**Technical assessment for**

REGENERATIVE AGRICULTURE

Sector: Food

Agency Level: Farmer, Land Manager

Keywords: Annual cropping, Biosequestration

August 2019

**Prepared by:**

Eric Toensmeier, Senior Fellow

Sarah Eicher, Research Fellow



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

Table of Contents

[List of Figures IV](#_Toc18437110)

[List of Tables IV](#_Toc18437111)

[Executive Summary V](#_Toc18437112)

[1 Literature Review 1](#_Toc18437113)

[1.1. State of Regenerative Agriculture 1](#_Toc18437114)

[1.2. Adoption Path 5](#_Toc18437115)

[1.2.1 Current Adoption 5](#_Toc18437116)

[1.2.2 Trends to Accelerate Adoption 7](#_Toc18437117)

[1.2.3 Barriers to Adoption 7](#_Toc18437118)

[1.2.4 Adoption Potential 7](#_Toc18437119)

[1.3. Advantages and disadvantages of Regenerative Agriculture 8](#_Toc18437120)

[1.2.1 Similar Solutions 8](#_Toc18437121)

[1.2.2 Arguments for Adoption 8](#_Toc18437122)

[1.2.3 Additional Benefits and Burdens 8](#_Toc18437123)

[1.2.4 Advantages and Disadvantages 10](#_Toc18437124)

[2 Methodology 12](#_Toc18437125)

[2.1 Introduction 12](#_Toc18437126)

[2.2 Data Sources 13](#_Toc18437127)

[2.3 Total Addressable Market / TLA 13](#_Toc18437128)

[2.4 Adoption Scenarios 14](#_Toc18437129)

[1.2.5 Reference Case / Current Adoption 15](#_Toc18437130)

[1.2.6 Project Drawdown Scenarios 15](#_Toc18437131)

[2.5 Inputs 16](#_Toc18437132)

[1.2.7 Climate Inputs 16](#_Toc18437133)

[1.2.8 Financial Inputs 18](#_Toc18437134)

[1.2.9 Other Inputs 19](#_Toc18437135)

[2.6 Assumptions 19](#_Toc18437136)

[2.7 Integration 19](#_Toc18437137)

[2.8 Limitations/Further Development 22](#_Toc18437138)

[3 Results 23](#_Toc18437139)

[3.2 Adoption 23](#_Toc18437140)

[3.3 Climate Impacts 25](#_Toc18437141)

[3.4 Financial Impacts 26](#_Toc18437142)

[3.5 Other Impacts 28](#_Toc18437143)

[4 Discussion 29](#_Toc18437144)

[4.2 Limitations 29](#_Toc18437145)

[4.3 Benchmarks 30](#_Toc18437146)

[5 References 31](#_Toc18437147)

[6 Glossary 33](#_Toc18437148)

# List of Figures

[Figure 3.1 World Annual Adoption 2020-2050 24](#_Toc18437149)

[Figure 3.2 World adoption as percent of Total Land Area 24](#_Toc18437150)

[Figure 3.4 Net Profit Margin Over Time 28](#_Toc18437151)

# List of Tables

[Table 1.1: Regenerative agriculture practices 2](#_Toc18437152)

[Table 1.2 Sequestration rates of regenerative agriculture sub-practices. 4](#_Toc18437153)

[Table 1.3 Adoption of some regenerative agriculture practices by farmers in the USA 6](#_Toc18437154)

[Table 1.4 Food Production Solutions Comparison: On-Farm Impacts 10](#_Toc18437155)

[Table 1.5 Food Production Solutions Comparison: On-Farm Impacts Social and Ecological Impacts 10](#_Toc18437156)

[Table 2.1 Climate Inputs 16](#_Toc18437157)

[Table 2.2 Financial Inputs for Conventional Technologies 18](#_Toc18437158)

[Table 2.3 Financial Inputs for Solution 18](#_Toc18437159)

[Table 3.1 World Adoption of the Solution 23](#_Toc18437160)

[Table 3.2 Climate Impacts 25](#_Toc18437161)

[Table 3.3 Impacts on Atmospheric Concentrations of CO2-eq 26](#_Toc18437162)

[Table 3.4 Financial Impacts 27](#_Toc18437163)

[Table 4.1 Benchmarks 30](#_Toc18437164)

# Executive Summary

Regenerative agriculture (RA) as defined here is any annual cropping system that includes at least four of the following six practices: compost application, cover crops, crop rotation, green manures, no-till or reduced tillage, and/or organic production. These practices sequester carbon and reduce emissions at modest rates, but have wide adoption potential and thus impressive mitigation capacity. Current adoption of annual Regenerative Agriculture is estimated at 10.04 Mha based largely on data from organic production.

In the absence of sufficient data about regenerative agriculture as such, this study builds on the Drawdown model developed for conservation agriculture, which uses three of the six RA practices (cover cropping, crop rotation, and no-till). Sequestration rates are based on the upper boundary from the conservation agriculture model, as RA creates additional sequestration potential. Adoption is modeled on the rapid growth of standards-based organic agriculture such as USDA Organic certifications.

Cumulative impacts from 2020-2050 for the *Plausible* Scenario are 23.28 Gt CO2-eq, with net profit margin of $3,241.95, and total adoption of 344.10 Mha. Cumulative impacts from 2020-2050 for the *Drawdown* Scenario are 31.20 Gt CO2-eq, with net profit margin of $4,354.56, and total adoption of 425.27 Mha. Cumulative impacts from 2020-2050 for the *Optimum* Scenario are 33.89 Gt CO2-eq, with net profit margin of $4,738.81, and total adoption of 422.88 Mha.

# Literature Review

## State of Regenerative Agriculture

Regenerative agriculture (RA) as defined here is an annual cropping system that includes at least four of the following six practices: compost application, cover crops, crop rotation, green manures, no-till or reduced tillage, and/or organic production. More broadly the term is used to mean farming systems that go beyond maintaining soil fertility and ecosystem services to actively restore and improve soil fertility and ecosystem health (The Rodale Institute 2014). These practices have all been shown to sequester carbon in soils.

The term itself is somewhat new and subject to differing definitions, some of which follow.

* “...An organic system refraining from the use of synthetic pesticides and inputs… It is a system designed to build soil health… [and is] comprised of organic practices including (at a minimum): cover crops, residue mulching, composting and crop rotation. Conservation tillage, while not yet widely used in organic systems, is a regenerative organic practice integral to soil-carbon sequestration.” (The Rodale Institute 2014)
* “…Not only ‘does no harm’ to the land but actually improves it, using technologies that regenerate and revitalize the soil and the environment. Regenerative agriculture leads to healthy soil, capable of producing high quality, nutrient dense food while simultaneously improving, rather than degrading land, and ultimately leading to productive farms and healthy communities and economies. It is dynamic and holistic, incorporating permaculture and organic farming practices, including conservation tillage, cover crops, crop rotation, composting, mobile annual shelters and pasture cropping…” (Regeneration International 2016)
* “…A system of farming principles and practices that increases biodiversity, enriches soils, improves watersheds, and enhances ecosystem services.” (Roland and Landua 2016)
* “…A set of practices that are intended to restore degraded lands and improve the health of soils and ecosystems while producing a yield. Many practices can accomplish this goal, including no-till and organic annual cropping, managed grazing, agroforestry, and perennial crops, although not all of them would be appropriate on any give site, with variations in soil and climate.” (Toensmeier 2016)

For purposes of this Project Drawdown only annual cropping systems are included. A broader definition could certainly include many other topics covered by their own Drawdown solutions, including biochar, farm water efficiency, grazing, improved rice production, multistrata agroforestry, nutrient management, perennial bioenergy, restoration of abandoned farmland, silvopasture, System of Rice Intensification, tree intercropping, and tropical tree staple crops.

To fit within the scope of Project Drawdown’s definition of regenerative agriculture, a given piece of annual cropland must utilize at least four of the following six practices: compost (including animal manure) application, cover crops, crop rotation, green manures, no-till or reduced tillage, organic production. See Table 1 for definitions of each. These are all well-known and widely-practiced techniques. To meet the definition of regenerative agriculture used here, a given parcel of land must practice at least four of the following six practices.

Table .: Regenerative agriculture practices

|  |  |  |
| --- | --- | --- |
| **Practice** | **Definition** | **Source** |
| Compost application | Spreading of compost on annual crop fields to increase organic matter, provide fertility, and increase water retention. | Gliessman (2014) |
| Cover crops | Cover crops are crops grown primarily to improved soil and smother weeds, as opposed to being a marketable crop themselves. | Clark (2008) |
| Crop rotation | Crop rotations change the crop grown on a given field crop year to year. These can be cyclical (e.g., corn follows soy follows corn follows soy) or noncyclical. In the latter case, planting each season is based on market and management needs and may or may not involve repetition of previously-planted crops. | Mohler and Johnson (2009) |
| Green manures | A subset of cover crops, typically nitrogen-fixing legumes. They are tilled under to release nitrogen fertilizer for the subsequent crop. | Mohler and Johnson (2009) |
| No-till or Reduced tillage | Techniques for reducing tillage (plowing). Herbicide, roller-crimpers, or other equipment kill crops, cover crops, or weeds. Crop are then sown in narrow furrows with a no-till planter. On a smaller scale, mulching can be used as a replacement for tillage. | Toensmeier (2016) |
| Organic production | “A holistic production management system which promotes and enhances agro-ecosystem health, including biodiversity, biological cycles, and soil biological activity. It emphasizes the use of management practices in preference to the use of off-farm inputs, taking into account that regional conditions require locally adapted systems. This is accomplished by using, where possible, agronomic, biological, and mechanical methods, as opposed to using synthetic materials, to fulfil any specific function within the system” | Food and Agriculture Organization of the United Nations (2015) |

***Carbon Sequestration and Emissions Reduction***

Few studies look at regenerative annual cropping. However, the system of conservation agriculture incorporates elements of RA: ***crop rotation, no-till,*** and residue retention sometimes with ***cover cropping.*** Conservation agriculture is well-researched and the subject of a Drawdown solution. A meta-analysis of conservation agriculture and cover cropping determined annual sequestration rates of 0.71, 0.56, 0.97, and 0.25 t C/ha/yr for tropical humid, tropical semi-arid, temperate/boreal humid, and temperate/boreal semi-arid climates respectively and a global average of 0.512 t C /ha/yr. Regenerative agriculture is expected to result in additional sequestration potential closer to the high statistic found in the CA analyses. Sequetration for this annual cropping solution is assumed to be all below-ground carbon storage. A separate meta-analysis found the average emissions reduction rate was 0.23 t CO2-eq/ha/yr.

***Compost application*** has several climate impacts. First are those of reducing landfill waste and subsequent methane emissions. These, and emissions from the composting process itself, are considered in the Project Drawdown compost solution and not here. Second, some of the carbon from the compost itself persists in soils. One study estimated that 45% remains after 20 years, 35% after 50 years, and 10% after 100 years. Compost application on cropland also increases carbon sequestration, with rates typically between 0.1-0.5 t/ha/yr. Finally, nitrogen in compost allows reduction of synthetic fertilizer use and associated emissions. This impact is estimated at 0.18 t CO2-eq/ha assuming ten dry tons of compost applied per hectare (Biala 2011).

***Green manures*** can replace synthetic nitrogen fertilizers, thereby reducing emissions from manufacturing and over-application. However legumes produce some nitrous oxide emissions themselves, and this is presumably the case with green manures (Toensmeier 2016). An analysis of climate impacts from cover cropping estimate that this practice can sequester 0.32 t C/ha/yr (Poeplau and Don 2015) and result in total offsets of about 1.5 t CO2e/ha/yr when total greenhouse gas fluxes and albedo are included (Kaye and Quemada 2017).

***Organic annual cropping*** is an interesting case in regards to climate mitigation. It clearly exhibits carbon sequestration, with one review noting rates of 0-0.5 t/ha/yr and another reporting 0.7-1.4 (Freibauer et al. 2004). Several individual studies have looked at regenerative organic agriculture, which incorporates practices like compost application, cover crops, crop rotation, and green manures. These studies report somewhat higher rates, notably from the Rodale Institute’s multi-decade study which shows 2.3 t/ha/yr. It is when it comes to reducing emissions that the picture becomes more complex. A review of studies in Europe found that organic farming showed lower emissions when measured on a per-hectare basis. However, this was not always the case when measured on a per-kilo of food produced basis (Tuomisto et al. 2012), because under many conditions there is a yield gap between organic and conventional production, especially for grains (Seufert, Ramankutty, and Foley 2012; Ponisio et al. 2015).

Table 1.2 Sequestration rates of regenerative agriculture sub-practices.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Practice** | **Location** | **Rate tC/ha/yr** | **Study type** | **Source** |
| Compost application | Drylands | 0.1-0.3 | Review | Freibauer et al 2004 |
| Compost application | Tropical areas | 0.2-0.5 | Review | Freibauer et al 2004 |
| Compost application | Europe | 0.4 | Review | Freibauer et al 2004 |
| Compost application | Global | 0.3-0.5 | Review | Biala 2011 |
| Conservation agriculture | Tropical humid | 0.63 | Review | Project Drawdown |
| Conservation agriculture | Tropical semi-arid | 0.61 | Review | Project Drawdown |
| Conservation agriculture | Temperate/boreal humid | 0.39 | Review | Project Drawdown |
| Conservation agriculture | Temperate/boreal semi-arid | 0.38 | Review | Project Drawdown |
| Conservation agriculture | Global | 0.6 | Review | (Srinivasarao et al. 2015) |
| Cover cropping | USA | 0.32 | Review | Poeplau and Don 2015 |
| Crop management | Global | 0.3 | Expert estimation | (IPCC 2000) |
| Crop rotation | USA | 0.1 | Expert estimation | COMET-Planner |
| No-till | USA | 0.1 | Expert estimation | COMET-Planner |
| No-till | Global | 0.3 | Review | (Powlson et al. 2014) |
| Organic annual cropping | Global | 0.7-1.4 | Review | Seebert-Everfeldt and Tapio-Bistrom |
| Organic farming | Europe | 0-0.5 | Review | Freibauer et al 2004 |
| Regenerative organic | Egypt | 0.9 | Single study | (Luske and Van Der Kamp 2009) |
| Regenerative organic | Iran | 4.1 | Single study | (Khorramdel et al. 2013) |
| Regenerative organic | USA | 2.3 | Single study | (The Rodale Institute 2014) |
| Zero tillage | Europe | 0.4 | Review | Freibauer et al 2004 |
| Regenerative | USA | 0.15 | 40-yr simulation based on meta-analysis, peer-reviewed | (Schipanski et al. 2014) |

Note that this table reports tons C, while Table 4 report tons CO2 equivalent. Every ton of C is equivalent to 3.67 tons of CO2.

**Yields and Regenerative Agriculture**

Does transitioning to regenerative annual cropping increase yields? Answers vary, in part due to the great range of practices included within the broad definition of RA. The answer is important, as lower yields could lead to clearing for forest for additional farmland, with huge emissions resulting. Conversion to RA practices (or other climate-friendly farming techniques) can result in yield reductions for 3-5 years as the practices are customized to the individual farm. After this period, yield increases of 20-120% are common (R. Lal 2014).

Conservation agriculture, which is not RA but include three of the practices and is well studied, has been shown to produce yield gains in drier climates. Globally, it is not clear if conservation agriculture increases yields or not due to great variation in results (Rusinamhodzi et al. 2011).

Pretty et al (2006) studied agroecological farming systems in the tropics, using a broad definition that included RA as well as mulching, agroforestry, livestock integration. Implementation of these practices was found to increase yields in these tropical, often degraded soils by 79%.

The subject of yields in organic systems is particularly contentious. This stems in part from the many practices that are subsumed under the organic umbrella. Some organic farms are fully regenerative, while others are operated much like conventional farms, with “input substitution” swapping out conventional inputs for certified organic off-farm inputs. One 2007 review found that organic yields were higher than conventional practice in the tropics, and lower in temperate climates (Badgley et al. 2007). This may reflect the degraded state of the initial tropical soils. An extensive meta-analysis found that alterantive/regenerative yields are 19.2% lower than industrial/conventional yields when all crops and locations are included, but notably this yield gap disappeared after three years when a combination of reduced tillage, residue retention, and crop rotation were employed (Ponisio and Ehrlich 2016). The authors proposed that organic yields could approach parity by incorporating RA techniques including cover cropping (Ponisio et al. 2015) and diversification (Ponisio and Ehrlich 2016). Other meta-analyses have also found that overall yields are lower in organic certified production (by ~24%) even when cover cropping, crop rotation, and green manure were examined, but this was highly variable by crop type and in location (Seufert, Ramankutty, and Foley 2012). For example, in North American systems using similar nitrogen input rates there was no yield gap (Seufert et al. 2012, supplementary information). Organic systems have been shown to yield higher than conventional in drought years, due to increased water holding capacity (The Rodale Institute 2014).

## Adoption Path

### Current Adoption

The total global area of annual cropland as of 2012 is 1,200 Mha (FAOStat 2016). It is difficult to determine the current adoption of regenerative agriculture, as data is not tracked as such. However we can gain insight through examining agroecological and organic farms. In some cases, we can also track particular practices.

Conservation agriculture, which includes three of the four necessary practices that define regenerative agriculture in this study, is currently practiced on 109 Mha. Between 2001-2012, it grew at an average rate of 7 Mha per year (Friedrich et al 2012). In theory, virtually all lands under Conservation Agriculture could be transitioned to annual Regenerative Agriculture systems.

A 2006 study looked at agroecological farming in the tropics. The study found 37 Mha in production, with agroecology defined as crop rotation, intercropping, agroforestry, cover crops, mulching, and/or livestock-crop integration. This suite of practices strongly overlaps with the definition of regenerative agriculture practices used here. The 37 Mha corresponds to 3% of annual farmland. Applying this 3% rate to world *cropland* (as this solution only looks at annual cropping) results in a figure of 36 Mha.

Another approach to determining current adoption looks at organic agriculture. The organic industry tracks organic adoption closely, and is able to do so due to the reach of national and international organic certification mechanisms. The latest data shows that 57.8 Mha of cropland and grassland are under organic management. Organic production has spread very rapidly in recent decades. As of 2014, an estimated 10.9 Mha of arable crop production is managed to organic standards (Willer, Lernoud, and Kemper 2018). It is not clear what portion of this organic land is regenerative according to Drawdown definitions. In the absence of better data, this study conservatively estimates 10.04 Mha of regenerative annual cropland globally as of 2014.

Another approach to determining current adoption of regenerative agriculture tracks the current hectares under a specific practice. As an example, the United States tracks several regenerative practices (Table 4). Some anecdotal reports allow some estimates of combinations of these practices. For example, about 82% of cover crops users also use no- or reduced tillage practices in a recent US farmer survey (CTIC 2017).

Table 1.3 Adoption of some regenerative agriculture practices by farmers in the USA

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| ***Practice*** | ***Location & Year*** | ***Scale of Current Adoption in Mha*** | ***As a Percentage of National Cropland*** | ***Source*** |
| Conservation tillage | USA, 2012 | 31.0 | 24% | USDA 2012 Census of Agriculture |
| Cover crops | USA, 2012 | 4.2 | 3% | USDA 2012 Census of Agriculture |
| No-till | USA, 2012 | 39.0 | 31% | USDA 2012 Census of Agriculture |
| Strip cropping | USA, 2012 | 2.2 | 1% | USDA (2018) Natural Resource Inventory |

### Trends to Accelerate Adoption

The IPCC rates the use of crop rotations and cover crops as having a medium potential global mitigation impact, with easy adoption by farmers, and ready for wide implementation in 5-10 years. They rate crop residue retention and reduced tillage as having high global mitigation potential, easy adoption by farmers, and as being ready for widescale adoption now (IPCC 2014).

Regenerative agriculture appears to be on the rise, whether under that label or otherwise. *Via Campesina* is a global food sovereignty network with roughly 300 million members. Their “Small Farmers Cool the Planet” campaign promotes smallholder and agroecological approaches (including those defined here as regenerative agriculture) as critical climate change mitigation strategies (Toensmeier 2016).

Another example is the emergence of “Organic 3.0”, a next-generation regenerative organic approach promoted by the International Federation of Organic Movements (IFOAM), the international organic umbrella NGO. IFOAM features over 800 NGOs in over 100 countries (IFOAM 2016). Among its goals are “continuous improvement toward best practice” (Markus 2016). IFOAM’s best practices include cover cropping, compost application, reduced tillage, green manures, and crop rotation (SOAAN 2013).

A coalition called Regeneration International, explicitly advocates for regenerative agriculture (broadly defined) for climate change mitigation (among other co-benefits). This coalition includes the Organic Consumers Association, IFOAM, and other NGOs, featuring a global network of 3.6 million members (Regeneration International 2016).

### Barriers to Adoption

Possible barriers to adopting regenerative agriculture vary by region and system. In developed countries accustomed to high-input commercial yields, farmers may be dissuaded by the potential lag in yield, especially during a transition period. In some regions, land tenure may be a concern because the fullest benefits of regenerative agriculture in terms of soil fertility, biodiversity, pest control, and yield improvements may take years to achieve. Access to markets capable of delivering premium prices for regenerative agriculture products may also be an obstacle if lower yields are not compensated by higher prices per unit. In areas where water is extremely scarce, it may be difficult to establish living cover crops at first. These are all topics needing additional research.

### Adoption Potential

A major difficulty to estimating rates of adoption and climate impacts of regenerative agriculture is the lack of studies showing the additive mitigation impact of multiple practices. Though many studies show the combination of rotation, cover crops, and no-till (collectively known as conservation agriculture), few combine the full set of regenerative practices. A Rodale Institute white paper included only four studies on regenerative organic annual cropping (The Rodale Institute 2014). Thus it is difficult to state the exact current area, per-hectare impact, or financial implications of this solution.

## Advantages and disadvantages of Regenerative Agriculture

### Similar Solutions

Some other Drawdown solutions have similarities with Regenerative Agriculture. Conservation Agriculture is the first step toward fully regenerative practices. Farmland Restoration employs regenerative agriculture practices to convert non-productive degraded grasslands back to food production. Sustainable Intensification practices can generally be used within regenerative agriculture systems. All these solutions occur on annually cropped farms and achieve benefits from farmer agency to sequester carbon and reduce global emissions.

### Arguments for Adoption

Regenerative agriculture is one of a suite of annual cropping practices with climate mitigation impacts. It is best suited to mild and moderate slopes, leaving steeper slopes for tree intercropping, or perennial farming systems. It is suited to soils from prime to marginal. Given its higher sequestration rate and generally superior co-benefits, it should be prioritized over conservation agriculture where possible, though both are better than conventional annual cropping with tillage in terms of climate impacts. Currently both conservation agriculture and tree intercropping are far more widely practiced. The sequestration rate of RA is intermediate between tree intercropping and conservation agriculture, and a key element of increasing soil sequestration is cover cropping.

Note that RA can be combined with many other practices on the same parcel of land, though Drawdown has not modeled this. For example, RA could comprise the annual cropping component of a tree intercropping system. RA is also compatible with emissions reduction strategies like nutrient management, farm water use efficiency, biochar, and smallholder intensification.

### Additional Benefits and Burdens

* RA practices increase soil organic matter. This increases soil fertility, water-holding capacity, nutrient leaching, and erosion (Harvey et al. 2014).
* Reducing or eliminating tillage greatly reduces erosion, and increases the diversity and abundance of life in the soil. This includes mycorrhizal fungi, which increase nutrient availability for plants (Harvey et al 2014).
* The increased water-holding capacity that comes with RA practices increases resilience in the face of drought and climate uncertainty (R. Lal 2014).
* Increased organic matter also increases yields (Lal 2014).
* RA systems involve less drastic changes to farming practice for annual crop farmers, which may make adoption more successful compared to practices like agroforestry that integrate trees into cropland.
* Regenerative annual cropping practices can restore degraded soils in many cases (Rattan Lal 2010).
* Strategies like zero-tillage and reduced tillage can increase yields in dry areas due to increase of soil water holding capacity. On the other hand in wet areas, they can increase damage from fungi, reduce seedling success, and increase risk of crop failure (Freibauer et al. 2004).
* Composting and crop rotation are noted for increasing long-term soil fertility (Freibauer et al. 2004).
* Organic systems can have lower yields than conventional in some contexts. See discussion in 1.1 above.
* Currently fields of mechanized farms can be organic, or no-till, but rarely both. Herbicide use is an important component of most conservation agriculture systems, with exceptions including much of Africa (Garrity et al. 2010). Mechanized organic no-till systems without herbicides have been developed but are as of 2016 used only by a few early-adopting, innovative farmers due to difficult adoption including the need for very precise timing (Moyer 2011; Montgomery 2017). However, many organic farmers used reduced or rotational tillage with potential increases in soil organic matter (Butler, Bates, and Eichler Inwood 2016).
* RA practices including no-till are noted as climate change adaptation strategies (Harvey et al 2014). Increased organic matter and cover crops are also noted as adaptation strategies (Lal 2014; Kaye and Quemada 2017).
* Green manures do more than provide nitrogen. They can increase soil organic matter, suppress weeds, reduce erosion, and provide habitat for beneficial organisms. The slow release of heir nutrients may result in more efficient uptake by crops (Cherr 2006).
* Cover crops have beneficial impacts include biodiversity, soil health, managing pests and diseases, water-holding capacity, weed control, and reducing erosion. (Clark 2015;) (Finney et al. 2017)

### Advantages and Disadvantages

Compared to other annual cropping systems, regenerative agriculture has higher profits and high adoption potential.

Table . 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.

This study does not perform meta-analysis on regenerative agriculture itself. Only a handful of studies address four or more practices concurrently. Nor can it be assumed that combining two practices for which sequestration rates are known will simply add their sequestration rates together. However, Drawdown completed a detailed analysis of conservation agriculture in a separate solution. Conservation agriculture is not regenerative, but it does by include two to three of the six RA practices (no or reduced tillage, crop rotation, and residue retention of from cover crops). With the limited available data, the conservation agriculture model was supplemented with new data on cover cropping and organic agriculture that had already been developed, then the ‘high’ value (that is, average plust one standard deviation) was used for sequestration rates in Regenerative Agriculture model upper. It is assumed that this will approximate the sequestration rate of RA, which is logically somewhat higher than CA alone as it adds soil carbon sequestration potential.

## Data Sources

This study uses the Project Drawdown conservation agriculture model, selecting the upper boundary to show slightly better carbon impact from the additional practices incorporated in RA. In addition the following resources were of particular importance:

* Altieri, et al “The scaling up of agroecology: Spreading the hope for food sovereignty and resiliency.” (Altieri and Nicholls 2012)
* Badgley, “Organic agriculture and the global food supply.” (Badgley et al. 2007)
* Biala, *Short Report: The Benefits of Using Compost for Mitigating Climate Change.* (Biala 2011)
* Farooq and Siddique, *Conservation Agriculture.* (Farooq and Siddique 2014)
* Lal, “Abating climate change and feeding the world through soil carbon sequestration.” (R. Lal 2014)
* Lal, “Managing soils and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security”. (Rattan Lal 2010)
* Mohler and Johnson, *Crop Rotations on Organic Farms: A Planning Manual.*(Mohler and Johnson 2009)
* Ponisio, “Diversification practices reduce organic to conventional yield gap.” (Ponisio et al. 2015)
* Pretty, et al “Resource-conserving agriculture increases yields in developing countries.” (Pretty et al. 2006)
* Rodale Institute, *Regenerative Organic Agriculture and Climate Change: A Down-to-Earth Solution to Global Warming.*(The Rodale Institute 2014)
* Seufert, et al, “Comparing the yields of organic and conventional agriculture.” (Seufert, Ramankutty, and Foley 2012)
* Toensmeier, *The Carbon Farming Solution: A Global Toolkit of Perennial Crops and Regenerative Agriculture Practices for Climate Change Mitigation and Food Security*.(Toensmeier 2016)
* Tuomisto, et al “Does organic farming reduce environmental impacts? A meta-analysis of European research.” (Tuomisto et al. 2012)
* USDA, *Census of Agriculture 2012.*(USDA 2014)
* USDA, *Natural Resource Inventory 2012.*(USDA 2018)
* Willer, and Lernoud, 2016 and 2018, *The World of Organic Agriculture: Statistics and Emerging Trends.*(Willer, Lernoud, and Kemper 2018)

## Total Addressable Market / TLA

The total land available is the same as that available for Conservation Agriculture. That is regenerative agriculture occurs on a subset of rainfed croplands allocated to Conservation agriculture. The regenerative agriculture model assumes conservation agriculture lands transition to the regenerative agriculture solution.

## Adoption Scenarios

Current adoption is estimated at 10.04 Mha based on interpolation of data on growth of organic farming from Willer et al (2016). The total available land is 685 Mha. Some of the scenarios feature late adoption. These assume conservation agriculture is a bridge technology, which will be adopted first but eventually transitioned to regenerative agriculture.

***Scenario One:*** Future regional adoption will increase linearly from that of organic production, and 60% of the projected adoption in 2050 will occur by 2030. It includes additional 20% of organic projections under the assumption that RA will include areas not covered by certified organic agriculture. This scenario is based on the low historical growth rate of organic agriculture in different regions.

***Scenario Two:*** Future regional adoption will increase according to exponential or polynomial growth and 60% of the projected adoption in 2050 will occur by 2030. It includes additional 20% of organic projections under the assumption that RA will include areas not covered by certified organic agriculture. This scenario is based on high historical growth rate of organic agriculture in different regions. Here growth in RA is capped to the total available land for this solution.

***Scenario Three:*** This scenario projected a that 60% of the TLA in each region is managed with the solution and assumes 80% of that will be achieved by 2030. Lands transitioning from the bridge solution Conservation Agriculture are included.

***Scenario Four:*** Future regional adoption will increase according to exponential or polynomial growth and 80% of the projected adoption in 2050 will occur by 2030. It includes additional 30% of organic projections under the assumption that RA will include areas not covered by certified organic agriculture. Lands transitioning from the bridge solution Conservation Agriculture are included. Here growth in RA is capped to the total available land for this solution.

***Scenario Five:*** Scenario 4 but using a linear adoption trend.

***Scenario Six:*** Conservative low growth of RA, projecting that 60% of TLA is managed with RA and 75% of that is achieved by 2040, independent of areas of CA.

***Scenario Seven:*** Conservative low growth of RA, projecting that 60% of TLA is managed with RA and 80% of that is achieved by 2040, independent of areas of CA.

**Scenario Eight**: Using CA scenario of adoption based on the (Prestele et al. 2018) topdown projection in which the maximum likely extent of CA is 641.32 mHa and CA achieves adoption on 292 mHa by 2030 and declines to 220 mHa by 2050.

**Scenario Nine**: Using CA scenario of adoption based on the (Prestele et al. 2018) bottom-up projection in which 186.4 mHa of land is under conservation agriculture by 2050.

Two different types of adoption scenarios were developed: a Reference (REF) Case which was considered the baseline, where not much changes in the world, and a set of Project Drawdown Scenarios (PDS) with varying levels of ambitious adoption of the solution. Published results show the comparison of one PDS to the REF, and therefore focus on the change to the world relative to a baseline.

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

In the reference case scenario, the extent of regenerative agriculture is held at 2014 current adoption levels of 10.04 million hectares based on global land under organic management, as tracked by the Research Institute of Organic Agriculture (FIBL) statistics (Willer et al. 2018).

### Project Drawdown Scenarios

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

#### Plausible Scenario - This scenario was determined through analysis of all nine custom adoption paths (represented as the low of all custom adoption scenarios equivalent to one standard deviation below the average) in which the land area under regenerative agriculture reaches 232 Mha by 2050

#### Drawdown Scenario – This scenario was determined through analysis of all nine custom adoption paths (represented as the average of all custom adoption scenarios) in which the land area under regenerative agriculture reaches 344 Mha by 2050

#### Optimum Scenario – This scenario was determined through analysis of all nine custom adoption paths (represented as the high of all custom adoption scenarios equivalent to one standard deviation above the average) in which the land area under regenerative agriculture reaches 457 Mha by 2050.

## Inputs

### Climate Inputs

Sequestration rates are set at 1.25, 0.66, 1.42, and 0.38 tons of carbon per hectare per year for tropical humid, temperate/boreal humid, tropical semi-arid, and temperate/boreal semi-arid zones, respectively. These are the result of meta-analysis of 61 data points from 41 sources, primarily based on the sequestration data from Conservation Agriculture solution. It is expected that regenerative practices further increase sequestration potential – therefore the high value (as the mean + 1 standard deviation) for sequestration in the Regenerative Agriculture model. Emissions reduction rates from *regenerative agriculture*are 0.23 tons of carbon dioxide-equivalent per hectare per year, based on meta-analysis of 16 data points from 8 sources.

Table . Climate Inputs

|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| --- | --- | --- | --- | --- | --- |
| Emissions reduction | *tCO2-eq/ha/yr* | -0.02-0.49 | 0.23 | 16 | 8 |
| Biosequestration tropical humid | *tC/ha/yr* | 0.31-1.24 | 1.25 | 22 | 13 |
| Biosequestration temperate/boreal humid | *tC/ha/yr* | 0.13-0.66 | 0.66 | 13 | 10 |
| Biosequestration tropical semi-arid | *tC/ha/yr* | -0.20-1.42 | 1.42 | 5 | 4 |
| Biosequestration temperate/boreal semi-arid | *tC/ha/yr* | 0.10-0.38 | 0.38 | 6 | 4 |

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

*Modeling Saturation*

Biosequestration does not have limitless potential. In most cases, there is a maximum amount of carbon that can be stored in soils and aboveground perennial biomass before they become saturated. Biosequestration continues after saturation but is offset by more or less equal emissions. In most cases, soils and biomass can return to their approximate pre-agricultural or pre-degradation levels of carbon. This takes anywhere between 10-50 years in agricultural cases, and sometimes somewhat longer in the case of ecosystems like forests. Data about saturation time is very limited (Poulton et al. 2018; Mayer et al. 2018).

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.

### Financial Inputs

Financial inputs for *regenerative agriculture*were determined via meta-analysis of 33 data points from 11 sources. First costs are estimated at US$355.05 [[4]](http://www.drawdown.org/solutions/food/conservation-agriculture#_edn4) per hectare; for all agricultural solutions, it is assumed that there is no conventional first cost, as agriculture is already in place on the land. Net profit is US$530.39 per hectare per year, compared to US$474.21 for the conventional practice.

Table . 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* | $198.17-$750.24 | $474.21 | 84 | 42 |
| Operating Cost (Conventional) | *US$2014/ha* | $0.00-$1,329.35 | $943.57 | 79 | 4 |

Table . Financial Inputs for Solution

|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| --- | --- | --- | --- | --- | --- |
| First costs Regenerative Agriculture | *US$2014/ha* | $175.73-$534.38 | $355.05 | 9 | 6 |
| Net profit Regenerative Agriculture | *US$2014/ha* | $308.23-$752.56 | $530.39 | 21 | 5 |
| Operating Cost Regenerative Agriculture | *US$2014/ha* | $489.35-$708.70 | $599.03 | 19 | 4 |

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 10 data points from 6 sources shows

that in the case of implementation of improved annual cropping solutions, net profits per hectare do not

exceed business-as-usual for 3.4 years. To account for this delay in profitability, the Drawdown model

assumes that net profit per hectare is 25% of the conventional rate until 4 years have elapsed.

### Other Inputs

Yield gains compared to business as usual annual cropping were set at negative 1 percent, based on meta-analysis of 11 data points from 7 sources.

## Assumptions

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

1. Sequestration and mitigation impacts of regenerative agriculture can be modeled on conservation agriculture (which includes three of four practices needed to be categorized as RA, out of the six defining practices) with some supplementation by limited data on systems employing cover crops with or without conservation agriculture.
2. Conservation agriculture is a bridge technology for RA, meaning that much land first transitions from conventional to conservation ag, and then later to RA.
3. In the absence of sufficient data, this study assumes, first cost, and net profit per hectare are identical to conservation agriculture.

## Integration

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

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

***The Agroecological Zone model***

Drawdown’s approach seeks to model integration between and within sectors, and avoid double counting. Several tools were developed to assist in this effort. The Agroecological Zone (AEZ) model categorizes the world’s land by: current cover (e.g. forest, grassland, cropland), thermal climate, moisture regime, soil quality, slope, and state of degradation.  Both Food (supply-side) and Land Use solutions were assigned to AEZs based on suitability. Once current solution adoption was allocated for each zone (e.g. semi-arid cropland of minimal slopes), zone priorities were generated and available land was allocated for new adoption. Priorities were determined based on an evaluation of suitability, consideration of social and ecological co-benefits, mitigation impact, yield impact, etc. For example, *Indigenous peoples’ land management* is given a higher priority than *forest protection* for AEZs with forest cover, in recognition of indigenous peoples’ rights and livelihoods. *Multistrata agroforestry* is highly prioritized in tropical humid climates due to its high sequestration rate, food production, and highly limited geophysical 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 used in Drawdown calculations is less than the technical potentially available land.

The total land area allocated to *conservation agriculture* and *regenerative agriculture* is the same: 788 million hectares of non-degraded croplands with minimal slopes.

***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 resulting from 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.

Adoption of *conservation agriculture* was constrained by several factors. These include: limiting adoption to cropland of minimal slope, competition for said cropland with rice solutions, and a higher priority for *regenerative agriculture*. The combined *conservation/regenerative agriculture* practice is assigned third-level priority for non-degraded cropland of minimal slopes. Only rice-based solutions are more highly prioritized.

## Limitations/Further Development

A major difficulty to estimating rates of adoption and climate impacts of regenerative agriculture is the lack of studies showing the additive mitigation impact of multiple practices. Though many studies show the combination of rotation, cover crops, and no-till (collectively known as conservation agriculture), few combine the full set of regenerative practices. A Rodale Institute white paper included only four studies on regenerative organic annual cropping (The Rodale Institute 2014)(Rodale 2014). Thus it is difficult to state the exact current area, per-hectare impact, or financial implications of this solution.

# Results

Nine scenarios were modeled (see 2.1.1 above). Results are reported for a) Plausible: low of all custom scenarios representing one standard deviation below the average, b) Drawdown: the average of all custom scenarios, c) Optimum: high of all custom scenarios representing one standard deviation above the average.

## 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 Mha by 2050 is 344.10, 425.27, and 422.88 for the *Plausible, Drawdown,* and *Optimum* scenarios respectively.

Table . World Adoption of the Solution

| **Solution** | **Units** | **Base Year (2014)** | **World Adoption by 2050** | | |
| --- | --- | --- | --- | --- | --- |
| **Plausible** | **Drawdown** | **Optimum** |
| Regenerative Agriculture | *Million hectares* | 10.04 | 344.10 | 425.27 | 422.88 |
| *(% market)* | 1.46% | 50.23% | 62.08% | 61.73% |

Figure . World Annual Adoption 2020-2050

Figure . World adoption as percent of Total Land Area

## 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).

In the *Plausible* Scenario, 2020-2050 impact is 23.28 Gt CO2-eq from biosequestration. In the *Drawdown* Scenario, 2020-2050 impact is 31.20 Gt CO2-eq from biosequestration. In the *Optimum* Scenario, 2020-2050 impact is 33.89 Gt CO2-eq from biosequestration.

Table . Climate Impacts

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Scenario** | **Maximum Annual Emissions Reduction** | **Total Emissions Reduction** | **Max Annual CO2 Sequestered** | **Total Additional CO2 Sequestered** | **Total Atmospheric CO2-eq Reduction** | **Emissions Reduction in 2030** | **Emissions Reduction in 2050** |
| *(Gt CO2-eq/yr.)* | *Gt CO2-eq/yr. (2020-2050)* | *(Gt CO2-eq/yr.)* | *Gt CO2-eq/yr. (2020-2050)* | Gt CO2-eq (2020-2050) | (Gt CO2-eq/year) | *(Gt CO2-eq/year)* |
| ***Plausible*** | 0.07 | 1.55 | 1.03 | 21.74 | 23.28 | 0.69 | 1.10 |
| ***Drawdown*** | 0.10 | 2.07 | 1.36 | 29.13 | 31.20 | 0.95 | 1.46 |
| ***Optimum*** | 0.10 | 2.25 | 1.36 | 31.64 | 33.89 | 1.12 | 1.45 |

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** | 1.96 | 0.08 |
| **Drawdown** | 2.62 | 0.10 |
| **Optimum** | 2.82 | 0.10 |

## Financial Impacts

Below are the financial results of the analysis for each scenario. For a detailed explanation of each result, please see the glossary. Cumulative first cost and marginal first cost were identical. See Table 6. Effect on yield (i.e. tons harvested per hectare) was modeled for commercial grain crops under conservation agriculture or organic practices and is net negative.

All values are in 2014 $USD. In the *Plausible* Scenario, cumulative impacts 2020-2050 are as follows : First cost $133.35, net operating savings $2,281.69, net profit margin $77.11, lifetime profit margin $279.03, lifetime cashflow savings NPV $355.78. In the *Drawdown* Scenario, cumulative impacts 2020-2050 are as follows: First cost $177.53, net operating savings $3,057.41, net profit margin $112.83, lifetime profit margin $375.88, lifetime cashflow savings NPV $483.08. In the *Optimum* Scenario, cumulative impacts 2020-2050 are as follows: First cost $181.95, net operating savings $3,321.15, net profit margin $173.18, lifetime profit margin $404.32, lifetime cashflow savings NPV $545.32.

Table . 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** | $133.35 | $133.35 | $2,281.69 | $77.11 | $279.03 | $355.78 |
| **Drawdown** | $177.53 | $177.53 | $3,057.41 | $112.83 | $375.88 | $483.08 |
| **Optimum** | $181.95 | $181.95 | $3,321.15 | $173.18 | $404.32 | $545.32 |

Figure . Net Profit Margin Over Time

## Other Impacts

Potential changes to global crop yield show reduced yields, a function of low synthetic inputs and greater emphasis on carbon sequestration.

# Discussion

In particular there is a need for research on regenerative agriculture in specific contexts and locations. Some practitioners have documented rapid and substantial improvements in soil quality and thus productivity when sub-prime farmlands start to employ regenerative practices such as green manure (Bunch 2012). Bunch describes smallholders who have doubled their yields or avoided complete crop loss during droughts when farmers used green manure systems, but notes that forethought must be used to find the right combination of species, timing, crop, slope, and climate in order to be successful. Furthermore, in order to identify best practices for successful regenerative agriculture, significant science-based resources are needed in the areas of variety testing, equipment development, and economic outcomes which have been almost entirely directed at industrial agriculture approaches to date. Many field station studies that attempt to document tradeoffs and benefits from regenerative approaches are using crop varieties, equipment, pest control, and fertilization recommendations that have been optimized for synthetic management, which is likely to favor the performance of industrial/ synthetic systems in side by side trials.

Nonetheless it can be seen that this solution has great mitigation and adoption potential and is beginning to be taken up by the scientific community more seriously as a climate solution (Griscom et al. 2017). Though it may be a ‘second wave” solution coming along after conservation agriculture, it is poised to serve as a foundation of mitigation for the 21st century.

## Limitations

Additional data is needed to identify land areas that currently employ regenerative agriculture, beyond those that are included in organic certification databases. Information on how multiple practices of regenerative agriculture cumulatively impact carbon sequestration and emissions is needed.

This study could be improved should better information become available on the sequestration and emissions reduction rates of regenerative annual cropping, with studies that incorporate multiple practices at the same time. Likewise data on current adoption, growth rates, and projected growth specifically regarding regenerative agriculture would enhance the study’s accuracy, including data on the frequency of conversion of conservation agriculture to RA.

## Benchmarks

Grisom et al. (2017) described several natural climate solutions including agriculture-related practices. Their study reports that sequestration from Conservation Agriculture (by which they mean only cover cropping) is 0.32 t C/ha/yr for a mitigation potential of 413 Tg (i.e. 0.41 Gt) CO2eq/yr. Their estimate of climate mitigation potential for all agriculture related natural climate solutions was . (Mayer et al. 2018) estimated that soil carbon sequestration rates of 0.02-1.15 t C /ha/yr could be achieved on about 400 mHa of cropland under “improved management” with practices that overlap with conservation agriculture and regenerative agriculture. This results in an upper bound of about 1.78 petagrams (gigatons) CO2eq/yr for climate mitigation from both cropland and grazing land management improvements. Lal (2018) modeled the impact of improved annual cropping systems, finding a sequestration rate of 0.1-1.0 t/ha/yr. This was applied to 613 Mha as a technical maximum, with an impact of 2.25-22.87 Gt CO2-eq from 2020-2100.

Table . Benchmarks

| **Source and Scenario** | **(Land) New Adoption million hectares** | **(Land) Mitigation Impact (i.e. Gt CO2-eq in 2030)** |
| --- | --- | --- |
| Mayer et al. 2018 | 400 | 0.83 |
| Griscom et al 2017  cover cropping | 352 | 0.41 |
| Project Drawdown – Plausible Scenario (PDS1) | 344.10 | 0.69 |
| Project Drawdown – Drawdown Scenario (PDS2) | 425.27 | 0.95 |
| Project Drawdown – Optimum Scenario (PDS3) | 422.88 | 1.12 |

# References

Altieri, Miguel A, and Clara Nicholls. 2012. “The Scaling up of Agroecology : Spreading the Hope for Food Sovereignty and Resiliency. A Contribution to Discussions at Rio + 20 on Issues at the Interface of Hunger , Agriculture , Environment and Social.” In *Rio +20*.

Badgley, Catherine, Jeremy Moghtader, Eileen Quintero, Emily Zakem, M. Jahi Chappell, Katia Avilés-Vázquez, Andrea Samulon, and Ivette Perfecto. 2007. “Organic Agriculture and the Global Food Supply.” *Renewable Agriculture and Food Systems* 22 (2): 86–108. https://doi.org/10.1017/S1742170507001640.

Biala, Johannes. 2011. “Short Report : The Benefits of Using Compost for Mitigating Climate Change.” New South Wales Dept. Environment, Climate Change and Water. http://www.epa.nsw.gov.au/resources/waste/110171-compost-climate-change.pdf.

Bunch, Roland. 2012. *Restoring the Soil. A Guide for Using Green Manure/ Cover Crops to Improve the Food Security of Smallholder Farms.* Canadian Foodgrains Bank. https://doi.org/10.1016/j.jtcvs.2018.04.032.

Butler, D.M., G.E. Bates, and S.E. Eichler Inwood. 2016. “Tillage System and Cover Crop Management Impacts on Soil Quality and Vegetable Crop Performance in Organically Managed Production in Tennessee.” *HortScience* 51 (8). http://hortsci.ashspublications.org/content/51/8/1038.short.

Clark, Andy. 2008. *Managing Cover Crops Profitably (3rd Ed. )*. DIANE Publishing.

CTIC. 2017. “Report of the 2016-17 National Cover Crop Survey.” September. West Lafeyette, Indiana. https://doi.org/10.3929/ethz-a-007116300.

Farooq, Muhammad, and Kadambot H. M. Siddique. 2014. *Conservation Agriculture*. Springer.

Finney, Denise M., Ebony G. Murrell, Charles M. White, Barbara Baraibar, Mary E. Barbercheck, Brosi A. Bradley, Sarah Cornelisse, et al. 2017. “Ecosystem Services and Disservices Are Bundled in Simple and Diverse Cover Cropping Systems.” *Agriculture & Environmental Letters* 2 (1): 0. https://doi.org/10.2134/ael2017.09.0033.

Food and Agriculture Organization of the United Nations. 2015. “Organic Agriculture: What Is Organic Agriculture?” 2015. http://www.fao.org/organicag/oa-faq/oa-faq1/en/.

Freibauer, Annette, Mark D. A Rounsevell, Pete Smith, and Jan Verhagen. 2004. “Carbon Sequestration in the Agricultural Soils of Europe.” *Geoderma* 122 (1): 1–23. https://doi.org/10.1016/j.geoderma.2004.01.021.

Garrity, Dennis Philip, Festus K. Akinnifesi, Oluyede C. Ajayi, Sileshi G. Weldesemayat, Jeremias G. Mowo, Antoine Kalinganire, Mahamane Larwanou, and Jules Bayala. 2010. “Evergreen Agriculture: A Robust Approach to Sustainable Food Security in Africa.” *Food Security* 2 (3): 197–214. https://doi.org/10.1007/s12571-010-0070-7.

Gliessman, Stephen R. 2014. *Agroecology : The Ecology of Sustainable Food Systems, Third Edition*. CRC Press. https://doi.org/10.1201/b17881.

Griscom, Bronson W., Justin Adams, Peter W. Ellis, Richard A. Houghton, Guy Lomax, Daniela A. Miteva, William H. Schlesinger, et al. 2017. “Natural Climate Solutions.” *Proceedings of the National Academy of Sciences* 114 (44): 11645–50. https://doi.org/10.1073/pnas.1710465114.

Harvey, Celia A., Mario Chacon, Camila I. Donatti, Eva Garen, Lee Hannah, Angela Andrade, Lucio Bede, et al. 2014. “Climate‐Smart Landscapes- Opportunities and Challenges for Integrating Adaptation and Mitigation in Tropical Agriculture.” *Conservation Letters* 7 (2): 77–90.

IFOAM, Organics International. 2016. “About Us | IFOAM.” 2016. https://www.ifoam.bio/en/about-us.

IPCC. 2000. *Land Use, Land-Use Change, and Forestry: Summary for Policymakers : A Special Report of the Intergovernmental Panel on Climate Change*. Geneva: WMO (World Meteorological Organization) : UNEP (United Nations Environment Programme).

———. 2014. *Climate Change 2014 Mitigation of Climate Change: Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9781107415416.

Kaye, Jason P., and Miguel Quemada. 2017. “Using Cover Crops to Mitigate and Adapt to Climate Change. A Review.” *Agronomy for Sustainable Development* 37 (1). https://doi.org/10.1007/s13593-016-0410-x.

Khorramdel, Surur, Alireza Koocheki, Mehdi Nassiri Mahallati, Reza Khorasani, and Reza Ghorbani. 2013. “Evaluation of Carbon Sequestration Potential in Corn Fields with Different Management Systems.” *Soil and Tillage Research* 133 (October): 25–31. https://doi.org/10.1016/j.still.2013.04.008.

Lal, R. 2014. “Abating Climate Change and Feeding the World Through Soil Carbon Sequestration.” In *Soil as World Heritage*, edited by David Dent, 443–57. Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-94-007-6187-2\_47.

Lal, Rattan. 2010. “Managing Soils and Ecosystems for Mitigating Anthropogenic Carbon Emissions and Advancing Global Food Security.” *BioScience* 60 (9): 708–21. https://doi.org/10.1525/bio.2010.60.9.8.

Luske, Boki, and Joris Van Der Kamp. 2009. “Carbon Sequestration Potential of Reclaimed Desert Soils in Egypt.” Louis Bolk Instituut; Soil & More International. http://orgprints.org/16438/1/2192.pdf.

Mayer, Allegra, Zeke Hausfather, Andrew D. Jones, and Whendee L. Silver. 2018. “The Potential of Agricultural Land Management to Contribute to Lower Global Surface Temperatures.” *Science Advances* 4 (8): 1–9. https://doi.org/10.1126/sciadv.aaq0932.

Mohler, Charles L., and Sue Ellen Johnson, eds. 2009. *Crop Rotation on Organic Farms: A Planning Manual*. NRAES 177. Ithaca, NY: Natural Resource, Agriculture, and Engineering Service (NRAES) Cooperative Extension.

Montgomery, David R. 2017. *Growing a Revolution: Bringing Our Soil Back to Life*. W. W. Norton & Company.

Moyer, Jeff. 2011. “Organic No-Till Farming. Advancing No-Till Agriculture—Crops, Soil, Equipment.” *Acres, USA, Austin, TX. Patrick M. Carr North Dakota State University, Dickinson Research Extension Center* 1041.

Poeplau, Christopher, and Axel Don. 2015. “Carbon Sequestration in Agricultural Soils via Cultivation of Cover Crops–A Meta-Analysis.” *Agriculture, Ecosystems & Environment* 200: 33–41.

Ponisio, Lauren C., and Paul R. Ehrlich. 2016. “Diversification, Yield and a New Agricultural Revolution: Problems and Prospects.” *Sustainability (Switzerland)* 8 (11): 1–15. https://doi.org/10.3390/su8111118.

Ponisio, Lauren C., Leithen K M ’gonigle, Kevi C Mace, Jenny Palomino, Perry De Valpine, and Claire Kremen. 2015. “Diversification Practices Reduce Organic to Conventional Yield Gap.” *Proceedings of the Royal Society B: Biological Sciences* 282 (20141396). https://doi.org/10.1098/rspb.2014.1396.

Poulton, Paul, Johnny Johnston, Andy Macdonald, Rodger White, and David S. Powlson. 2018. “Major Limitations to Achieving ‘4 per 1000’ Increases in Soil Organic Carbon Stock in Temperate Regions: Evidence from Long-Term Experiments at Rothamsted Research, United Kingdom.” *Global Change Biology* 24 (6): 2563–2584. https://doi.org/10.1111/gcb.14066.

Powlson, David S., Clare M. Stirling, M. L. Jat, Bruno G. Gerard, Cheryl A. Palm, Pedro A. Sanchez, and Kenneth G. Cassman. 2014. “Limited Potential of No-till Agriculture for Climate Change Mitigation.” *Nature Climate Change* 4 (8): 678–683. https://doi.org/10.1038/nclimate2292.

Prestele, Reinhard, Annette L. Hirsch, Edouard L. Davin, Sonia I. Seneviratne, and Peter H. Verburg. 2018. “A Spatially Explicit Representation of Conservation Agriculture for Application in Global Change Studies.” *Global Change Biology* 24 (9): 4038–4053. https://doi.org/10.1111/gcb.14307.

Pretty, J. N., A. D. Noble, D. Bossio, J. Dixon, R. E. Hine, F. W. T. Penning de Vries, and J. I. L. Morison. 2006. “Resource-Conserving Agriculture Increases Yields in Developing Countries.” *Environmental Science & Technology* 40 (4): 1114–19. https://doi.org/10.1021/es051670d.

Regeneration International. 2016. “Why Regenerative Agriculture?” Regeneration International. 2016. https://regenerationinternational.org/why-regenerative-agriculture/.

Rusinamhodzi, Leonard, Marc Corbeels, Mark T. van Wijk, Mariana C. Rufino, Justice Nyamangara, and Kenneth E. Giller. 2011. “A Meta-Analysis of Long-Term Effects of Conservation Agriculture on Maize Grain Yield under Rain-Fed Conditions.” *Agronomy for Sustainable Development* 31 (4): 657. https://doi.org/10.1007/s13593-011-0040-2.

Schipanski, Meagan E., M Barbercheck, M R Douglas, D M Finney, K Haider, Jason P. Kaye, A R Kemanian, et al. 2014. “A Framework for Evaluating Ecosystem Services Provided by Cover Crops in Agroecosystems.” *Agricultural Systems* 125: 12–22. https://doi.org/10.1016/j.agsy.2013.11.004.

Seufert, Verena, Navin Ramankutty, and Jonathan A. Foley. 2012. “Comparing the Yields of Organic and Conventional Agriculture.” *Nature* 485 (7397): 229–232. https://doi.org/10.1038/nature11069.

Srinivasarao, Ch., Rattan Lal, Sumanta Kundu, and Pravin B Thakur. 2015. “Conservation Agriculture and Soil Carbon Sequestration.” In *Conservation Agriculture*, edited by Muhammad Farooq and Kadambot H. M. Siddique, 479–524. Cham: Springer International Publishing. http://link.springer.com/10.1007/978-3-319-11620-4\_19.

The Rodale Institute. 2014. “Regenerative Organic Agriculture and Climate Change.” Emmaus, PA. http://rodaleinstitute.org/assets/WhitePaper.pdf.

Toensmeier, Eric. 2016. *The Carbon Farming Solution: A Global Toolkit of Perennial Crops and Regenerative Agriculture Practices for Climate Change Mitigation and Food Security*. Chelsea Green Publishing.

Tuomisto, H. L., I. D. Hodge, P. Riordan, and D. W. Macdonald. 2012. “Does Organic Farming Reduce Environmental Impacts? – A Meta-Analysis of European Research.” *Journal of Environmental Management* 112 (December): 309–20. https://doi.org/10.1016/j.jenvman.2012.08.018.

USDA. 2014. “Volume 1 - Geographic Area Series - Part 51.” 2012 United States Census of Agriculture. https://www.agcensus.usda.gov/Publications/2012/Full\_Report/Volume\_1,\_Chapter\_1\_US/usv1.pdf.

———. 2018. “Summary Report: 2015 Natural Resources Inventory.” U.S. Natural Resources Conservation Service. https://www.nrcs.usda.gov/Internet/FSE\_DOCUMENTS/nrcseprd1422028.pdf.

Willer, Helga, Julia Lernoud, and Laura Kemper. 2018. “The World of Organic Agriculture 2018: Summary,” 10.

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