and return to production the following year (World Agroforestry Centre 2014). Productivity in tropical tree staple systems is often year-round and can provide a safety network for farmers during the “hungry season” when little food from annual crops is available – particularly in diversified production systems such as *multistrata agroforests* (Toensmeier 2016).

These benefits make perennial crops an important climate adaptation strategy (Harvey et al., 2014). The IPCC notes that they are easily adopted by farmers and could have a “medium” mitigation impact based on the scale of potential adoption (Smith 2014).

***Drawbacks and Tradeoffs***

When a tropical tree staple plantation reaches the end of its productive life it is typically cut down and replanted. This can theoretically result in significant carbon losses, although there is much variation depending on management approaches and end-use of biomass (e.g., burning, biochar, building materials, etc.) (Nair et al., 2010). However, many tropical staple tree crops have long lives (Toensmeier, 2016). See Table 3 for representative lifespans.

Tropical tree staples have relatively high establishment and maintenance costs and their yields sometimes take longer than annual crops before becoming profitable. In addition, tropical tree staple systems can be difficult to mechanize, reducing labor efficiency when compared to mechanized annual cropping systems (Wojtkowski, 1999). Nevertheless, many tropical staple tree crops are associated with high prices, high demand and relatively low operational costs following farm establishment. They are therefore very lucrative for farmers. Common staple tree crops such as avocado or oil palm can be associated with significant challenges (González-Estudillo, González-Campos, Nápoles-Rivera, Ponce-Ortega, & El-Halwagi, 2017; Mosnier et al., 2017). While this solution has incredible potential, there remains a real risk that land-use change from increased adoption of tropical staple tree monocultures may have serious negative environmental, human, and climate consequences (Clay, 2004). To address this, it is important to focus expansion on already degraded grasslands, and to foster regulation policies that support sustainable management practices.

Table 1.3:  **Estimated productive lifespan of tropical tree staple plantings**

Source: (Toensmeier, 2016)

|  |  |
| --- | --- |
| **Productive lifespan** | **Tropical tree staple crops** |
| 25-49 years | Breadfruit, Mayan breadnut, date palm |
| 50-99 years | Peach palm, carob, coconut, Tahitian chestnut, karuka, avocado, mesquite |
| 100-499 years | Pecan |
| 1000-2000 years | Brazil nut |

## Adoption Path

Current adoption of tropical tree staples is estimated at about 58 Mha. An increase in future adoption would necessitate increased recognition of the solution’s potential as well as its integration into national and regional strategies and improved market valuation for tropical tree staple crops. Increased recognition of the tangible benefits of the practice, particularly in comparison with annual staple crops, 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. Policies addressing high initial costs through flexible financing approaches would contribute to increased adoption, as would the development of specialized mechanization technologies designed to reduce labor intensity in tropical staple tree crop plantations.

### Current Adoption

As discussed in Section 1.1 above, the current global area (as of 2016) of tropical tree staple crops is estimated at 58 Mha. Historical FAOSTAT data tracking the planting area for 9 major tropical tree staple species (avocado, banana, brazil nut, carob, cashew, coconut, date, shea nut, oil palm and plantain) between 1963 to 2016 indicates impressive growth rates over this time period. In addition, literature documenting the extent of current sago plantations indicates a similarly rapid growth trend over the last decades (Jong et al. 2018). However, tropical tree staple planting area numbers reported both through FAOSTAT and current literature (Table 4) do not distinguish between plantations established through forest clearing or those established through conversion of degraded grasslands. The rates of “climate-smart” adoption expansion (for instance excluding further forest clearing) in the future might therefore be lower than historical numbers.

Table 1.4: **Current Regional Adoption of Tropical Tree Staples**

*Source:* (FAO, 2016) *and* (Ehara, 2017) *(for sago cultivation area estimates).*

Regions are defined as standard Project Drawdown regions.[[2]](#footnote-2)

As the most comprehensive global estimate of current regional adoption available to date, this data is useful in establishing a baseline scenario. Nevertheless, it should be noted that i) the numbers presented here do not distinguish previous land-use for current tropical tree staple cultivation area, and may include establishment on degraded areas or through forest clearing; and ii) primary use of current crop extent is not assumed to be for livestock consumption.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Total Mha in production by year** | | | | | | |
| **Regions** | **1962** | **1972** | **1982** | **1992** | **2002** | **2012** | **2016** |
| **Asia (sans Japan)** | 5.98 | 8.16 | 11.35 | 14.28 | 19.67 | 26.75 | 36.92 |
| **Latin America** | 1.59 | 2.19 | 2.38 | 3.90 | 4.21 | 4.81 | 5.06 |
| **Middle East and Africa** | 6.95 | 7.54 | 8.13 | 10.32 | 13.17 | 15.45 | 16.33 |
| **OECD 90** | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.03 | 0.03 |
| **Total** | **14.54** | **17.91** | **21.87** | **28.52** | **37.08** | **47.04** | **58.35** |

### Opportunities for Accelerated Adoption

Tree-based cropping systems provide a wide range of benefits including soil and water conservation and carbon sequestration (Pimentel et al., 2012). For this reason, agroforestry systems, and more generally tree-based food systems, have been gaining traction at the international stage as a strategy for “climate-smart” agriculture, landscape restoration and carbon sequestration. Increased interest in such “climate-smart” practices may provide significant opportunity to scale up the adoption of tropical tree staple systems, as their impact on both is powerful (Harvey et al., 2014; Montagnini, 2015). This is compounded by steadily increasing global demand for and high profitability of common staple tree crops such as oil palm or avocado (González-Estudillo et al., 2017; Mosnier et al., 2017).

Several additional factors influence the viability of future adoption of this solution. While the labor efficiency of mechanized harvest of tree staples is poor when compared to mechanized annual staple crops (Toensmeier, 2016), tree staple cultivation can be highly competitive in certain contexts, for instance on land unsuitable for annual crop cultivation, or areas in where mechanization is not widely adopted.

Land suitability for cultivation is a key determinant of the adoption and profitability of specific crops. Climate change will alter the suitability of current annual croplands and increasing occurrences of large-scale yield declines in annual crop yield systems due to land degradation, pests, droughts or floods have already been documented in major growing regions (Deutsch et al., 2018; Tito, Vasconcelos, & Feeley, 2018). For example, global maize production has already declined by 4-12% in the last decades and is projected to decrease further (Tito et al., 2018). Growing populations and resulting increases in food demand will exacerbate pressures on annual staple cultivation systems in the coming decades. Mainstreaming alternative agricultural practices like tropical staple tree cultivation could help address future food security problems.

Anticipated reduction in the suitability of current agricultural land for staple crop production might signify a shift towards new cultivation areas. Agricultural expansion of both annual or perennial staple crops at the expense of forests results in a net loss of carbon and is thus undesirable (Nair, 2012). The conversion of degraded grasslands, which have low soil organic carbon stocks, can however result in impressive carbon sequestration. The current extent of degraded land is estimated at between 1-6 billion ha, including tropical cropland areas (Gibbs & Salmon, 2015). In addition, tropical tree staples are easier to grow on steep slopes than annual staples. Conversion of steeply sloping land that is currently cultivated with annual crops or unused could therefore be a prime target for this solution. This would not only contribute to reduced carbon emissions but also improve soil erosion and water infiltration, providing flood mitigation. There is significant potential for expansion in this context as the current area of steeply sloping cropland in the tropics is estimated at 30.1 million hectares (FAO, 2011).

Level of mechanization is another important consideration. An estimated 175.2 million hectares of cropland in the developing world is occupied by smallholders who are minimally mechanized at best (IFAD & UNEP, 2013) and can therefore not compete with large-scale mechanized annual crop production. In this context, tropical staple tree systems can be quite competitive. Smallholders’ positive perception of staple tree crops is another advantage, as smallholders have been shown to consistently identify tree crops (including many nuts and staple fruits) as top breeding priorities in participatory programs around the world (Leakey, 2012).

Since tropical tree staples are associated with high yields and carbon sequestration potential, as well as other ecosystem benefits, a shift towards more reliance on them for human and livestock diets could contribute to decreased greenhouse gas emissions and increased resilience to climate and food security risks. There is additional potential for accelerated adoption in this context as the management of tropical tree crops can be optimized for increased benefits through diversification, for instance by *tree intercropping* with annuals or conversion to *multistrata agroforestry* production systems. The inclusion of tree-based staple crop system in improved market incentivization schemes for carbon-friendly agriculture, for instance REDD+ certification or Payment for Ecosystem Service programs, would lead to increased recognition of their benefits.

### Barriers to Adoption

Ramping up the implementation of this Drawdown solution will entail many challenges, including:

* High initial establishment costs. For instance, obtaining sufficient planting material of tropical tree staple crops can often be difficult, particularly for lesser known species, whereas certain trees typically may not begin bearing for 2-5 years in the tropics. However, this can be offset by intercropping with annuals during establishment years.
* Higher labor and input requirements, which might require changes to harvest and processing machinery.
* Current market-demand for climate-smart and sustainably grown staple crops remains limited. One controversial case study is that of oil palm cultivation, which accounts for about 36% of tropical tree staple cultivation area and has contributed significantly to tropical deforestation rates (Carlson et al., 2012; Mosnier et al., 2017). As a response, initiatives like the Roundtable on Sustainable Palm Oil (RSPO) have been developed to increase the sustainability of tree-staple cultivation. Still, developing and implementing more effective market-incentives in conjunction with stronger policy regulations to ensure sustainable management and limit establishment on degraded lands is crucial for successful shift towards this solution (Milder et al., 2015; Mosnier et al., 2017).
* Risks associated with unsustainable establishment or management practices for this solution.

### Adoption Potential

This study appears to be the first to investigate the adoption potential of this solution.

## Advantages and disadvantages of Tropical Tree Staples

Project Drawdown’s *tropical tree staple* solution is one of a handful of staple-crop cultivation strategies that have carbon sequestration potential. Other strategies include *conservation agriculture*, *tree intercropping*, and *perennial grains*:

* *Conservation agriculture* and other sustainable annual cropping practices have relatively low carbon sequestration rates of under 1 ton/ha. For instance, a recent review of conservation agriculture cites rates of 0.6 t/ha/yr (Srinivasarao, Lal, Kundu, & Thakur, 2015). In these systems, mechanization, food processing, and market familiarity are all fully established, making them relatively cost-effective.
* *Tree intercropping* includes a range of agroforestry techniques that integrate annual staple crops with crop trees (e.g., fruit or timber), protective trees (e.g., windbreaks or riparian buffers), and/or supportive trees (e.g., nitrogen fixing trees). Project Drawdown’s *tree intercropping* solution has higher carbon sequestration rates of 2.7 and 1.4 t/ha/yr for tropical and temperate tree intercropping systems respectively. As with conservation agriculture, most tree intercropping systems require little change in the way we grow, process, and markets annual staple crops, as long as spacing between the woody elements is set properly to allow for mechanized access where needed.
* *Perennial grains* are a novel staple-crop production approach still under development (Crews et al., 2018), with few options currently scaled up to commercial production levels, and none yielding competitively with annual grains outside of research trials. Carbon sequestration rates for perennial grain cultivation are expected to be quite modest at 0.2-0.8 t/ha/yr, though the impact could be much more substantial on degraded and sloping lands (Toensmeier, 2016). Like tree intercropping and conservation agriculture, little modification is needed in terms of equipment and markets.

Trade-offs associated with these three alternative solutions indicate that while they are mostly viable in terms of infrastructure, market readiness, labor efficiency and/or mechanization, their carbon sequestration potential is low (with the exception of *tree intercropping*). For *tropical tree staples*, associated trade-offs are somewhat the reverse. Although a handful of major tree staples are already produced at large scales and are internationally-traded commodities, this is not the case for most species. Carbon sequestration rates are much higher than those of *conservation agriculture* and *perennial grains*, though they are comparable to those of other tree intercropping systems. Although some tree staples are already produced with mechanization, their labor efficiency of the systems is quite poor when contrasted with that of mechanized annual grains (Toensmeier, 2016). Significantly increasing the amount of tropical tree staples in the food system would require significant developments in terms of processing equipment. It also would entail development of new markets, though this could be to some degree addressed by beginning with replacing the one third of annual cropland which is used to produce staple foods for livestock with perennial staples.

Table 1.5 demonstrates that scaling up tree staplecropping systems is not an ideal strategy in every situation. However, the systems have significant potential the tropics, particularly on slopes too steep for annual cropping, and in non-mechanized areas. The need to develop mechanized harvest and processing equipment, and development of markets and food system familiarity are key current limitations.

Table 1.5:  **Carbon-sequestering of staple crop production practices compared**

Adapted from (Toensmeier, 2016), p. 133. Sequestration rates in t/ha/yr: very low (0-0.5), low (0.5-1), medium (1-5), high (5-10). Global perennial staples each have annual trade value over $1 billion US. Regional and minor perennial staples are domesticated and cultivated, but with less than $1 billion US annual trade value.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **Major tropical staple tree crops** | **Minor tropical staple tree crops** | **Perennial grains** | **Conservation agriculture** | **Tree intercropping** | **Conventional annual staple crops** |
| **Readiness of practice or crops** | High | Medium to high | Unready | High | High | High |
| **Carbon sequestration rate per hectare** | Medium | Medium | Very low to low | Low | Low to high | Very low |
| **Yields in to humid tropics** | High | High | Very low | High | High | Medium |
| **Yields in dry tropics** | Medium | High | Very low | Low to medium | Low to medium | Low to medium |
| **Yields in temperate and boreal regions** | Low | Low | Very low | High | High | High |
| **Suitability to steep slopes** | High | High | Low | Low | Medium | Low |
| **Mechanized labor efficiency** | Low | Very low | High | High | Medium to high | High |
| **Food system readiness (e.g. markets and processing)** | High | Low | High | High | High | High |

### Arguments for Adoption

A shift away from annual cropping and towards more reliance on tropical tree-based systems for the provision of staple crops has the potential of contributing to carbon sequestration rates since tree-based systems have higher long-term carbon stocks in both soils and aboveground biomass. Tropical tree staple systems also have potential positive impacts on food security and resilience to climate risks as they can provide high yields per hectare and contribute to ecosystem services such as soil and water conservation. Overall, this solution’s outstanding per-hectare yield and climate impact make it a viable strategy for ramping up climate-smart agriculture while addressing human livelihood demands and food security needs. Inherent limitations (high establishment costs, limited mechanizability, 2+ years until financial returns) and risks (increased deforestation, socioeconomic impacts) associated with the solution have been identified. Nevertheless, these can be addressed through prioritized establishment on well-suited land (e.g. degraded grasslands), and through the application of sustainable management approaches and clear policy regulations.

### Additional Benefits and Burdens

Here this solution is compared with other solutions in the food production cluster for farm, ecosystem, and social impacts. While tropical staple tree crops are associated with high start-up costs and a long delayed-profit period, they are also associated with high yield gains, high net profits and high climate impacts compared to other land-use and food solutions.

Table 1.6 **Food Production Solutions Comparison: On-Farm Impacts**

**Yield Gains:** loss of yield “loss”,no impact “n/a”,1-9% low, 10-24% medium, 25%+ high. **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+. **Delayed Profit Period:** Short is 0-2, Mid is 3-6, Long is 6+

|  | **Yield Gains** | **Startup Cost** | **Net Profit** | **Delayed Profit Period** |
| --- | --- | --- | --- | --- |
| Conventional cropping | n/a | n/a | Medium | n/a |
| Conventional grazing | n/a | n/a | Medium | n/a |
| Conservation agriculture | Low | Medium | High | Mid |
| Farmland restoration | High | Medium | Medium | Short |
| Farm water use efficiency | n/a | Expensive | Medium | Short |
| Improved rice | Loss | Free | High | Mid |
| Managed grazing | Medium | Medium | Medium | Mid |
| Multistrata agroforestry | n/a | Expensive | High | Long |
| Nutrient management | n/a | Free | Low | Short |
| Regenerative agriculture | Low | Medium | High | Mid |
| Silvopasture | Medium | Expensive | High | Long |
| System of Rice Intensification | High | Free | High | Mid |
| Tree intercropping | Low | Expensive | Medium | Long |
| **Tropical staple tree crops** | **High** | **Expensive** | **High** | **Long** |
| Women smallholders | high | Free | High | Short |

**Table 1.7 Food Production Solutions Comparison: On-Farm Impacts Social and Ecological Impacts**

**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+ tCO2-eq/yr (3+tC). **Global Adoption Potential:** Low 0-100Mha, Medium 101-500 Mha, High 500+ Mha

|  | **Ecosystem Services** | **Social Justice Benefits** | **Climate Impact/ha** | **Global Adoption Potential** |
| --- | --- | --- | --- | --- |
| Conventional cropping | n/a | n/a | n/a | n/a |
| Conventional grazing | n/a | n/a | n/a | n/a |
| Conservation agriculture | Low | Relevant | Low | Medium |
| Farmland restoration | Medium | Relevant | Medium | Medium |
| Farm water use efficiency | Low | Relevant | Low | Medium |
| Improved rice | Medium | Relevant | high | Low-medium |
| Managed grazing | Low | Relevant | Low | Medium-high |
| Multistrata agroforestry | High | Relevant | High | Low |
| Nutrient management | Medium | Relevant | Low | High |
| Regenerative agriculture | Medium | Relevant | Low | Medium-high |
| Silvopasture | High | Relevant | High | Low-medium |
| System of Rice Intensification | Medium | Targeted | Medium | Low |
| Tree intercropping | High | Relevant | Medium | Medium |
| **Tropical staple tree crops** | **Medium** | **Relevant** | **High** | **Low-medium** |
| Women smallholders | n/a | Targeted | Low | Low |

# 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[[3]](#footnote-3)) is what constituted the results.

Drawdown’s *tropical tree staples* solution models adoption in tropical climates on degraded grassland only. This approach rules out other climates and adoption on other land-use types such as forest or peatland.

Current adoption is estimated at 58 million hectares as of 2016, although for modeling purposes the baseline adoption of 25.7 Mha on degraded grasslands in 2014 is predominantly used in the model. Future adoption rates used in the Drawdown model are based on growth rates interpolated from historical data documenting global cultivation area for major tropical tree staples from 1963 – 2016 (Ehara, 2017; FAO, 2016).

*Agency Level*

The land manager, farmer, or rancher 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 FAO statistical service online, (Toensmeier, 2016)), and peer reviewed literature.

* Sequestration rates are based on a literature search that included 20 tropical tree staple species for which yield data is also available.
* Current area of planted perennial staple crops is derived from (FAO, 2016) data and literature (Ehara, 2017).
* Data for financial variables were derived from scientific literature as well as grey literature, primarily government and university financial resources for farmers.
* Data for price comparison of annual versus perennial staple crops is derived from (FAO, 2016).
* Total available land is calculated by the Drawdown model and based on the full area of tropical humid and tropical semi-arid cropland of all slopes and soil types, due to the diversity of perennial staple crops and their wide adaptability.
* General information on perennial staple crops is derived from (Toensmeier, 2016)) and current literature.
* Perennial staple crop yields and yield comparisons with annual staple crops is from (Toensmeier, 2016)) and (FAO, 2016).

## 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 tropical tree staples is modeled specifically on degraded grassland in tropical regions.

Replacing healthy *natural grassland* with perennial crops is undesirable for several reasons including competition for water resources with needs downstream, loss of habitat, and emissions from land us change. However, to date many grasslands have been established following clearing and degradation of forests and other ecosystems (UNCCD, 2017). These grasslands are often referred to as *semi-natural* (Faber-Langendoen & Josse, 2010). Restoration of such areas has significant potential for carbon sequestration and ecosystem rehabilitation.

To date, data on the extent of *degraded* or *semi-natural grasslands* is unavailable, both in the tropics and at global levels. However, existing evidence suggests they are widespread. For example, *Imperata* grasslands, established as a result of deforestation or abandonment of cropland, dominate tropical landscapes in Asia, where they constitute 33-66% of all grasslands in the region and cover 35 Mha (Garrity et al., 1996). Project Drawdown has calculated the total global area of *degraded grassland* as 979 million hectares based on meta-analysis of 12 data points from 8 sources. In the humid tropics, Drawdown’s analysis of (Dixon, Faber-Langendoen, Josse, Morrison, & Loucks, 2014), including supplemental materials, showed an extent of 681 million hectares of *degraded humid grassland*.

Based on this existing data regarding available degraded grassland area in the humid tropics, as well as land allocation as determined through the Drawdown Agro-Ecological Zone model, the maximum area allocated to tropical tree staples is 169 million hectares. 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.

For this solution, Drawdown’s future adoption models are built on projection of regional data from 1962-2012 (FAO, 2016). Six custom adoption scenarios were developed using linear, 2nd polynomial and exponential projections from historic adoption rates, and include both “regular” and “early” (70% by 2030) adoption:

1. ***Custom adoption scenario one***: This scenario is built on the historical (1962-2016) average global growth rate of tropical staple crops (Ehara, 2017; FAO, 2016). Future projections up to 2060 were interpolated based on an exponential best-curve fit applied to historical data available at decadal intervals for the given time-period. In the "Adoption Data" sheet we used this interpolated data: we first subtracted current (2014) adoption from projected 2050 adopted values and calculated the remaining proportion of TLA projected to be converted to tropical tree stables by 2050. This proportion (65.90%) was used to estimate adoption by 2050 on regional grassland TLA - in cases where estimated adoption is lower than current adoption, we use current adoption values.
2. ***Custom adoption scenario two***: This scenario is built on the historical (1962-2016) average global growth rate of tropical staple crops (Ehara, 2017; FAO, 2016). Future projections up to 2060 were interpolated based on a 2nd order polynomial best-curve fit applied to historical data available at decadal intervals for the given time-period. In the "Adoption Data" sheet we used this interpolated data: we first subtracted current (2014) adoption from projected 2050 adopted values and calculated the remaining proportion of TLA projected to be converted to tropical tree stables by 2050. This proportion (87.68%) was used to estimate adoption by 2050 on regional grassland TLA - in cases where estimated adoption is lower than current adoption, we use current adoption values.
3. ***Custom adoption scenario three***: This scenario is built on the historical (1962-2016) average global growth rate of tropical staple crops based on (Ehara, 2017; FAO, 2016). Future projections up to 2060 were interpolated based on a linear best-curve fit applied to historical data available at decadal intervals for the given time-period. In the "Adoption Data" sheet we used this interpolated data: we first subtracted current (2014) adoption from projected 2050 adopted values and calculated the remaining proportion of TLA projected to be converted to tropical tree stables by 2050. This proportion (46.6%) was used to estimate adoption by 2050 on regional grassland TLA - in cases where estimated adoption is lower than current adoption, we use current adoption values.
4. ***Custom adoption scenario four***: This is scenario one with an early adoption of 70% by 2030.
5. ***Custom adoption scenario five***: This is scenario two with an early adoption of 70% by 2030.
6. ***Custom adoption scenario six***: This is scenario three with an early adoption of 70% by 2030.

### Reference Case / Current Adoption

### Current adoption is 58 million hectares, based on current adoption value in 1962, 1972, 1982, 1992, 2002, 2012 and 2016 (Ehara, 2017; FAO, 2016). This data is interpolated to get the current adoption value in the year 2018. As noted above this is allocated to forest and cropland areas in the AEZ model.

### Project Drawdown Scenarios

Three Project Drawdown scenarios (PDS) were developed for each solution with the goal of comparing the impact of an increased adoption of the solution to a reference case scenario. They are as follows:

#### 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 2” where future adoption is projected based on the 2nd order polynomial growth rate.

## Inputs

### Climate Inputs

Carbon sequestration rates are set at 7.7 tons per hectare per year, based on 9 data points from 3 sources. It is assumed that all sequestered carbon is re-emitted at the end of a plantation’s useful life, which here is set at 37.5 years, based Toensmeier (2016)’s review of the life-spans of different tropical staple tree crops (see Table 3).

**Table 2.1 Climate Inputs**

|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| --- | --- | --- | --- | --- | --- |
| Biosequestration | *tC/ha/yr* | 4.0 -11.4 | 7.7 | 9 | 3 |

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[[4]](#footnote-4).

*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 *tropical tree staples*) 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.

*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). The lifespan of tropical tree staples is calculated to be 37.5 years, and thus outside the scope of Drawdown’s 30-year modeling window.

### Financial Inputs

For all agricultural solutions, it is assumed that there is no conventional first cost, as conventional grazing (in this case) is already in place on the land. Results are based on meta-analysis of 20 data points from 9 sources. Net profit per hectare is US$1152.56 per year (20 data points from 9 sources), compared to US$154.12 per year for the conventional practice (18 data points from 13 sources).

Establishment costs are US$1,298.43 per hectare, based on meta-analysis of 12 data points from 6 sources. Net profit per hectare is calculated at US$3,419.99 per year for the solution (based on meta-analysis of 20 data points from 10 sources). Tropical staple trees are not as labor-efficient as annual crops, in a mechanized context. However, 175 million hectares of the world’s farms are smallholders with little mechanization. The net profit per hectare figure shows that these crops are economically viable despite higher labor costs.

***Table 2.2 Financial Inputs for Conventional Practice***

|  | **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* | $12.67-$366.90 | $153.23 | 15 | 11 |
| Operating Cost (Conventional) | *US$2014/ha* | $28.06-$1,144.50 | $328.41 | 9 | 8 |

***Table 2.3 Financial Inputs for Solution (Tropical Tree Staples)***

|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| --- | --- | --- | --- | --- | --- |
| First costs (Solution) | *US$2014/ha* | $346.66 - $3,423.63 | $1,298.43 | 12 | 6 |
| Net profit (Solution) | *US$2014/ha* | $370.62 - $7,415.62 | $3,574.26 | 19 | 9 |
| Operating Cost (Solution) | *US$2014/ha* | $127.45 - $8,863.91 | $1,919.50 | 14 | 7 |

Farmers and ranchers transitioning to carbon-friendly practices face a period of reduced income. This reflects an individual learning curve, customization of the system to their farm or ranch, and time for the practice to begin to have an impact on productivity. Meta-analysis of 12 data points from 7 sources shows that in the case of implementation of tropical staple tree solutions, net profits per hectare do not exceed business-as-usual for 6.1 years. To account for this delay in profitability, the Drawdown model assumes that net profit per hectare is 25% of the conventional rate until 6 years have elapsed.

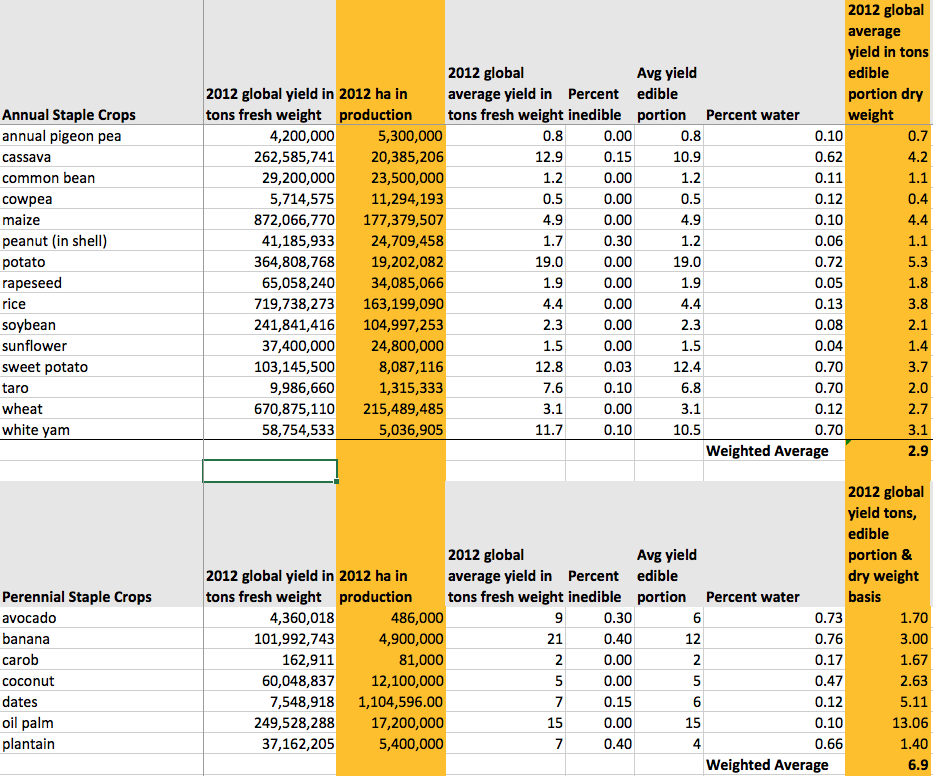
### Other Inputs

*Yields*

The weighted average yield of tropical staple trees is 2.4 times greater than that of annual staples, based on analysis of data from 7 tree-based staple crops and 15 annual staple crops (FAO, 2016).

Using FAO average global yields for leading annual and tree-based staples, average yields were compared. Weighted averages were based on the global area in production of each crop in question. The weighted average yield for annual staple crops was calculated at 2.9 t/ha/yr, while that of tropical tree staple crops was 6.9. Thus tropical tree staples are calculated to yield 2.36 times as much as annual staples.

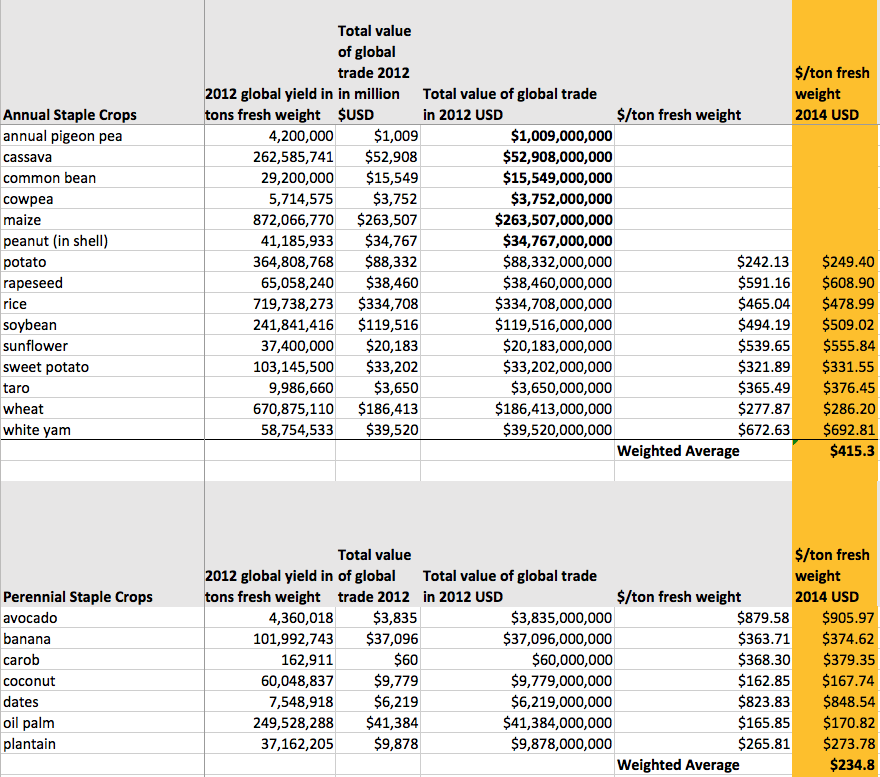
**Table 2.4: Weighted yields of annual vs tree staples**



*Prices*

Average prices from FAO Statistical Service were also used to develop weighted averages. The weighted average price of annual staple crops is $415 per ton fresh weight, while that of tropical tree staples is $234.80. Prices for tropical tree staples are therefore 0.56 times those of annual staples. Thus tree staples yield more tons per hectare, but are worth less dollars per ton.

**Table 2.5: Weighted prices/ton of annual vs tree staples**



## Assumptions

Six overarching assumptions have been made for Project Drawdown models to enable the development and integration of individual model solutions: 1) infrastructure required for solution is available and in-place; 2) policies required are already in-place; 3) no carbon price is modeled; 4) all costs accrue at the level of agency modeled; 5) improvements in technology are not modeled; 6) 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:

1. All new area planted will be established degraded grassland, with no land clearing for new plantings. This is a major assumption, as much of current growth in staple tree crops like oil palm and avocado is planted at the expense of newly-cleared forest. Land clearing for tree crops and agroforestry systems results in net emissions and is highly undesirable from a climate standpoint (Montagnini and Nair 2004).
2. Although adoption of the solution will shift to degraded land, adoption rates will follow current rates as interpolated from historical data from 1962-2016 to meet current demand projections. This is also a major assumption, because up to now current cultivation area has often been established through forest or peatland clearing.
3. Emission rates will not change and thus need not be modeled.
4. Harvest and processing equipment will not present an overwhelming barrier to perennialization of livestock feeds.
5. The ratio of 1/3 of cropland used to produce livestock feed is true in the tropics as it is for global cropland as a whole.
6. Carbon sequestration and yield rates are the same in both semi-arid and humid tropical regions. Sufficient data to make this distinction is currently unavailable, though mesquite yields (for example) are very high in semi-arid regions (Toensmeier 2016).
7. End of productive life of the plantings is at least 30 years and occurs after 2050.

## 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.

*Tropical tree staples* is part of Drawdown’s Food sector, specifically the supply-side set that incorporate food production. Within agriculture it is part of a cluster of solutions based on perennial crops production.

***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.

Total available land for this solution is 194 million hectares. *Current* adoption of the given solution is allocated both on the cropland and grassland AEZs, however, *future* adoption is allocated only on the grassland AEZs because of the allocation of other high priority annual and perennial cropping-based solutions on the cropland AEZs. Thus, the modelling results are only derived from the adoption of this solution on the grassland AEZs, where the TLA is 169 million hectares and the current adoption by 2014 is half of total global adoption (26.3 million hectares) of total current adoption (53.6 million hectares). Adoption of *tropical staple trees*was the second-highest priority for degraded grassland and the sixth-highest for degraded cropland.

***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 both produces crops and, as it is adopted on degraded grassland, 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 from *forest protection, Indigenous Peoples’ forest management, mangrove protection,* and *peatland protection*, 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.

This solution is integrated in the biomass model as a source of crop residues from prunings and orchard end-of-life.

## Limitations/Further Development

One of the major limitations for this solution is the current unavailability of the future prognostications for the adoption of this solution. Future adoption projections of the solution were projected based on existing historical data. Although, this solution could be applied on degraded or annual croplands, Drawdown models allocate new adoption of this solution solely on grassland AEZs. Thus, all financial comparisons of this solution are made with reference to conventional grazing practices, instead of conventional cropping practices.

# Results

## Adoption

1. 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.
2. Total adoption in the *Plausible* Scenario is 147.08 million hectares in 2050, representing 47 percent of the total suitable land. Of this, 97.08 million hectares are adopted from 2020-2050.
3. Total adoption in the *Drawdown* Scenario is 166.55 million hectares in 2050, representing 54 percent of the total suitable land. Of this, 116.55 million hectares are adopted from 2020-2050.
4. Total adoption in the *Optimum* Scenario is 174.25 million hectares in 2050, representing 56 percent of the total suitable land. Of this, 124.25 million hectares are adopted from 2020-2050.

Table 3.1 World Adoption of the Solution

| **Solution** | **Units** | **Base Year (2014)** | **New adoption on degraded grassland by 2050** | | |
| --- | --- | --- | --- | --- | --- |
| **Plausible** | **Drawdown** | **Optimum** |
| Tropical tree staples | Mha | 50 | 97.08 | 116.55 | 124.25 |
| % Total Land Available | 16% | 47% | 54% | 56% |

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

**.**

## 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).

Biosequestration impact is 21.32, 25.59 and 47.37 Gt of CO2 eq. 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*** | -- | -- | 1.19 | 21.32 | 21.32 | 0.53 | 1.19 |
| ***Drawdown*** | -- | -- | 1.428 | 25.59 | 25.59 | 0.63 | 1.43 |
| ***Optimum*** | -- | -- | 2.136 | 47.37 | 47.37 | 1.49 | 2.14 |

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** | 1.816 | 0.090 |
| **Drawdown** | 2.180 | 0.108 |
| **Optimum** | 3.972 | 0.151 |

**Figure 3.2 World AnnualGreenhouse Gas Emissions Reduction**

## 3.3 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, cumulative first cost is US$143.56 billion. Marginal first cost is the same as cumulative first cost. Net operating savings is US$-4,085.08 billion. Net profit margin is US$3,095.57 billion, and lifetime profit margin is US$6,718.04. Lifetime cashflow savings NPV is $-686.48.

For the Drawdown Scenario, cumulative first cost is US$172.35 billion. Marginal first cost is the same as cumulative first cost. Net operating savings is US$-4,904.06 billion. Net profit margin is US$3,716.17 billion, and lifetime profit margin is US$8,064.88 billion. Lifetime cashflow savings NPV is $-824.10 billion.

For the Optimum Scenario, cumulative first cost is US$275.74 billion. Marginal first cost is the same as cumulative first cost. Net operating savings is US$-9,077.18 billion. Net profit margin is US$7,304.76 billion, and lifetime profit margin is US$13,205.66 billion. Lifetime cashflow savings NPV is $-1,702.47 billion.

**Table 3.4 Financial Impacts**

| **Scenario** | **Cumulative First Cost** | **Marginal First Cost** | **Net Operating Savings** | **Net Profit Margin** | **Lifetime Profit Margin** | **Lifetime Cashflow Savings NPV (of All Implementation Units)** |
| --- | --- | --- | --- | --- | --- | --- |
| *2015-2050 Billion USD* | *2015-2050 Billion USD* | *2020-2050 Billion USD* | *2020-2050 Billion USD* | *2020-2050 Billion USD* | *Billion USD* |
| **Plausible** | $143.56 | $143.56 | $-4,085.08 | $3,095.57 | $6,718.04 | $-686.48 |
| **Drawdown** | $172.35 | $172.35 | $-4,904.06 | $3,716.17 | $8,064.88 | $-824.10 |
| **Optimum** | $ 275.74 | $ 275.74 | $-9,077.18 | $7,304.76 | $13,205.66 | $-1,702.47 |

**Figure 3.3 Net Profit Margin Increase**

## 3.4 Other Impacts

Based on average values in existing literature, tropical staple tree crops can lead to significant yield increases of 210% compared with annual staples. However, at this time, the calculation of total yield gains from adoption of this solution at global scales is not feasible, due to discrepancy in the reporting units of yields from grasslands (generally absolute tons of cattle or liters of milk), and those of tropical staple tree crops (generally tons per hectare).

# Discussion

Though little discussed, this solution has significant potential to mitigate climate change while generating profits and contributing to increased global food yields. Unlike *perennial grains*, which have also received limited attention, tropical tree staples are already cultivated on tens of millions of hectares. With supportive policies targeting improved education, availability of superior seeds and plants, financing, and development of markets and processing infrastructure, this strategy could have an impressive impact. Its adoption is likely to be greatest on degraded land, sloping land, and smallholder operations - together totaling many millions of hectares. This solution can offer the high sequestration rates of *afforestation* while providing food – in fact, while increasing food yields. It should also be noted that there are staple trees for cold climates, though their yields are not yet competitive with annual crops.

## Limitations

Additional data on financials, sequestration rates, and yields would improve this study. The potential adoption area could be increased to include arid regions, as many tropical staple trees like mesquite are suited to arid conditions.

Agroecological production systems (as alternatives to monoculture production) should be studied, developed and promoted. Selection and dissemination of superior varieties, and development of appropriate–scale harvest, processing, and transport technology is also important. Many organizations, including the World Agroforestry Centre, are already working on these types of initiatives (Leakey, 2012).

## Benchmarks

Benchmarks for this solution are unavailable.

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# 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. This is not to say that tree staples have no potential outside the tropics. Lower yields can be improved with breeding or can compensated for by developing intercropping systems with annual crops to achieve a Land Equivalent Ratio (the ratio of yield from a given area of monoculture to the yield of an equivalent area of polyculture) equal to or greater than 1.0. A global reduction of livestock consumption, or shift to smaller-scale, more intensive farms could also make these crops viable (in terms of world food production, as they are already profitable for the individual farmer) in a global *food security and avoided deforestation* scenario. [↑](#footnote-ref-1)
2. Asia is defined to include East, South, and Southeast Asia but not West Asia. Note that this includes a few small islands that are OECD90, with relatively tiny growing areas. Latin America includes all tropical growing regions of N and S America, as N America has very little tropical growing area. Middle East and Africa here include Africa and West Asia. OECD 90 here is represented by Australia and New Zealand as the only large land masses in OECD with tropical production, excluding a few Pacific islands classed as OECD90 which are included in Asia sans Japan. [↑](#footnote-ref-2)
3. 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-3)
4. 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-4)