Technical assessment for Farmland Restoration

Sector: Food

Agency Level: Land Manager, Farmer/Rancher

Keywords: Biosequestration, Degraded Land, Abandoned Farmland

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*Note: For some of the technical reports, the result section is not yet updated. Kindly refer to the model for the latest results.

DRAWDOWN

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EXECUTIVE SUMMARY

Project Drawdown describes *Farmland Restoration* as a set of processes for restoring degraded, abandoned grassland to productive annual regenerative agriculture. Climate impact is via biosequestration. This solution does not replace a conventional practice. Current adoption is estimated at 20.03 million hectares.

Globally, an estimated 414 million hectares of farmland have been abandoned in the last two centuries. Land owners abandon farmland when these lands do not produce the desired economic benefits. The loss of agricultural productivity of these lands poses a threat to food security. These lands have also lost substantial carbon from soil and biomass in the process of becoming degraded.

Restoring these lands to productivity sequesters carbon, while bringing land back into production. This can also result in substantial reduced emissions from avoided deforestation, though that impact is not modeled here. This model looks only at agricultural restoration, restoration to forests and other agroecosystems is also practiced on abandoned farmland and may be addressed in other solutions.

Given the urgency of preventing emissions from deforestation, and the pressure of meeting food demand given the trend towards increasing meat consumption, *Farmland Restoration* is highly desirable. Its impressive carbon sequestration impact, along with these co-benefits, makes it an essential component of efforts to reduce emissions and sequester carbon.

For the *Plausible* Scenario, *Farmland Restoration* was adopted on 146.44 million hectares of abandoned farmland. Biosequestration impact was 10.17 gigatons of carbon dioxide equivalent from 2020-2050. Net profit margin 2020-2050 was $2,684.50 billion USD.

For the *Drawdown* Scenario, *Farmland Restoration* was adopted on 218.69 million hectares of abandoned farmland. Biosequestration impact was 15.97 gigatons of carbon dioxide equivalent from 2020-2050. Net profit margin 2020-2050 was $4,218.75 billion USD.

For the *Optimum* Scenario, *Farmland Restoration* was adopted on 290.94 million hectares of abandoned farmland. Biosequestration impact was 21.78 gigatons of carbon dioxide equivalent from 2020-2050. Net profit margin 2020-2050 was $5,753.00 billion USD.

1 LITERATURE REVIEW

1.2 STATE OF THE PRACTICE

Farmland Restoration is the conversion of abandoned, degraded grasslands into annual crop production using Regenerative Agriculture techniques of reduced tillage, cover cropping, residue retention, crop rotation, composting, and organic production. This solution does not replace a conventional practice in the model. Abandoned land is defined as an area that is no longer in its previous land use (agriculture or pasture) and the duration of abandonment has been much longer than a typical fallow period of one to three years in most regions. (Gibbs and Salmon 2015) describe abandoned farmland as areas with low-productivity cropping. However, it is difficult to clearly define when a parcel of land has become abandoned, as it is a transitional process and are often non-linear (Lambin and Meyfroidt 2011). Farmland abandonment starts when a parcel of land ceases to generate an income and there are limited or exhausted opportunities to reverse the process (McDonald and Schrattenholzer 2001). Therefore, a transition can be observed from productive land to semi-abandoned land to fully abandoned land over a period (Keenleyside, Tucker, and McConville 2010).

Terminology

The following search terms helped identify literature and reports on Farmland Restoration.

- *Abandoned farmland or agricultural land*
- *Reclaiming old fields*
- *Recultivation*
- *Reclaimed cropland*
- *Restoration of degraded lands*
- *Retired lands*
- *Extended fallow*
- *(not mine reclamation)*
- *Marginal croplands*

Abandonment of crop and pasture land is a common phenomenon occurring globally over the last two centuries. However, abandonment has accelerated in the last century.

The current global abandoned farmland area ranges between 385-472 Mha (Gibbs and Salmon 2015). Analysis at the regional level shows significant spatial variability in the abandoned farmland area (Figure

1). The abandonment is a significant problem in Asia and Africa and occurs at lower rates in Australia and Pacific regions (Gibbs and Salmon 2015).

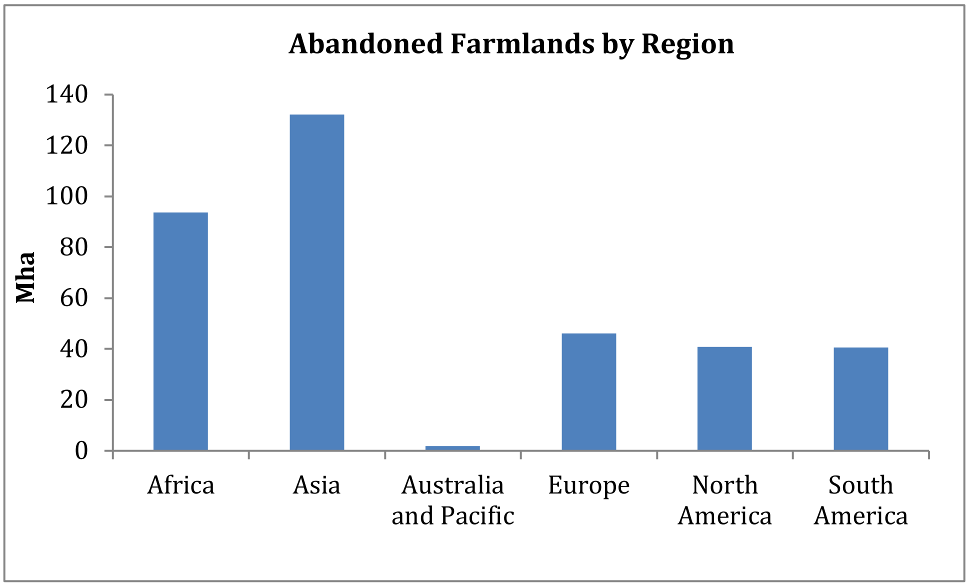

Figure 1.1 Estimates of abandoned farmland by region adapted from Gibbs and Salmon 2015.

(Waisanen and Bliss 2002) reported a higher rate of abandonment in western US from 1940-2000. Abandoned farmlands were found to increase by 34% in less than 20 years (1992-2011) in North America (Porensky et al. 2014). Similar results were also found by other researchers in Europe and North America (Brown et al. 2005; Lambin and Meyfroidt 2011; Ramankutty and Foley 1999). (Cramer, Hobbs, and Standish 2008) reported cases of farmland abandonment in the tropical regions.

Farmland abandonment is a complex and gradual process and there are many biophysical and socio-economic drivers that accelerate the process of land abandonment (Keenleyside, Tucker, and McConville 2010). (J. R. Benayas et al. 2007) performed a meta-analysis of 45 studies and reported the various drivers for land abandonment (Table 1). Biophysical drivers causing poor productivity and profitability include climate, slope, and soil characteristics (depth, erosion, and fertility). The socio-economic drivers include demography, economy, market, management, and policy.

Table 1.1 Identified drivers of land abandonment. Adapted from Benayas et al. 2007

Identified Drivers		Biomes	Regions
Bio-physical	Climate	Mediterranean, tropical ecosystems	Southeastern Spain, tropics
	Slope	Temperate mountain, Mediterranean, tropical forest	Northern Spain, Greece, Swiss Mountains, Honduras

	Soil depth	Mediterranean, wetlands and riparian forests	Greece, Wisconsin, Swiss Mountains
	Soil erosion	Mediterranean	Greece
	Soil fertility	Temperate grassland, wetlands and riparian forests	Europe, Wisconsin, China
Socio-economic	Migration, rural depopulation	Dry shrubland, Mediterranean, tropical forest, temperate mountain, temperate forest, various	Central Mexico, Spain, Western Europe, Puerto Rico, Italian Alps, Southeast Poland, Ireland. Europe
	New economic opportunities (tourism, industrialization, housing, etc.)	Tropical forest, tropical coast, Mediterranean, wetlands and riparian forests	Puerto Rico, Tanzania, Brazil, tropics, Spain, Wisconsin, Swiss Mountains
	Land-tenure system	Temperate mountain, temperate forest	Northern Spain, Denmark
	Accessibility by road, proximity to town or city	Temperate mountain, tropical forest	Northern Spain, Brazil, Panama, Northern Italy, Peru. Swiss Mountains
	Market incentives	Tropical forest, temperate grassland	Brazil, Panama, Eastern Europe, Peru
	Agrarian policy	Mediterranean, temperate grassland, temperate forest, wetlands and riparian forests	Spain, Europe, Denmark, Central Italy, Wisconsin, Ex-USSR
	Input and output prices Farmer age	Temperate forest, Mediterranean	Europe Denmark, Spain, Europe
	Mismanagement-induced desertification, over-exploitation	Semi-arid shrubland, tropical forests, Mediterranean, temperate ecosystems	Northern China, tropics, Southern Spain, China, Europe, Northern Spain

Source: Adapted from Benayas et al 2007

Carbon sequestration and emissions from abandoned farmlands

Farmland abandonment decreases the share of productive land for food production, and increases the pace of resource degradation of water, biodiversity, and especially soils. This in turn increases greenhouse gas

(GHG) emissions and limits CO2 sequestration potential. The CO2 emissions from the global soil erosion occurred after post-industrialization was reported to be 26±9 Gt CO2 by (R. Lal 2003), based on the estimates of (Noble et al. 2000; Ruddiman 2003). Depletion of soil organic carbon has contributed 78±12 Pg of carbon to the atmosphere (R. Lal 2003). Abandoned farmlands have potential to minimize carbon emissions and sequester carbon by the adoption of suitable restoration practices.

Building soil organic carbon could lead to a global sequestration of 0.9±0.3 Pg C/year (R. Lal 2003). Land management techniques can restore degraded soils, enhance biomass production, filter surface and ground waters, and reduce atmospheric CO2 by offsetting emissions from fossil fuels (Lal et al. 2018). Therefore, restoration of these abandoned farmlands is extremely important - the cost of inaction far outweighs the cost of action[1].

Restoration of abandoned farmlands

Restoration of abandoned agricultural fields has become an important conservation strategy regionally. The restoration of abandoned farmlands can be passive or active restoration.

Passive Restoration

Passive restoration involves minimal management practices and allows natural ecological community succession to occur. Many permanently abandoned farmlands will eventually return to forest ecosystems under passive restoration. Thus, the establishment and operational costs of this approach are minimal but complete restoration takes years or decades. The length of time needed for natural succession depends on the condition of the land and cause of the farmland abandonment. The re-forested land can be returned to cultivation and may reduce pressure on cutting native forests for new cropland. Therefore, the application of passive restoration is limited and restoration may be incomplete (Munson and Lauenroth 2012; Scott and Morgan 2012). Active restoration measures are required (Suding, Gross, and Houseman 2004) in order to achieve rapid reversal of degraded farmland into productive cropland.

Active restoration

Active restoration involves targeted management measures for the restoration of abandoned farmlands. This involves addressing the cause of abandonment by one or several measures. Active restoration involves

[1] Cost of action considers, the cost of reestablishment of high value biome lost and the opportunity cost of foregoing the benefits drawn from the lower value biome that is being replaced. For example, if a forest were replaced with degraded land, the cost of planting trees or allowing natural regeneration (if it still feasible) and cost of maintaining the new plantation and protecting the trees until they reach maturity should be considered. If there is any opportunity cost of the lower biome land (eg degraded land), then that cost should also be considered in estimating the cost of action.

conversion of abandoned farmlands to forest, grasslands, cropland, agroforestry, silvopasture, annual-tree intercropping or other resource conservation or diversified farming systems. Restoration measures can vary from soil conservation, soil fertility improvement, land leveling, erosion control, in-situ and ex-situ water conservation, establishing irrigation facilities, stress-tolerant seed varieties, controlled grazing, organic/inorganic nutrient management, and community management (Hemstrom et al. 2002; Shinneman, Baker, and Lyon 2008). The costs of establishment and annual operation of active restoration measures are higher than that of the passive restoration. However, the benefits derived in terms of productivity gain, CO2 sequestration, GHG emission reduction, and ecosystem services are much higher in this case. Moreover, abandoned farmlands can be restored in much lesser time under active measures.

Both passive and active restoration measures, involving either natural regeneration of biomass or specific management techniques like afforestation, reforestation, agro-forestry, lead to a significant amount of carbon sequestration, both in aboveground biomass and the soil profile. Because these restoration measures involve minimal disturbance to the soil and provide for continuous soil cover, restored soils are less exposed to erosion and other degradation processes that affect soil structure and fertility. Over time soil organic matter content increases and leads to substantial carbon sequestration belowground. The subsequent improvement in plant productivity aboveground sequesters additional atmospheric carbon. In the Farmland Restoration solution, Drawdown models the potential for returning degraded grasslands that are abandoned farmlands into productive annual cropping systems based on practices used for Regenerative Agriculture. Other solutions address land conversions to forests, agro-forestry and silvo-pastoral systems.

1.3 Adoption Path

1.2.1 Current Adoption

The total land area available for the Farmland Restoration solution is 397.48 Mha of degraded grasslands not suitable to other solutions based on the GAEZ model. This is in addition to the land area allotted to Regenerative Agriculture.

Estimates of current adoption of abandoned farmland restoration for several countries or regions are shown in Table 1.2. Successful restoration of abandoned farmlands in many regions has been reported with case studies. However, there is not a comprehensive estimate of global adoption of this solution. The Drawdown model therefore begins scenarios with a current adoption set to 20.03 million hectares which is 5.04% of the total land available for this solution (397 million hectares of degraded grassland).

Table 1.2: Current area under Farmland Restoration

Location	Restored (Mha)	Future Restoration Goals (Mha)	Source
Global		150-350	(Climate Focus 2015)
US	10		USDA 2016
Niger	5		WRI 2016
Ethiopia	0.1000	15	WRI 2016
Tanzania	0.5000		WRI 2016
Africa		100	WRI 2016
India	0.0850		Benton A, 2014
China	41.6	57	(Trac et al. 2013)
Northern China	1.2		(Wang et al. 2015)
China		20 (By 2020)	WRI 2016
Brazil		3.2 (By 2020)	WRI 2016
Australia	0.0015		(Neilan et al. 2006)
Former Soviet Union	20		(Vuichard et al. 2008)
Latvia	1.2		(Nikodemus et al. 2005)
Czech Republic	0.2300		(JONGEPIEROVÁ 2014)
Indonesia		47	(Lamb 2011)
Philippines		5.5	(Lamb 2011)
Viet Nam		5	(Lamb 2011)
Republic of Korea	0.0000345		Lafarge Halla Cement Co., 2012

Several national and international organizations and conventions that support restoration activities.:

- UNFCCC: Restoration of degraded land through afforestation/reforestation under the clean development mechanism.
- United Nations Convention to Combat Desertification (UNCCD): Restoration of drought affected degraded land through national action programs.
- Convention on Biological Diversity (CBD): Ecosystem restoration is one of the key goal of CBD, thus restoration of abandoned farmlands can get support from their programs.
- International Soil Conservation Organization: Restoration of marginal productive lands through effective soil and water conservation measures.
- Reducing emissions from deforestation and forest degradation (REDD+): This can support the restoration measures towards afforestation.

Table 1.3: Goals for restoration of degraded land

Source	Land Type	Adoption (Projected Year)	Total Degraded Land (Mha)	Future Adoption Area (Mha)	Future Adoption %	
					Low	High
IPCC 2011	Degraded land	n/a			20	40
UNEP 2013	Degraded land	By 2050	1216 (GLASOD)	161-319	13	26
UNEP 2013	Degraded land	By 2050	6140 (FAO Terrastat)	161-319	3	5
UNEP 2013	Degraded land	By 2050	3678 (Average)	161-319	4	9
				Average	**10**	**20**

WRI (2016) estimated that globally the restoration opportunities for land degradation is more than two billion hectares. The majority of these degraded lands are in tropical and temperate areas. They have further classified the restoration into three classes: wide scale (0.5 billion hectares), remote (0.2 billion hectares of far northern boreal land), and mosaic (1.5 billion hectares) which contains the lands generally suited to agroforestry and smallholder agriculture which are addressed by Farmland Restoration solution.

1.2.2 Adoption Trends

Institutional changes can have a direct effect on rates at which farmland is removed from production or recultivated. For example, the collapse of the Soviet Union led to widespread abandonment in Russia, Ukraine, and Belarus (Schierhorn et al. 2013). In contrast, set-aside programs in the European Union removed 15% of its farmland from production (Estel et al. 2015) and Conservation Reserve Program payments in the US resulted in long-term fallowing of 36 million acres (14.6 million hectares) of marginal or environmentally sensitive cropland (Kuntz, Beaudry, and Porter 2018). The method of classifying land cover influences detection of abandoned and recultivated areas (Estel et al. 2015; Figure 2).

1.2.3 Research Needs

The absence of consistent data across countries and Drawdown regions limits the accuracy of the adoption and sequestration prognostications.

- Global to local level mapping: Very little data is available on the rates of farmland abandonment and restoration. More data is available for land degradation in general, but not specifically on abandoned farmlands. An accurate mapping database of abandoned farmlands globally and regionally would allow a better estimate of land available for the Farmland Restoration solution.
- Identification of the cause of abandonment: The causes of land abandonment vary from place to place and include both biophysical and socio-economic factors. Thus, identification of the specific causes in a location is necessary to take appropriate active restoration measures that address risks of reabandonment.

- Policy impacts: Market and environmental policies toward annual commodity crops affects the profitability of farmland and thus the decision to abandon marginally productive lands. Additional research on how specific regional policy changes related to abandonment and recultivation rate is need. Policy advocacy is required so that the policy makers can value the importance of abandoned farmlands restoration, both in terms of productivity gains and CO_2 sequestration.

1.2.4 Barriers to Adoption

- Establishment cost: The establishment cost of restoration measures may be high especially where infrastructure is required; however, a combination of passive and active restoration measures can reduce the establishment cost. Moreover, it depends on the state of land degradation; low-cost measures can be taken for restoration of abandoned lands with minimal degradation problems.
- Delayed net profit margin and carbon sequestration results: abandoned lands are often in marginally productive areas, and multiple cropping seasons may be required to restore profitable production systems.
- Intensive manual labor requirements (in some places): In some locations where the degradation is very severe or the areas are inaccessible, restoration measures require intensive labor. The role of machinery is also restricted to the location and land size, for eg abandoned farmlands in hilly regions, fragmented abandoned farmlands etc.

1.3 Advantages and disadvantages of Farmland Restoration

Restoration of abandoned farmlands brings back the lost productivity of the lands. (R. Lal 2003) estimated that each ton of increased soil carbon in degraded cropland can improve the crop yield by 20 to 40 kilograms per hectare (kg/ha) for wheat, 10 to 20 kg/ha for maize, and 0.5 to 1 kg/ha for cowpeas. The restoration of abandoned farmlands also leads to many ecosystem services such as improvement of soil conditions, water retention, recharge and quality, biomass production, species richness and biodiversity. The degradation of productive lands removes economic opportunity for farming communities. With restoration of those degraded abandoned farmlands, farmers have potential to earn income from those lands and place less demand on existing farmland, reducing the likelihood of further farmland degradation.

Restoration of abandoned land reduces the socio-economic incentives of deforestation for virgin farmland, and provides a protective mechanism to preserve native, mature forests and grasslands that are critical carbon sinks.

Restoration of severely degraded abandoned farmlands does not immediately produce high quality, highly productive farmland, particularly in the arid and semiarid regions. Some types of cropland restoration will be especially slow or challenging such as in large tropical fields with very compacted ground, and abandoned tropical cropland colonized by a dense carpet of weeds (J. M. R. Benayas 2005).

Farmland Restoration should be prioritized on land that is not suitable for solutions with higher sequestration rates.

Table 1.4 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 1.5 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

Other solutions that employ similar ecological processes for terrestrial carbon sequestration are addressed in Afforestation, Managed Grazing, Multistrata Agroforestry, Perennial Biomass, Silvopasture, Conservation Agriculture, and Regenerative Agriculture.

2 METHODOLOGY

2.1 INTRODUCTION

Project Drawdown's models are developed in Microsoft Excel using standard templates that allow easier integration with each other since integration is critical to the bottom-up approach used. The template used for this solution was the Land Model which accounts for 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[2]) is what constituted the results.

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.

For Farmland Restoration, there is no conventional practice in place.

It is assumed that the process of restoration takes one year, after which the land returns to production. Restored land is assumed to be in Drawdown's *regenerative agriculture* annual cropping solution, as the majority of restoration measures are based on improving soil fertility through organic inputs. This area, however, is not included in the total adoption area for the *regenerative agriculture* solution. Once automated linkages between solutions are realized via the Python-based interface, we recommend directly transferring accounting of Farmland Restoration cost and benefits to the Regenerative Agriculture model after a 1-3 year transition period. The practices of Regenerative Agriculture will eliminate reversion to abandoned farmland.

[2] 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.

2.2 Data Sources

The key data sources include IPCC, world bank, and well cited peer reviewed research papers and books.

2.3 Total Available Land

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

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

The total available land for the *Farmland Restoration* solution is 309 million hectares, which is the global area of degraded grassland that is not suitable for other solutions. The model projects the restoration of abandoned farmland from 2020-2050 based on the historical rates of recultivation or restoration available for certain countries or regions.

2.4 Adoption Scenarios

2.4.1 Current Adoption

Current (2014) adoption is estimated based on the summation of several regional or country reports of recultivated areas. For regions in which more than one estimate was available, the interpolated values for 2014 were averaged for a given region then the areas were summed to yield a global estimate of current Farmland Restoration: 20.03 million hectares.

Global projections on restoration of abandoned farmland are unavailable. However, abandoned farmland is a subset of degraded farmland, for which published targets are available. Thus, six custom adoption scenarios were developed, based on the Intergovernmental Panel on Climate Change (IPCC) and United Nations Environment Program (UNEP)'s 2013 low and high targets for restoration of degraded land. In the absence of targeted data, this study assumes that both abandoned and degraded land will follow similar trends.

Six custom adoption scenarios were generated to project future restoration of the abandoned farmland:

1. ***Custom adoption scenario one***: This scenario assumes a 10 percent annual rate of adoption (linear) of the solution by 2050, based on the highest short-term adoption rates reported for any region.
2. ***Custom adoption scenario two***: This scenario assumes adoption of Farmland restoration on 63 percent of the TLA by 2050, based on the highest reported adoption of restored lands as a percent of degraded farmland in India.
3. ***Custom adoption scenario three***: This scenario assumes 100 percent adoption of the solution by 2050, considering the highest adoption rate projected by IPCC for the degraded land area restoration.
4. ***Custom adoption scenario four***: This scenario assumes a linear annual adoption of 6.96% based on interpolations of reported historical farmland reclamation in Whenzhoue province, China (Lin et al. 2017).
5. ***Custom adoption scenario five***: This scenario assumes a linear annual adoption rate of 5.68% based on interpolations of reported historical farmland recultivation in Europe (Estel et al. 2015).
6. ***Custom adoption scenario six***: This scenario assumes a linear annual adoption rate of 5.12% based on interpolations of reported historical farmland recultivation in Kazakhstan (Dara et al. 2018).

Impacts of increased adoption of *Farmland Restoration* from 2020-2050 were generated based on three growth scenarios,

2.4.2 Project Drawdown Scenarios

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

1 *Plausible Scenario*: Modest adoption based on the "low of all" custom adoption scenarios of Farmland Restoration.

2 *Drawdown Scenario*: Aggressive adoption based on the "average of all" custom adoption scenarios of Farmland Restoration.

3 *Optimum Scenario*: Maximum adoption based on the "high of all" custom adoption scenarios of Farmland Restoration.

2.5 INPUTS

2.5.1 Climate Inputs

Sequestration for Farmland Restoration is set at 1.33 tons per hectare per year, based on a meta-analysis of 30 data points from 4 sources on degraded farmland. Soil carbon sequestration rates should be similar to those used for Regenerative Agriculture and specific to the thermal moisture regime. Future model updates may benefit from incorporating sequestration rates from Regenerative Agriculture solutions.

Table 2.1 Climate Inputs

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Biosequestration	*tC/ha/yr*	0.13– 2.45	1.29	32	5
Emissions Reduction	*tCO2-eq/ha/yr*	-0.02-0.49	0.23	14	7å

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

Modeling Saturation

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

The Drawdown land model takes the conservative approach that all land units currently adopted for agricultural solutions (including 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.

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

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

2.5.2 Financial Inputs

First cost for the Farmland Restoration solution is US$629.89 per hectare, [5] based on meta-analysis of 14 data points from 4 sources. There is no conventional first cost for comparison, as the land is assumed to have been abandoned for some time. The net profit margin is US$1233.04 per hectare per year, based on 6 data points from 4 sources. There is no conventional net profit as abandoned land is by definition not currently in production.

Table 2.2 Financial Inputs for Solution

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
First costs (Solution)	*US$2014/ha*	0-996.90	629.89	14	4
Net profit (Solution)	*US$2014/ha*	639.36 – 1826.71	1233.04	6	4
Operating Cost (Solution)	*US$2014/ha*	0-780.97	380.44	13	4

Since the alternative to Farmland Restoration is unproductive land of zero cost and zero potential profit, farmers have the opportunity for increased income when employing the solution. Operating costs and profits are assumed to be similar to those in Regenerative Agriculture.

2.5.3 Other Inputs

Farmland Restoration places unproductive land into food or feed production, thus by definition there is a net yield gain. Yields for Farmland Restoration should be similar to that of annual crops in Regenerative Agriculture under a given thermal-moisture regime. As in Regenerative Agriculture, there is an expected lag time of a few years between first conversion and maximum sustainable yields. The model uses an additional variable field of yields reported from restored degraded lands from a single source (Nkonya et al. 2016) resulting in an average corrected yield of 3308.89 kg/ha/yr. An alternative method for calculating yield gains would be to use the average percent change in yield from Regenerative Agriculture (-1%) applied to its conventional practice weighted average yield (3789.88 kg/ha/yr, +/- Standard deviation of 2808.71) for a gross estimate of expected yield gains from Farmland Restoration of 3751.98 kg/ha/yr.

2.6 Assumptions

Six overarching assumptions have been made for Project Drawdown models to enable the development and integration of individual model solutions. These are that infrastructure required for solution is available and in-place, policies required are already in-place, no carbon price is modeled, all costs accrue at the level of agency modeled, improvements in technology are not modeled, and that first costs may change according to learning. Full details of core assumptions and methodology will be available at www.drawdown.org. Beyond these core assumptions, there are other important assumptions made for the modeling of this specific solution. These are detailed below.

Assumption 1: It is assumed that the future restoration of abandoned farmland will follow the same adoption rate as that for the restoration of the degraded land, as abandoned farmland is a subset of the degraded land area.

Assumption 2: It is assumed that emissions from abandoned farmlands occurred prior to abandonment (i.e. under conventional cropping practices). Thus, they are not considered a current direct or indirect source of greenhouse gas emissions.

Assumption 3: Restored farmland is assumed to be recultivated using techniques appropriate to Regenerative Agriculture and will not revert back to conventional cropping practices.

Assumption 4: Based on assumption three, it is also assumed that the climate benefits of the restored abandoned farmlands will be realized from year one, though a one-year lagtime in profit is assumed.

Assumption 5: Currently, this solution is allocated on the degraded grassland area in the GAEZ. However, as these degraded areas are restored, it is proposed to transfer them to the category of “non-degraded” cropland area. This needs to be done in the future upgrades of the model and will be facilitated by direct data linkages through Python.

2.7 Integration

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

Farmland Restoration 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 annual crop 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.

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.

Farmland restoration is included in the yield model in two ways. First, it brings new land into crop production. Second, new adoption takes place on degraded grassland, displacing grazing.

2.8 Limitations/Further Development

The study has used a fixed TLA for modelling the financial and climate results, however the abandonment of marginal lands is an ongoing process. The study can be further enhanced by using a projected TLA based on the existing annual rate of abandonment/ degradation.

3 RESULTS

3.1 ADOPTION

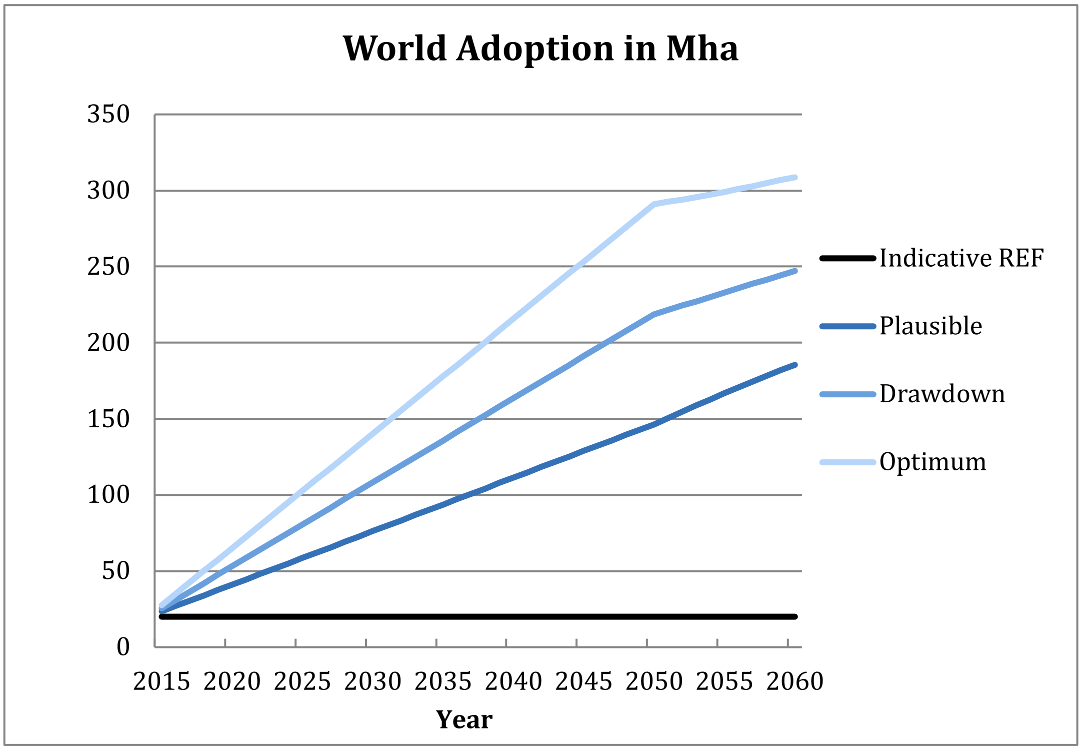
Total adoption in the *Plausible S*cenario is 146.44 million hectares in 2050, representing 49.39 percent of the total available land. Of this, 126.41 million hectares are adopted from 2020-2050.

Total adoption in the *Drawdown* Scenario is 218.69 million hectares in 2050, representing 70.77 percent of the total available land. Of this, 198.66 million hectares are adopted from 2020-2050.

Total adoption in the *Optimum* Scenario is 290.94 million hectares in 2050, representing 94.15 percent of the total available land. Of this, 270.87 million hectares are adopted from 2020-2050.

Table 3.1 World Adoption of the Solution

Solution	Units	Base Year (2014)	New Adoption by 2050		
			Plausible	Drawdown	Optimum
Farmland Restoration	Mha	20.03	126.41	198.66	290.94
	% Total Land Available	6.48%	49.39%	70.77%	94.15%



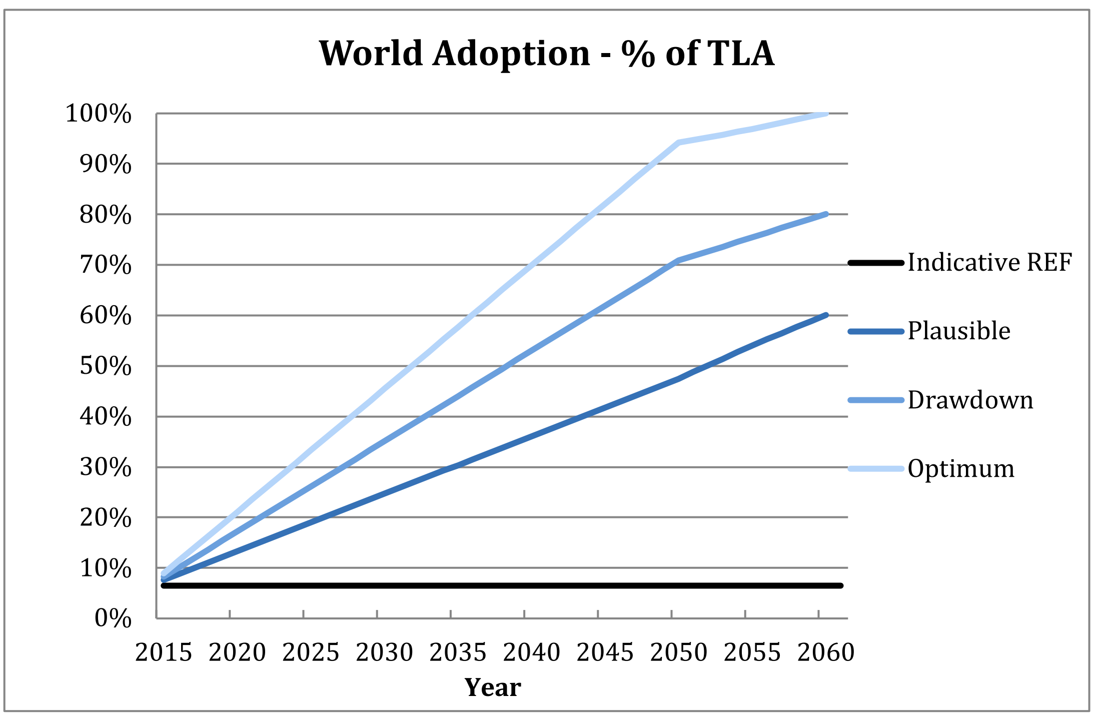


Figure 3.1 Global adoption of Farmland Restoration

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 in the *Plausible S*cenario is 10.16 gigatons of carbon dioxide equivalent from 2020-2050, equal to 0.93 parts per million of carbon dioxide. The annual impact in 2050 is 0.87 gigatons of carbon dioxide equivalent, or 0.04 parts per million per year 2049-2050.

Biosequestration impact in the *Drawdown S*cenario is 15.97 gigatons of carbon dioxide equivalent from 2020-2050, equal to 1.36 parts per million of carbon dioxide. The annual impact in 2050 is 0.89 gigatons of carbon dioxide equivalent, or 0.07 parts per million per year 2049-2050.

Biosequestration impact in the *Optimum S*cenario is 21.78 gigatons of carbon dioxide equivalent from 2020-2050, equal to 1.86 parts per million of carbon dioxide. The annual impact in 2050 is 1.21 gigatons of carbon dioxide equivalent, or 0.09 parts per million per year 2049-2050.

Table 3.2 Climate Impacts

Scenario	Maximum Annual Emissions Reduction	Total Emissions Reduction	Max Annual CO_2 Sequestered	Total Additional CO_2 Sequestered	Total Atmospheric CO_2-eq Reduction	Emissions Reduction in 2030	Emissions Reduction in 2050
	(Gt CO_2-eq/yr.)	*Gt CO_2-eq/yr. (2020-2050)*	*(Gt CO_2-eq/yr.)*	*Gt CO_2-eq/yr. (2020-2050)*	Gt CO_2-eq (2020-2050)	(Gt CO_2-eq/year)	*(Gt CO_2-eq/year)*
Plausible	0.00	0.00	0.57	10.16	10.16	0.25	0.57
Drawdown	0.00	0.00	0.89	15.97	15.97	0.40	0.89
Optimum	0.00	0.00	1.21	21.78	21.78	0.54	1.21

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 CO_2-eq

Scenario	GHG Concentration Change in 2050	GHG Concentration Rate of Change in 2050
	PPM CO_2-eq (2050)	*PPM CO_2-eq change from 2049-2050*
Plausible	0.93	0.04
Drawdown	1.36	0.07
Optimum	1.86	0.09

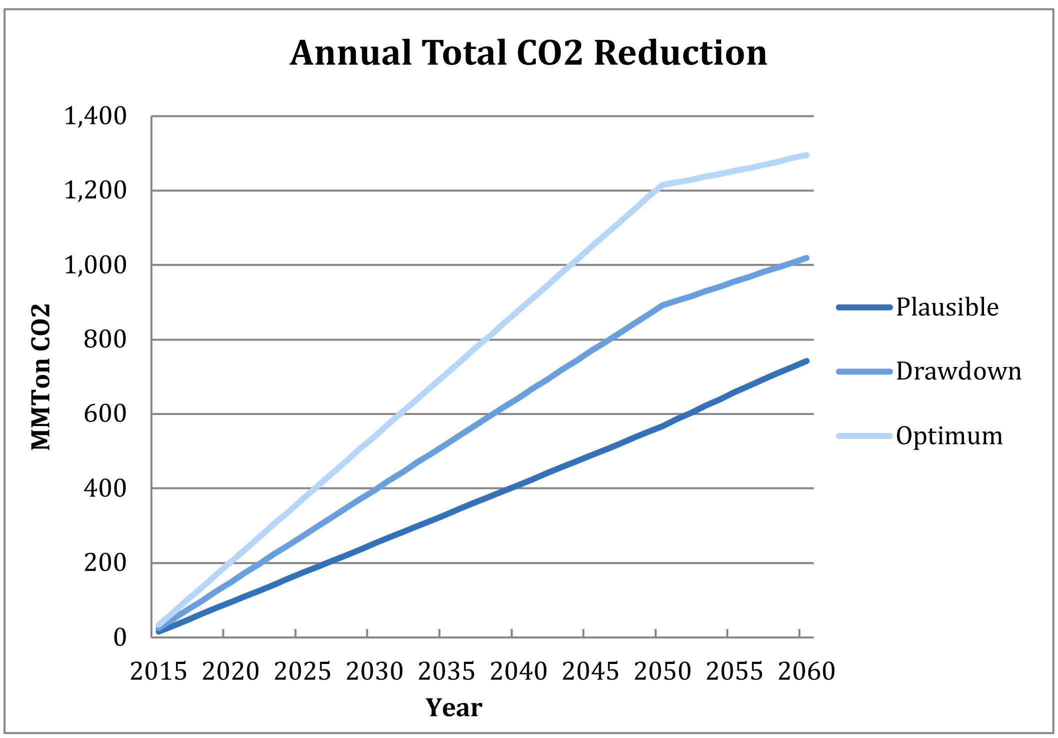


Figure 3.2. World Annual Sequestration

3.3 Financial Impacts

Below are the financial results of the analysis for each scenario (Table 3.4). 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.

In the *Plausible* Scenario*,* cumulative impact 2020-2050 is as follows, with all in 2014 USD: cumulative first cost $60.69 billion, marginal first cost equal to cumulative first cost; net operating savings $-861.67 billion; net profit margin $2,662.85 billion; lifetime profit margin $5.299.73 billion; lifetime cashflow savings NPV $-159.35 billion.

In the *Drawdown* Scenario*,* cumulative impact 2020-2050 is as follows, with all in 2014 USD: cumulative first cost $142.52 billion, marginal first cost equal to cumulative first cost; net operating savings $-1,354.13 billion; net profit margin $4,184.73 billion; lifetime profit margin $5.299.73 billion; lifetime cashflow savings NPV $-250.41 billion.

In the *Optimum* Scenario*,* cumulative impact 2020-2050 is as follows, with all in 2014 USD: cumulative first cost $194.35 billion, marginal first cost equal to cumulative first cost; net operating savings $-1,846.59 billion; net profit margin $5,706.60 billion; lifetime profit margin $11,357.53 billion; lifetime cashflow savings NPV $-341.48 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	$60.69	$60.69	$-861.67	$2,662.85	$5,299.73	$-159.35
Drawdown	$142.52	$142.52	$-1,354.13	$4,184.73	$8,328.63	$-250.41
Optimum	$194.35	$194.35	$-1,846.59	$5,706.60	$11,357.53	$-341.48

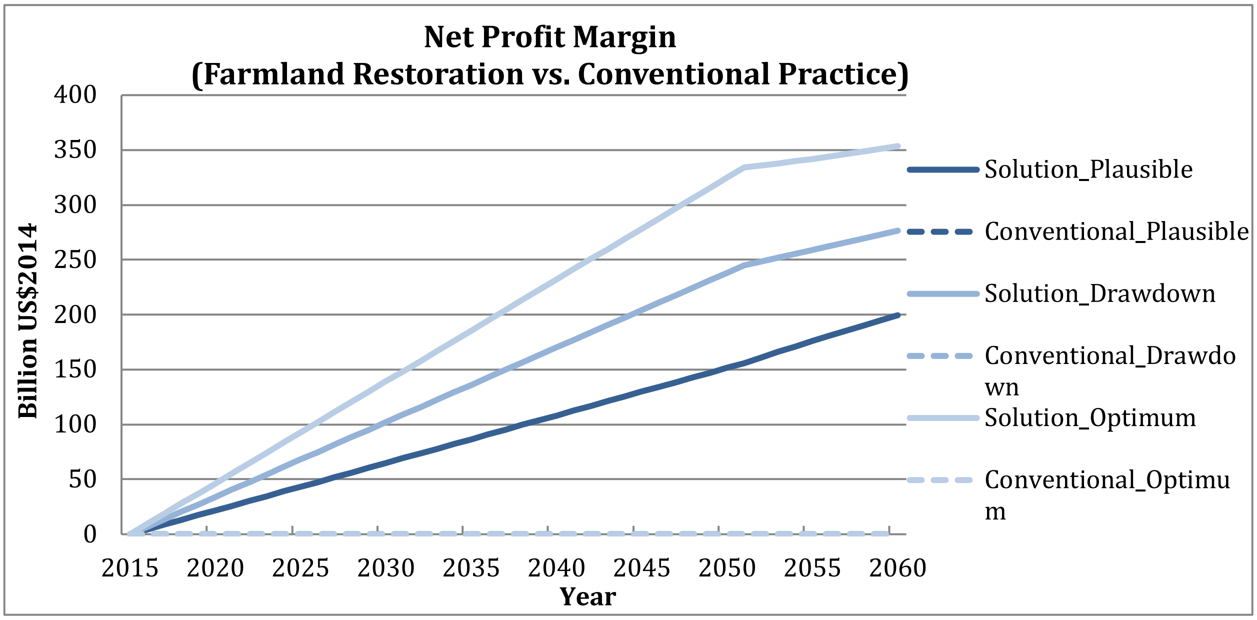


Figure 3.3. World Net Profit Margin

3.4 Other Impacts

Table 3.5 Potential additional yield resulting from Farmland Restoration under different adoption scenarios.

Scenario	Potential Additional Yield for Farmland Restoration
	Million metric tons (2020-2050)
Plausible	7,569.21
Drawdown	11,895.16
Optimum	16,221.12

4 Discussion

Globally, we have limited availability of productive farmland to meet the food, fodder, and fuel demand of an increasing population. Some of these lands are losing their productivity, thus are yielding lesser and lesser net profit margins. Thus, these unproductive lands become abandoned over the period, which in turn limits their CO2 sequestration potential. Globally, the current abandoned land area is reported to be 207-472 Mha, the study has taken an average value of 415 Mha. This is a significant amount of land which is devoid of any productive use. Thus, it is extremely important to restore these abandoned farmlands not only to bring back their productivity and make them useful for producing food, fodder and fuel, but also to build their CO2 sequestration potential.

The findings of the model clearly show significant CO2 sequestration potential of the solution over a lifespan of 30 years. The first cost for cropping restoration is rather low and it also has a good return in terms of net profit margin, this makes it a sustainable restoration solution. The solution has not captured the ecosystem services derived from the adoption of this solution. The solution seems viable, from the perspective of climate, food security and financial implications. This is of particular importance in the context of increasing population and the shift to resource-intensive livestock-centered diets. Furthermore the new yield available through Farmland Restoration can reduce pressure on land clearing for food production, and input demands for intensification efforts, as well as providing residue biomass feedstocks for bioenergy and advanced biofuel production.

It should be seen as somewhat embarrassing for humanity that we continue to clear land for agriculture while leaving degraded, once-fertile lands behind in an abandoned state. The multiple mitigation benefits associated with *Farmland Restoration* provide strong incentive to bring these lands back into production and care for them thereafter.

4.2 Limitations

For future updates of this solution, it would be useful to further investigate how “abandoned farmland” is categorized and how it is distinct from degraded lands in general. Additional financial information would be helpful to identify an accurate lag time for achieving full profit.

4.3 Benchmarks

Projected impacts for this solution align very closely with IPCC projections for the restoration of degraded land. The IPCC estimates an impact of 0.1-0.7 gigatons of carbon dioxide-equivalent per year by 2030

(Smith et al. 2007), while the Drawdown model shows 0.27 – 0.73 gigatons of carbon dioxide equivalent per year in 2030, within the benchmark range.

Table 4.1 Benchmarks

Source	**Scenario**	**Mitigation Impact (Gt CO_{2-eq} in 2030)**
Smith (2007)	IPCC: Restoration of degraded land	0.10-0.70
Plausible Scenario	Restoration of abandoned farmland	0.25
Drawdown Scenario	Restoration of abandoned farmland	0.40
Optimum Scenario	Restoration of abandoned farmland	0.54

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6 GLOSSARY

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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