**Technical assessment for**

**Multistrata Agroforestry**

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# Executive Summary

*Multistrata agroforests* are complex systems characterized by multiple canopy layers. Their structures, consisting of an overstory of tall trees and an understory of one or multiple layers of crops, are similar to those of natural forests, though they are often more simplified in terms of species composition and diversity. With an average carbon sequestration rate of 5.3 tC/ha/yr, significantly higher than that of other agricultural and ecosystem restoration solutions, multistrata agroforestry systems offer significant climate benefits through biosequestration. They also offer impressive co-benefits, notably ecosystem services like habitat, erosion control, and water quality. In fact, tropical homegardens, a multistrata system, have been described by scientists as “the epitome of sustainability.”

The current extent of multistrata agroforestry systems, which range from shaded cocoa and coffee to homegardens, is estimated to be about 100 million hectares globally. The practice is largely confined to the humid tropics. To date, further adoption potential is constrained by climate, high establishment costs, difficulty of mechanization, and complexity of management.

In Drawdown’s Agroecological Zone model this solution replaces grazing on tropical humid grassland. Growth rates are based on the New York Declaration on Forests and the Bonn Challenge, which include agroforestry as a part of restoration targets of 150 Mha by 2020 and 350 Mha by 2030.

Under the projected *Plausible* Scenario, total adoption is 142.60 million hectares in 2050. The sequestration impact of this scenario is 13.37 Gt CO2 eq. by 2050. Cumulative first cost is US$65.96 billion, with a net profit margin of US$1,046.28 billion. Under the *Drawdown* Scenario, total adoption is 170 million hectares in 2050. The sequestration impact under this scenario is 23.53 Gt of CO2 eq. by 2050. Cumulative first cost is US$113.39 billion, with net profit margin of US$1,869.78 billion. Under the *Optimum* Scenario, projected total adoption is 201.40 million hectares in 2050. The sequestration impact under this scenario is 33.69 Gt of CO2 eq. by 2050. Cumulative first cost is US $160.81 billion, with net profit margin of US$2,693.28 billion.

Multistrata agroforestry receives far less attention than other land-uses such as conservation agriculture and managed grazing, perhaps due to both its complexity and climate constraints. It is often lumped into “agroforestry” with tree intercropping and silvopasture though these practices are quite different.Its high sequestration rates and forest-like ecosystem services make *multistrata agroforestry* worthy of consideration on its own. Despite modest adoption potentials, multistrata systems can have a disproportionately high mitigation impact and should be prioritized in mitigation efforts.

# Literature Review

## State of the Practice

Agroforests are tree-based agricultural systems and are widely recognized for their high potential for carbon sequestration (e.g. Nair & Nair, 2014). Agroforestry systems take extremely varied and diverse forms. They have been classified into three separate Drawdown solutions due to their differing characteristics and carbon sequestration potentials: 1) *silvopasture* systems, in which trees are integrated in livestock pastures; 2) *tree intercropping* systems, where trees are planted individually or along hedges with annual crops to provide nutrient inputs and soil improvements; and 3) *multistrata agroforestry* systems.

***Multistrata Agroforestry Systems***

*Multistrata agroforests* are complex systems characterized by multiple canopy layers. Their structures, consisting of an overstory of tall trees and an understory of one or multiple layers of crops, are similar to those of natural forests, though they are often more simplified in terms of species composition and diversity. Multistrata agroforests contribute significantly to climate regulation through the sequestration of atmospheric carbon dioxide (CO2) which is stored in above- and below-ground biomass of trees and other crops, and in soil organic matter. The majority of multistrata agroforests are small and managed by smallholders.

The structure and composition of multistrata agroforestry systems across the world is highly diverse and variable. They often incorporate multiple species of woody crops, as well as shrubs, annual crops and/or livestock and fungi, and have been described as “intensive, multispecies, tree-based farming systems” (Nair, 2012). Though coffee and cacao are the most well-known products of multistrata agroforests, they also produce timber, fruits, spices and other cash crops (see Table 1.1). Multistrata agroforests have been around for a long time; traditional systems such as tropical homegardens date back over 13,000 years in Southeast Asia (Kumar & Nair, 2006).

Table .: Selected understory shade crops

Source: (Elevich, 2015; Manner, 2015; Toensmeier, 2016)

|  |  |
| --- | --- |
| **Category** | **Sample species** |
| Stimulants | Coffee, cacao, kava, tea, guayusa, yerba mate |
| Medicine | Ginseng, goldenseal, goldthread, *Ammomum villosum* |
| Fruits | Pineapple, Surinam cherry, mangosteen, currant |
| Spices | Black pepper, ginger, turmeric, cardamom, vanilla, mioga |
| Tuber crops | Taro, giant taro, cocoyam, konjak |
| Vegetables | Eru, chaya, edible hibiscus, Okinawa spinach, bago |
| Mushrooms | Shiitake, oyster |

The most common multistrata agroforestry typologies are described below (Table 1.2 provides additional examples):

* *Shade production of perennial cash crops such as coffee, cocoa, jungle rubber or tea*. In shaded systems, primary tree crops are grown under the canopy of shade-tree species. Shade canopies can consist of pre-existing thinned natural forest or of planted species (farmers often introduce nitrogen-fixing species in shade systems to increase soil fertility). This shade overstory is typically pruned to maintain an ideal level of partial shade (Filho, 2015).
* *Complex agroforests* feature useful species in both the overstory (fruits, timber, nuts, etc.) and understory (fruits, vegetables, stimulants, medicinal plants, etc.). They can cover 50-70% of entire islands (Manner, 1993) and are commonly found on Pacific Islands.
* *Tropical homegardens* are highly diverse, home-scale multistrata systems. In many regions they are ubiquitous. They have been practiced for 13,000 years in some regions and are present on millions of hectares worldwide today (Kumar & Nair, 2006).

While many multistrata agroforestry systems produce perennial staple crops such as bananas, avocado or coconuts, cropping systems primarily based on such crops are addressed separately in Drawdown’s *tropical staple trees* solution (Toensmeier, 2017).

Table .: Sample multistrata systems

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **System** | **Region** | **Orientation (market, home use)** | **Overstory species** | **Understory species** | **Source** |
| Shade coffee | Highland humid tropics global | Market | Timber, nitrogen-fixing species, native forest species | Coffee | Filho 2015 |
| Shade cacao | Lowland humid tropics | Market | Timber, nitrogen-fixing species, native forest species | Cacao | Nair 2010 |
| Shade tea | China | Market | Timber, tallow trees | Tea | Wehnhua 2001 |
| Jungle rubber | Indonesia | Market | Rubber, timber | Fruits, medicinal plants, rattan etc. | Toensmeier 2016 |
| Tropical homegardens | Humid tropics global | Home use, some market crops | Highly diverse fruits, nuts, more | Highly diverse fruits, vegetables, more | Nair and Kumar 2006 |
| Complex traditional agroforests | Pacific islands | Mixed | Coconut, breadfruit, fruits, timber, nuts | Tubers, pineapple, kava, spices, etc. | Manner 2015 |
| *Chagga* | Tanzania | Mixed | Timber, firewood | Coffee, fruits, banana, cardamom, annual crops | Toensmeier 2016 |
| Living trellis | Tropical Africa | Market | Nitrogen-fixing *Sesbania* | Passionfruit | Elevich and Wilson 2000 |
| Macadamia-coffee | Hawaii | Market | Macadamia | Coffee | Elevich and Wilson 2000 |

To date, multistrata systems are largely limited to the humid tropics (lowlands and highlands), where there are currently an estimated 100 million ha in production (Nair, 2012). This includes 7.8 million ha in shade cacao (Zomer, Trabucco, Coe, & Place, 2009), 6.1 million ha of shade coffee (Jha 2014), and 2.8 million in jungle rubber systems in Indonesia (Wibawa, Joshi, Noordwijk, & Penot, 2006). Areas of tropical homegardens have been estimated for the following regions: Indonesia, 5.1 million ha; Kerala, India, 1.3 million ha; Philippines, 70% of all households; Sri Lanka, 1 million ha; Bangladesh, 540,000 ha (Kumar & Nair, 2006).

Multistrata agroforests are emerging systems outside of tropics as well, notably in the form of temperate homegardens (Toensmeier, 2016). For instance, researchers at the University of Illinois in the US are testing commercial multistrata models (Lovell, n.d.). The USDA Natural Resource Conservation Service is increasingly funding multistrata agroforestry establishment and acknowledges the system’s potential for carbon-sequestration in their online COMET-Planner tool (USDA, n.d.). At this time, nevertheless, commercial-scale production of temperate multistrata agroforests remains lacking (Toensmeier, 2016) and they are therefore not included in Drawdown calculations for this solution.

***Yields in Multistrata Systems***

It is often assumed that yields are lower in multistrata systems or in any polyculture or intercropping system. The level of complexity and diversity makes measurement and modeling difficult (Miccolis et al., 2014). However, with proper design and species selection, yields can be higher than monocultures. Growing cacao under coconuts increases coconut yields by 95%, due to the benefits of the thick leaf litter from cacao (Ohler, 1999). In fact, coconut yields benefit from most intercrops, and yields of most understory species also show little reduction (Ohler, 1999). A study in Brazil found that oil yields of African oil palm in polycultures reached 8.7 t/ha/yr, compared to a high of 5 t/ha/yr for monocultures in the same region. This polyculture system also yielded cacao, passionfruit, and other products (Miccolis et al., 2014). The reverse can also be shown. Shade-grown coffee yields less than coffee in full sun, though plants live 2-3 times longer, reducing the cost of replanting (Clay, 2004).

This variation in yield impact is a challenge when it comes to modeling impacts on productivity. The great diversity of types of multistrata systems is one factor, as is the great diversity of crops grown in the overstory and understory. Shade, density of plantings, and interactions between crops (e.g. positive impacts like nitrogen fixation, and negative impacts like competition for water or nutrients) make it difficult to generalize the yield impact of multistrata systems.

***High Annual Sequestration Rates***

Multistrata systems demonstrate very high sequestration rates, among the highest of all food production systems. Leading agroforestry researcher P.K. Nair estimates that newly planted multistrata systems sequester 1-18 t/ha/yr, while established systems sequester 2-10 t/ha/yr (Nair, 2012). Table 1.3 shows a range of data points from reviews and expert estimations demonstrating these high annual levels of sequestration. Table 1.4 shows results of recent meta-analysis by (Feliciano et al, 2018), released after publication of *Drawdown*), showing lower rates.

Table . Annual carbon sequestration rates of multistrata agroforestry systems

|  |  |  |  |
| --- | --- | --- | --- |
| **System** | **Region** | **Sequestration Rate t/ha/yr** | **Source** |
| Newly planted multistrata systems | Humid tropics global | 2-18 | Nair 2012 |
| Established multistrata systems | Humid tropics global | 2-10 | Nair 2012 |
| Tropical homegardens | Humid tropics Africa | 2-18 | Nair and Nair 2014 |
| Shaded perennial crops | Humid tropics Africa | 5-15 | Nair and Nair 2014 |

Table . Mean aboveground biomass and soil organic carbon sequestration rates by region

Adapted from Tables 3 and 4 from (Feliciano et al, 2018), which was published after the publication of *Drawdown.*

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Continent** | **Agroforestry System Type** | **Aboveground Biomass Sequestration Rate t/ha/yr** | | | **Soil Organic Carbon Sequestration Rate t/ha/yr** | | |
| **Mean** | **Variance** | **# of Observations** | **Mean** | **Variance** | **# of Observations** |
| Africa | homegarden | .52 | .07 | 5 | .19 | - | 1 |
| shade systems | 2.27 | 2.36 | 18 | 1.91 | 13.01 | 3 |
| Asia | homegarden | 2.77 | 5.8 | 27 | 3.83 | 2.36 | 19 |
| Latin America | homegarden | 3.25 | - | 1 | -1.17 | - | 1 |
| shade systems | 2.87 | 2.79 | 22 | 1.05 | 5.75 | 21 |

Generally speaking, sequestration is highest in natural forests. Multistrata systems have relatively high sequestration rates as well and are followed by tree plantations, with annual agriculture the lowest (Nair, 2012). However, there are cases in which multistrata agroforestry systems sequester more carbon than nearby natural secondary forests (Brakas & Aune, 2011).

Despite this, these systems are often overlooked as a climate change mitigation strategy. When agroforestry is considered, multistrata systems are typically lumped in with annual crop-tree intercropping systems that feature far lower sequestration rates (Toensmeier, 2016). For example, the IPCC assigns “agroforestry” in humid tropical climates a sequestration rate of 0.2 t/ha/yr (Smith, Martino, Cai, & Gwary, 2007).

***High Lifetime Carbon Stocks***

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. Multistrata agroforestry have exceptionally high carbon stocking potential for both of these carbon pools. They feature the highest potential SOC stock rates of any agricultural system at up to 300 t/ha (Toensmeier, 2016), as shown in Figure 1.1. They additionally have the capacity to store high amounts of carbon in aboveground biomass (see Table 1.5) – this is significant especially when compared to the essentially absent biomass stocks in annual cropping and grazing systems.

Figure 1.1 Lifetime potential soil carbon stocks of various carbon-sequestering agriculture systems compared

Adapted from (Toensmeier, 2016).

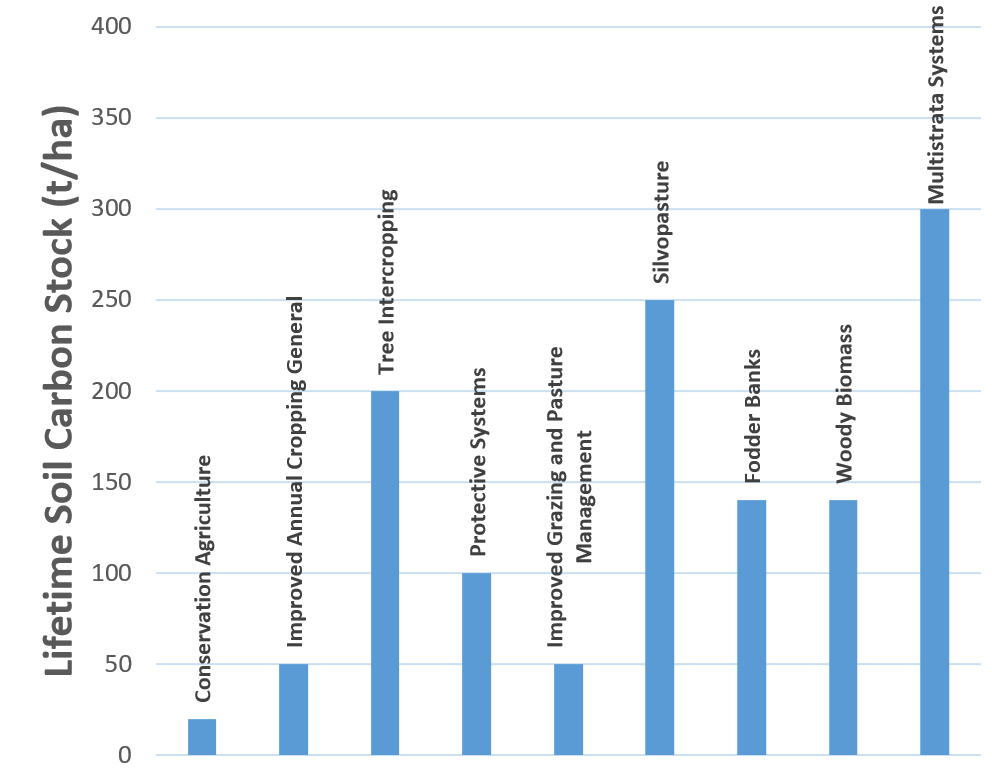


Table . Lifetime carbon stocks of aboveground biomass of multistrata agroforestry systems

Adapted from Montagnini (2015) and (Lasco, 2006). Note that these are carbon stocks, not annual sequestration rates.

|  |  |
| --- | --- |
| **System** | **Carbon Stocks t/ha** |
| Shade coffee | 47-237 |
| *Yerba mate* with overstory | 12-169 |
| Commercial multistrata systems | 3-114 |
| Shade crops | 41-74 |
| Tropical homegarden | 72 |
| Forest trees with food crops | 64-69 |
| Commercial multistrata systems | 64 |
| Indigenous multistrata agroforestry system | 59 |
| Forest-grown coffee and cacao | 19-47 |
| Organic coffee with *Inga* overstory | 46 |
| Organic forest-grown coffee | 39 |
| Non-organic shade coffee | 39 |
| Shade coffee | 22-35 |
| Shade cacao | 24 |
| Jungle rubber (SE Asia) | 304 |
| *Gmelina*- cacao (SE Asia) | 116 |

***Variables in Carbon Sequestration Within Multistrata Systems***

Within multistrata agroforests, carbon sequestration rates over-time are influenced by many factors. The following address some of them:

* Clearing forest for any kind of agriculture is always a net loss of carbon. This includes when forest is cleared to make way for multistrata agroforestry systems (Nair, 2012).
* Within multistrata systems, higher carbon sequestration is associated with higher species diversity, higher density, and longer lifespan of trees (Nair, 2012).
* Nitrogen-fixing trees are frequent components of multistrata agroforestry systems, often in the overstory of shade coffee and cacao systems for example. Nitrogen-fixing trees are consistently found to sequester 20-100% more soil organic carbon than other species, though some of this is offset by emissions of nitrous oxide (Nair, 2012).
* Most aboveground biomass carbon in multistrata systems is sequestered in the woody overstory. Within the understory, more carbon is found in woody shrubs than in herbaceous crops and grasses (Udawatta & Jose, 2011).
* C sequestration in below-ground root biomass is a major source of SOC (Lorenz & Lal, 2018).
* Overstories comprised of deciduous or semi-evergreen species allow more light to reach the understory, often permitting higher density and thus greater sequestration impact (Nair, Nair, Mohan Kumar, & Showalter, 2010).
* Polycultures mixing warm-season (C4 respiration pathway, active in warm season) and cool-season (C3 respiration pathway, active in cool season) species can sequester more carbon, as can other strategies or partitioning resources among members of polyculture systems (Mosquera-Losada, McAdam, Romero-Franco, Santiago-Freijanes, & Rigueiro-Rodróguez, 2008).

Within a given system, it is difficult to accurately measure C sequestration as whole-tree harvesting to assess above-ground biomass and root biomass is extremely time and labor-intensive. Calibrated allometric equations are frequently used to circumvent this; while they provide less accurate estimates, they facilitate larger-scale measurements at farm- or landscape-levels. Due to the high variance in multistrata agroforest types and structures which are likely to influence the factors outlined above, annual carbon sequestration rates across these systems are highly variable. This is exacerbated by the influence of site-specific factors influencing carbon sequestration processes, such as climate and soil-types (P. R. Nair & Nair, 2014). Overall, it is therefore difficult to accurately extrapolate C sequestration from one multistrata system to another. Nevertheless, the estimates used in the Drawdown model draw on data published in well-recognized peer-reviewed journals. Model projections are thus as realistic as possible but remain very conservative due to the above-mentioned uncertainties.

***Ecosystem Services***

Multistrata agroforests contribute to ecosystem functioning and resilience in numerous ways. They support higher biodiversity levels than other managed systems (P. K. R. Nair, 2006) with little impact on crop yields (Clough et al., 2011; Leakey, 2014). For instance, homegardens in Mesoamerica can feature 348 plant species per hectare (Montagnini, 2006). While they are no substitute for natural forests, multistrata agroforests provide suitable habitat for insect, bird and mammal species, and can serve as critical biological corridors to link fragmented habitats (Caudill, DeClerck, & Husband, 2015; Jose, 2009) .

In multistrata agroforests, the inclusion of a diversity of perennial crops can contribute to high organic matter inputs and nutrient recycling. This can lead to soil fertility increases and provide benefits in terms of yield and soil structure, nutrient storage and water holding capacity (Lal, 2014). Multistrata systems have been shown to be effective in restoration of degraded land (Albrecht & Kandji, 2003; Cooper, Leakey, Rao, & Reynolds, 1996). They can also significantly contribute to reduced erosion on slopes (P. K. R. Nair, 1993; Young, 1989).

As tree-based systems, multistrata agroforests also recycle precipitation and transpire water for cloud creation. They have a much higher contribution to water cycle regulation than annual or herbaceous cropping systems (Ellison et al., 2017; Leakey, 2013). Trees in multistrata systems further increase rainwater infiltration, reducing downstream flooding and recharging groundwater (De Leeuw, Njenga, Wagner, & Iiyama, 2014), though they can also compete for water with annual crops. As mentioned above, perennial crops contribute to erosion control and have been shown to have nutrient leaching rates of less than 5% of rates found in annual cropping systems (Jordan et al., 2007). This contributes to their excellent impacts on downstream water quality.

***Socio-Economic Impacts***

In addition to ecosystem service benefits, multistrata agroforests also have a number of socio-economic impacts. Increased diversity in multistrata perennial-based systems increases ecosystem resilience and can reduce the impacts of pests on crops (Ewel, 1986; Pumariño et al., 2015). The inclusion of relevant trees in multistrata systems can contribute to timber and firewood production. In regions where firewood is the primary fuel, every hectare of agroforestry can prevent the deforestation of 5-20 hectares of natural forest (Montagnini & Nair, 2004). Multistrata systems also require minimal fossil fuel inputs (e.g. pesticides, fertilizer and/or fuel) - the ranking of systems from least to most fossil fuel inputs is multistrata systems, other agroforestry systems, perennial monocultures, annual cropping systems (Cox, Crews, & Jackson, 2014; B. M. Kumar, 2006). The diversification of crop and income-sources within multistrata systems also contributes to food security (Mbow et al., 2014) and provides economic safety-nets for farmers (Tscharntke et al., 2011), as more resilient and diverse multistrata systems support yield and income security during droughts, market crashes, and other challenging times (De Leeuw et al., 2014).

The benefits listed above make multistrata systems an important strategy for climate change resilience (Montagnini, 2015). They are thus considered ideal mitigation-adaptation systems (Harvey et al., 2014).

***Establishment & Maintenance Costs***

Establishment and maintenance costs for multistrata agroforests are considerably higher than for other carbon-friendly farming systems or soil and water conservation techniques (Liniger, 2007). Establishing multistrata agroforestry systems tends to be labor-intensive compared to other agricultural practices. For example, the establishment period of a *maramihang pagtatanim* system, developed in the Philippines, occurs over 4-5 years. In a first step, land is prepared using hand tools and draft animals; coconuts are planted in year one, and after 3-4 years, the middle-story of bananas, coffee, and papayas is planted. Finally, the understory of pineapples and root crops is planted. Establishment of this system requires 50 person-days and 32 hours of animal traction per hectare. A similar example is that of a shaded coffee system (*Café arbolado*) which requires 2 years for establishment. All labor is done by hand, for a total of 100 person-days per hectare. Land is surveyed to lay out contours for coffee and lemon grass strips, and prepared, followed by planting of the trees. Both examples are from (Liniger, 2007). The majority of multistrata systems have similarly high establishment and maintenance costs (both in terms of financial inputs and labor) (Ginoga, Wulan, Lugina, & Djaenudin, 2004; Nunoo & Owusu, 2017).

***Profitability***

However, once they are established, multistrata systems can be quite profitable (D. Hervé Bertin Bisseleua, Fotio, Yede, Missoup, & Vidal, 2013; D.H.B. Bisseleua, Missoup, & Vidal, 2009), with long term benefits perceived positively by farmers (Liniger, 2007). This is evidenced by the wide utilization of shade systems in cacao production: of 9.7 million hectares in production in 2014 (FAO Statistical Service), 80% (7.8 million hectares) are grown in multistrata systems (Toensmeier, 2016).

***Drawbacks and Tradeoffs***

In addition to the high establishment and maintenance costs outlined above, one of the principal drawbacks of multistrata systems is that in the short-term, yields do not necessarily compete with those of monoculture or annual cropping systems, although this is not at all always the case (Clay, 2004; Ohler, 1999). While overall ecosystem functioning is improved in multistrata systems, crops can also compete for light, water, and nutrients with each other and adjacent or downstream crop fields (Koko, Snoeck, Lekadou, & Assiri, 2013; P. K. R. Nair, 1993; Van Noordwijk, Lawson, Hairiah, & Wilson, 2015). However, competition can be reduced through good planting and management techniques and the long-term benefits of multistrata systems make them attractive solutions in comparison with other cropping systems. Nevertheless, multistrata systems have thus far proven difficult to mechanize, reducing labor efficiency when compared to mechanized annual cropping systems (Wojtkowski, 1999). Another consideration is that certain component trees of multistrata systems can emit greenhouse gases such as nitrous oxide (Nair et al., 2010) or methane (Covey, Wood, Warren, Lee, & Bradford, 2012), although absolute impacts are still not well understood. Another associated risk is that of land expropriation and forest clearing for multistrata system establishment (e.g. for oil palm). This kind of carbon-based land grab has serious negative environmental, human, and climate consequences (Clay, 2004).

## Adoption Path

### Current Adoption

As discussed in 1.1 above, the global area of multistrata systems is estimated at 100 Mha. This includes shade coffee and cacao, tropical homegardens, complex agroforests, and simplified production polycultures of various kinds. Coconuts are particularly suited to serve as overstory in multistrata systems. In Tonga 85% of coconut production is intercropped, with figures at 70% and 43% for Papua New Guinea and the Philippines respectively (Ohler, 1999). Using 2016 production data from (FAOStat 2019) and applying the rate from the Philippines to all of Asia and Oceania provides an illustrative figure of 4.4 Mha in coconut agroforestry.

### Opportunities for Accelerated Adoption

Agroforestry has been gaining traction at the international stage as a strategy for landscape restoration and carbon sequestration. For instance, the Bonn Challenge and New York Declaration on Forests set ambitious, non-binding targets for restoration of degraded land. Agroforestry as a general practice has been cited among the restoration tools specified, though specific targets have not been established (“Bonn Challenge: A World of Opportunity | Global Partnership on Forest and Landscape Restoration,” 2016; UNFCCC, 2014). Nevertheless, a Bonn Challenge report (Minnemeyer, Laestadius, Sizer, Saint-Laurent, & Potapov, 2011) notes that of 2 billion hectares of degraded and deforested land, 1.5 billion are best suited to mosaic restoration, for which agroforestry is a suitable use. Similarly, signatories to the Paris Agreement submitted Intended Nationally Determined Contributions detailing their plans to address climate change. Of 22 Nationally Determined Contributions of tropical countries assessed, over 85% listed agroforestry as a strategy (Duguma, Nzyoka, Minang, & Bernard, 2017). Of the 15 of these that experience deforestation, 80% could meet their NDC targets just by converting 25% of this recently deforested land to agroforestry systems. While these initiatives do not focus specifically on the potential of multistrata agroforests, this increasing recognition regarding the potential of tree-based systems in terms of helping countries achieve their NDC goals may speed adoption rates in the next decades.

Increased interest in “climate-smart” agricultural practices linked to climate change adaptation and mitigation may provide an additional opportunity to scale up the adoption of multistrata systems, as their impact on both is powerful (Harvey et al., 2014; Montagnini, 2015). Further interest in related solutions could provide an additional opportunity for multistrata systems. For instance, *tropical staple tree* systems (see Drawdown solution report) are often well-suited to diversification and conversion to multistrata production systems.

Multistrata systems provide a wide range of benefits including poverty alleviation, carbon sequestration and biodiversity conservation (Caudill, DeClerck, & Husband, 2015; Jose, 2009; N. P. A. Kumar, Khan, & Balakrishnan, 2019). The inclusion of multistrata 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. Such actions could result in improved valuation through higher price premiums for products derived from multistrata systems, and ultimately increase the economic viability of this solution by increasing farmer incentives for further adoption (De Beenhouwer et al., 2016; N. P. A. Kumar et al., 2019).

Given the high cost of establishment and complexity of management, scaled-up adoption of multistrata systems is unlikely in the absence of official recognition of their high sequestration benefits. As Drawdown is modeling an ideal policy environment, it is assumed that recognition has taken place and active efforts including free-market price incentives, protected area buffers, specially allocated financing, and payment for environmental services are implemented.

Currently the majority of multistrata systems are limited to humid tropical areas. At global scales there are certain biophysically suitable sites and socioeconomic contexts in which adoption is more likely and/or beneficial. Limiting factors include: current land cover; level of mechanization, population, and intensification; steeper slopes; and level of degradation.

Current land cover is a key variable in determining suitability. Clearing forest to plant multistrata systems results in a net loss of carbon and is thus undesirable (Nair, 2012). On the other hand, the conversion of savannah or degraded grasslands, which have low soil organic carbon stocks, can result in impressive carbon sequestration. For instance, a study in Cameroon has shown that the establishment of shaded cocoa on savannah led to high carbon accumulation rates over an 80-year period (Nijmeijer, Lauri, Harmand, & Saj, 2018). Finally, intensification of existing monoculture plantations of timber, fruits, or other tree crops through conversion to multistrata systems could increase both carbon sequestration as well as overall productivity.

Level of mechanization is another important consideration. Multistrata systems are difficult to mechanize due to their complexity (Wojtkowski, 1999). This results in poor labor efficiency when compared to mechanized annual crops. However, 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). In this smallholder context, multistrata systems can be quite competitive. In fact, they have been identified as one of the most energy-efficient farming systems in the world, with only 0.2 calories of energy required to produce one calorie of food energy for some traditional Pacific multistrata systems (Manner, 2015). Multistrata systems are an intensive land use and are most commonly found where populations are high (Leakey, 2012). Thus densely-populated smallholder areas are prime locations to target for increased adoption.

Steep slopes are poorly suited to annual cropping. Multistrata systems are suited to highly steep slopes, often implemented at 60˚ or steeper (Liniger, 2007; Young, 1989, p. 198). The area of steeply sloping cropland in the tropics is estimated at 30.1 million hectares (FAO 2011). Multistrata systems are also suited to degraded cropland, in fact serving to restore it to some degree (Albrecht & Kandji, 2003; Cooper et al., 1996). Globally the area of degraded land is estimated at between 1-6 billion ha, including tropical cropland areas (Gibbs & Salmon, 2015).

### Barriers to Adoption

Globally, the total area of land allocated to multistrata systems has held roughly steady for decades. Researchers have asked why there have been virtually no efforts to increase adoption of multistrata practices like tropical homegardens.

One barrier is the very uniqueness and complexity of multistrata agroforests such as homegardens that makes them so ecologically desirable. This complexity also makes these systems difficult to study and model, with a degree of limitation of supporting evidence as a result (Nair, 2012). Researchers have identified three priorities regarding to role of multistrata systems in terms climate change mitigation: 1) conserve existing systems, 2) intensify them, and 3) increase adoption in new areas (B. M. Kumar, 2006).

Moreover, many plantation polycultures like shade coffee, cacao, or tea produce commodities that have limited market expansion potential. In Latin America, for instance, the current lack of a specific market valuing multistrata agroforestry products is a major obstacle to faster adoption rates of these systems. This leads even agroforestry promoters to conclude that prospects for expansion are poor (Nair, 2012). In the case of tropical homegardens, some existing systems are moreover somewhat under threat by urbanization and other challenges (B. M. Kumar, 2006), although they are also increasing in other areas (P. K. R. Nair, 2006). This trend towards simplification of complex agroforests has been linked to current market trends (P. K. R. Nair, 2006).

Increased labor linked to the need for intensive management of shade canopies to allow sufficient sunlight to reach understory crops are other factors limiting the diversification and intensification of shade crop production systems (Rapidel, 2015). Multistrata agroforests are, as detailed above, non-mechanized, complex, intensive systems. In comparison with other carbon sequestering agriculture systems they are associated with high cost of establishment and maintenance, particularly in terms of labor. Robust financing would be required to overcome this limitation. See Table 5 for examples.

### Adoption Projections

Projections of the adoption potential of multistrata agroforestry *as such* are quite rare. We must turn to estimates of the potential adoption of agroforestry more broadly instead. Former World Agroforestry Centre director Roger Leakey has estimated that 900 million hectares are suitable for conversion to agroforestry globally (Leakey, 2012). The Intergovernmental Panel on Climate Change has estimated 630 million hectares are suitable in the tropics (Duguma et al., 2017).

## Trade-Offs Associated with Multistrata Agroforestry

### Similar Solutions

How do multistrata agroforestry systems compare with other land solutions for the humid tropics? Carbon sequestration rates in multistrata systems are comparable with those obtained through *afforestation* and *forest restoration*. However, unlike those strategies, multistrata systems additionally provides food and diversified income sources. *Silvopasture* (trees on pasture) systems have similar sequestration rates as well, but features the drawbacks of methane emissions from ruminant livestock, and lower food production per hectare (Cassidy, West, Gerber, & Foley, 2013), though they also have far lower labor requirements. *Tree intercropping* systems sequester less carbon but are more easily mechanized and produce commonly accepted annual crops. *Conservation agriculture* and *regenerative agriculture* likewise have the advantage of mechanizability and marketable annual crops but feature lower sequestration rates.

Currently, multistrata agroforest systems are mostly constrained to the humid tropics, thus limiting total adoption potential. They do however hold an advantage over annual cropping systems due to their applicability on degraded and sloping land. Multistrata systems further can and should play a role in mosaic restoration, serving as protection buffers or biological corridors for intact and restored forest areas.

### Arguments for Adoption

No other food production system can compete with the sequestration rates of multistrata agroforests, which have the highest long-term carbon stocks in both soils and aboveground biomass. Multistrata agroforests also have particularly high positive impacts on biodiversity and other ecosystem services. Despite inherent limitations (high establishment costs, limited mechanizability, 6+ years until financial returns), this solution’s outstanding per-hectare climate impact recommends it as the gold standard of agricultural bio-sequestration.

### Additional Benefits and Burdens

Here this solution is compared with other solutions in the food production cluster for farm, ecosystem, and social impacts. While multistrata agroforests are associated with high start-up costs and a long delayed-profit period, they are also associated with high net profits as well as high climate impacts and high ecosystem benefits, 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 . 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 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.

Drawdown’s *multistrata agroforestry* solution models adoption in humid tropical climates on non-degraded grassland only. This approach rules out other climates (where the solution could be seen as a Coming Attraction), and adoption on cropland, including degraded and steep cropland, to which this solution is also well-suited.

Current adoption is estimated at 100 million hectares (Nair, 2012). Future adoption rates used in the Drawdown model are based on low (10 percent), medium (20 percent), and high (30 percent) targets for agroforestry-based restoration of degraded land through the Bonn Challenge and New York Declaration in Forests (“Bonn Challenge: A World of Opportunity | Global Partnership on Forest and Landscape Restoration,” 2016; UN Climate Summit, 2014).

*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 from 43 sources, including 26 peer-reviewed articles and 17 reports from agricultural agencies, extension agencies and international organizations, was used in the model. Key resources for the literature review include Toensmeier *The Carbon Farming Solution* (2016)*,* Kumar and Nair *The Carbon Sequestration Potential of Agroforestry Systems* (2011)*;* Kumar & Nair *Tropical Homegardens: A Time-Tested Example of Sustainable Agroforestr* (2006)*;* andMontagnini *Sistemas Agroforestales: Funciones Productivas, Socioeconómicas y Ambientales* (2015)*.* The adoption scenarios used for the Drawdown model of this solution are based in part on commitments from The Bonn Challenge and the New York Declaration on Forests. FAO Statistical Service provided key data for current adoption and annual global adoption data since 1961 for the data interpolator.

## 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.

While multistrata agroforestry is suited to multiple agroecological zones, in the Drawdown model new adoption potential is modeled specifically on non-degraded grassland in the humid tropics.

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.

Multistrata agroforestry was Drawdown’s highest-priority solution for grasslands in the humid tropics. Based on this existing data regarding available non-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 multistrata agroforestry is 360 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.

Six adoption scenarios were modeled. In the absence of adoption data, indeed in the absence of evidence of net adoption, the scenarios propose modest adoption levels and timelines based on the presence of agroforestry in the Bonn Challenge and New York Declaration on Forests commitments to restore a total of 350 million hectares of degraded land by 2030.

Six custom adoption scenarios were generated to model i) projected adoption rates of 10%, 20%, or 30% of the land allocated to multistrata agroforestry in the AEZ model; and ii) early adoption rates, with 70% of all adoption occurring by 2030). These scenarios are not unreasonable in light of the Bonn Challenge and New York Declaration of Forests which propose to complete all restoration by 2030. The six scenarios are described below:

* *Custom adoption scenario one:* This scenario projects adoption on 10% of the allocated land by 2050.
* *Custom adoption scenario two:* This scenario projects adoption on 20% of the allocated land by 2050.
* *Custom adoption scenario three:* This scenario projects adoption on 30% of the allocated land by 2050.
* *Custom adoption scenario four:* This is scenario one, with the added proviso that 70% of adoption is completed by 2030.
* *Custom adoption scenario five:* This is scenario two, with the added proviso that 70% of adoption is completed by 2030.
* *Custom adoption scenario six:* This is scenario three, with the added proviso that 70% of adoption is completed by 2030.

### Reference Case / Current Adoption

Current adoption is estimated at 100 million hectares based on (Nair, 2012). As noted above this is allocated to 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 - This scenario derives the result from the "low of all" custom adoption scenarios as discussed above.

#### Drawdown Scenario – This scenario derives the result from the "average of all" custom adoption scenarios as discussed above.

#### Optimum Scenario - This scenario derives the result from the "high of all" custom adoption scenarios as discussed above.

## Inputs

### Climate Inputs

Sequestration rates are set at 4.45 tons of carbon per hectare per year, based on meta-analysis of 16 data points from 9 sources. Unlike some other Drawdown perennial crop solutions, *multistrata agroforestry* does not address the emissions and financial impacts of replacement, as established multistrata systems can last decades or even centuries in the case of homegardens, even as individual trees may be replaced.

Table . Climate Inputs

|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| --- | --- | --- | --- | --- | --- |
| (i.e., Biosequestration, methane reduction, indirect emissions, etc.) | *tC/ha/yr* | 1.295-7.597 | 4.45 | 16 | 9 |

Note: Project Drawdown data set range is defined by the low and high boundaries which are respectively 1 standard deviation below and above the mean of the collected data points[[2]](#footnote-2).

*Modeling Saturation*

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

To address this 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.

*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.

The lifespan of multistrata agroforestry plantings ranges between 30 years for coffee and cocoa cultivation systems to indefinite for homegardens where individual trees or layers may be replaced but the system as a whole is long-lived. It is therefore assumed that end-of life emissions lie outside the scope of Drawdown’s 30-year modeling window.

### Financial Inputs

Establishment costs of *multistrata agroforestry*are estimated at US$1335.74 per hectare, based on meta-analysis of 15 data points from 12 sources. For all grazing solutions, it is assumed that there is no conventional first cost, as grazing is already in place on the land. Net profit per hectare from *multistrata agroforestry*is US$1,799.45 per year (21 data points from 12 sources). Operating cost is $442.17 based on 8 data points from 8 studies.

Yields are assumed to be equal to business-as-usual annual cropping, due to the great variation in crops and cropping systems in *multistrata agroforestry*. However, the conventional practice is grazing as new adoption is modeled exclusively on non-degraded grassland.

**Table 2.2 Financial Inputs for Conventional Technologies**

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

***Table 2.3 Financial Inputs for Solution***

|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| --- | --- | --- | --- | --- | --- |
| First costs (Solution) | *US$2014/ha* | $677.15 - $1,994.34 | $1335.74 | 15 | 12 |
| Net profit (Solution) | *US$2014/ha* | $262.21 - $3,336.69 | $1,799.45 | 21 | 12 |
| Operating Cost (Solution) | *US$2014/ha* | $122.80 - $761.55 | $442.17 | 8 | 8 |

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 in impact on productivity. Meta-analysis of 12 data points from 7 sources shows that in the case of implementation of agroforestry 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.

## 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 additional assumptions specific to multistrata agroforestry systems as a solution. These are detailed below:

1. Given the wide variation in typology and yields of multistrata agroforests (see Section 1.1), Drawdown models assume that yields of multistrata systems are equivalent to the systems they are replacing, though they may be higher, lower, or of a different commodity entirely.
2. Drawdown models assume that multistrata systems are limited to the humid tropics, though there are some examples of commercial systems in both colder and drier regions. This is because the great majority of commercial multistrata agroforestry is confined to the humid tropics, and sequestration rates may differ for the few examples in other climates.
3. As Drawdown is modeling an ideal policy environment, models assume that recognition of the per-hectare impact of multistrata agroforestry has taken place, and active efforts including free-market price incentives, protected area buffers, specially allocated financing, and payment for environmental services are implemented. However, Drawdown models do not take into account carbon pricing.
4. Drawdown models do not take into account the additional potential of converting existing orchards and forest plantations to multistrata systems, in part because spacing in afforestation projects is likely to provide too much shade for productive use of understory. This approach however is also worth pursuing where possible.
5. It is assumed that the “agroforestry” adoption commitment component of the Bonn Agreement and the NY Declaration on Forests includes multistrata systems though this is not specified, nor is the percentage of commitments that will be agroforestry specified.

## Integration

The complete Project Drawdown integration documentation (will be available at [www.drawdown.org](http://www.drawdown.org)) details how solution models within each Drawdown 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.

*Multistrata agroforestry* 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 have been allocated for each zone (e.g. semi-arid cropland of minimal slopes), zone priorities are generated and available land is allocated for new adoption. Priorities are 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 is 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.

In the Drawdown Agroecological Zone (AEZ) model, current adoption of this solution is allocated to cropland, 100 million hectares. New adoption is allocated to non-grassland in the humid tropics (see Section 2.3). As multistrata agroforestry systems constitute food production systems, they are included in Yield model projections, which track global food demand, supply, and land use change (see below). However, the results shown in this report are derived only from new adoption of the solution on grassland.

***The Yield model***

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

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

All three Drawdown scenarios show agricultural production sufficient to meet food demand and provide a surplus that can be used in bio-based industry, for example as feedstock for *bioplastic*production*.*Due to this surplus, no land clearing is necessary, resulting in impressive emissions reduction from avoided deforestation.  Because population change (resulting from *educating girls*and *family planning*),*plant-rich diet*, and *reduced food waste* are the principal drivers of this effect, Drawdown allocates the resulting reduction in emissions from land clearing to these solutions. However, as the impacts of population on yield and food demand are highly complex, we do not include avoided land conversion emissions associated with population change in the final emissions calculations for those solutions.

Drawdown’s Agro-Ecological Zone model allocates current and projected adoption of solutions to the planet’s forest, grassland, rainfed cropland, and irrigated cropland. This solution is limited to humid tropical climates. Adoption of *multistrata agroforestry* has been determined as the third priority for non-degraded grassland, the top priority for degraded grasslands, and the fourth priority for non-degraded croplands, particularly those with steep slopes (all of this land was allocated to other solutions with none remaining for this solution).

*Multistrata agroforestry* increases crop production, but also displaces grazing at new adoption occurs on degraded grassland.

***The Biomass Model***

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

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

## Limitations/Further Development

Current adoption is based on an expert estimate from (Nair, 2012), but accurate real-time estimates of the current global extent of multistrata systems are currently lacking. An alternative approach would be to use national-level data, where available, to generate regional adoption estimates – however, even at national and regional levels there are huge knowledge gaps in terms of current extent of the solution. In addition, the lack of projected adoption data is a significant constraint to this study. Commitments in Bonn and the NY Declaration on Forests report “agroforestry” but do not differentiate between multistrata, tree intercropping, silvopasture, and other forms of agroforestry. A real-time assessment of current adoption extent of multistrata agroforests, and of future projected adoption rates, would provide valuable insight regarding this solution’s potential for global carbon sequestration. Additional financial data, particularly regarding the profitability of multistrata system establishment on degraded grasslands, would also enhance the study.

# Results

## Adoption

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

Total adoption in the *Plausible* Scenario is 142.6 million hectares in 2050, representing 40 percent of the total suitable land. Of this, 42.6 million hectares are adopted from 2020-2050.

Total adoption in the *Drawdown* Scenario is 172 million hectares in 2050, representing 48 percent of the total suitable land. Of this, 72 million hectares are adopted from 2020-2050.

Total adoption in the *Optimum* Scenario is 201.4 million hectares in 2050, representing 56 percent of the total suitable land. Of this, 101.4 million hectares are adopted from 2020-2050.

Table . World Adoption of the Solution

| **Solution** | **Units** | **Base Year (2014)** | **New Adoption by 2050** | | |
| --- | --- | --- | --- | --- | --- |
| **Plausible** | **Drawdown** | **Optimum** |
| Multistrata Agroforestry | Mha | 100 | 43 | 72 | 101 |
| % Total Land Available (316 Mha) | 28% | 40% | 48% | 56% |

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

## Climate Impacts

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

Biosequestration impact is 13.37, 23.53, and 33.69 gigatons of carbon-dioxide equivalent in the *Plausible, Drawdown,* and *Optimum* Scenarios respectively.

**Table 3.2 Climate Impacts**

| **Scenario** | **Maximum Annual Emissions Reduction** | **Total Emissions Reduction** | **[Land] Max Annual CO2 Sequestered** | **[Land] 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*** | 0.00 | 0.00 | 0.69 | 13.37 | 13.37 | 0.35 | 0.69 |
| ***Drawdown*** | 0.00 | 0.00 | 1.17 | 23.53 | 23.53 | 0.67 | 1.17 |
| ***Optimum*** | 0.00 | 0.00 | 1.65 | 33.69 | 33.69 | 0.99 | 1.65 |

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 . 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** | 1.133 | 0.051 |
| **Drawdown** | 1.987 | 0.086 |
| **Optimum** | 2.841 | 0.120 |

**Figure 3.2 World AnnualGreenhouse Gas Emissions Reduction**

## 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$65.96 billion. Marginal first cost is the same as cumulative first cost. Net operating savings is US$-93.29 billion. Net profit margin is US$1,046.28 billion, and lifetime profit margin is US$ 2,131.18. Lifetime cashflow savings NPV is US$-32.53.

For the *Drawdown* Scenario, cumulative first cost is US$113.39 billion. Marginal first cost is the same as cumulative first cost. Net operating savings is US$-164.23 billion. Net profit margin is US$1,869.78 billion, and lifetime profit margin is US$3,685.50. Lifetime cashflow savings NPV is US$-59.30.

For the *Optimum* Scenario, cumulative first cost is US$160.81 billion. Marginal first cost is the same as cumulative first cost. Net operating savings is US$-235.17 billion. Net profit margin is US$2,693.28 billion, and lifetime profit margin is US$ 5,239.82. Lifetime cashflow savings NPV is US$-86.07.

**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** | $65.96 | $65.96 | $-93.29 | $1,046.28 | $2,131.18 | $-32.53 |
| **Drawdown** | $113.39 | $113.39 | $-164.23 | $1,869.78 | $3,685.50 | $-59.30 |
| **Optimum** | $160.81 | $160.81 | $-235.17 | $2,693.28 | $ 5,239.82 | $-86.07 |

**Figure 3.3 Net Profit Margin Increase**

# Discussion

Though the scope of adoption is modest, this solution has a disproportionate impact due to extremely high per-hectare sequestration rates. This leads highly competitive results compared to other agricultural mitigation strategies, even when these competing solutions are adopted at a much wider scale. For example, when compared to the combined *conservation agriculture* and *regenerative agriculture* improved annual cropping solutions, multistrata agroforestry shows roughly 23% of the climate impact on only 3% of the land.

Multistrata agroforestry systems also offer outstanding co-benefits, both on-farm and to the surrounding environment. Given this potential, multistrata systems should be prioritized wherever possible within the humid tropics to which they are constrained for the time being.

Establishment costs of multistrata agroforestry establishment are higher than other agricultural mitigation options. For this reason, a robust palette of financing options should support conversion, including national Payment for Environmental Service programs, loans, grants, and access to premium prices and/or secure markets. In tropical humid climates, efforts to protect and scale up *multistrata agroforestry* should be a high priority.

Net operating savings and lifetime cashflow savings are both negative, reflecting higher operating costs for this practice than the conventional practice it replaces. Nonetheless net profit margin for multistrata agroforestry is quite high, reflecting the higher profitability overall.

Multistrata agroforestry receives far less attention than strategies like conservation agriculture and managed grazing, perhaps due to both its complexity and climate constraints. This neglect can be seen in the absence of benchmarks looking specifically at multistrata systems. It is often lumped into “agroforestry” with tree intercropping and silvopasture though these practices are quite different.Its high sequestration rates and forest-like ecosystem services make *multistrata agroforestry* worthy of consideration on its own. Despite modest adoption potential, multistrata systems can have a disproportionately high mitigation impact and should be prioritized in mitigation efforts.

## Limitations

Very few benchmarks are available that break out multistrata systems as a subset of agroforestry. Another significant limitation is that adoption data is currently mostly unavailable. Global and regional assessments of the current extent of multistrata agroforests would significantly improve this study, as would additional financial data regarding benefits and trade-offs of its establishment on degraded grasslands.

## Benchmarks

Benchmarks for the climate change mitigation impact of *multistrata agroforestry* as such are unavailable, as it is typically considered part of an undifferentiated “agroforestry” solution if it is considered at all. A highly-cited study (Albrecht & Kandji, 2003) estimated sequestration of 4.0-8.0 gigatons of carbon dioxide-equivalent per year for all tropical agroforestry by 2050. This figure includes current as well as future adoption. By comparison, the combined agroforestry solutions of *tree intercropping, multistrata agroforestry* and *silvopasture* show an impact of 1.59-3.05 gigatons of carbon dioxide-equivalent per year in 2030. Drawdown, however, focuses only on new adoption, making the conservative assumption that current adoption has already reached saturation and no longer sequesters net carbon.

**Table 4.1 Benchmarks**

| **Source and Scenario** | **New Adoption in million hectares** | **Mitigation Impact (i.e. Gt CO2-eq in 2030)** |
| --- | --- | --- |
| Albrecht and Kandji (2003) all tropical agroforestry | 585-1215 | 4.0-8.0 |
| Project Drawdown – Plausible Scenario (PDS1) | 142.60 | 0.35 |
| Project Drawdown – Drawdown Scenario (PDS2) | 172.00 | 0.67 |
| Project Drawdown – Optimum Scenario (PDS3) | 201.40 | 0.99 |

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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. For most results, only the differences between scenarios, summed over 2020-2050 were presented, but for the net first cost, the position was taken that to achieve the adoptions in 2020, growth must first happen from 2015 to 2020, and that growth comes at a cost which should be accounted for, hence net first cost results represent the period 2015-2050. [↑](#footnote-ref-1)
2. In some cases, the low boundary is negative for a variable that can only be positive, and in these cases the lowest collected data point is used as the “low” boundary. [↑](#footnote-ref-2)