TECHNICAL ASSESSMENT FOR FARMLAND IRRIGATION

SECTOR: FOOD

AGENCY LEVEL: FARMER

KEYWORDS: EMISSIONS REDUCTION, ANNUAL CROP PRODUCTION

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DRAWDOWN

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EXECUTIVE SUMMARY

Irrigation is key to achieve high crop yields in arid and semi-arid areas. Currently global irrigated land provides 40% of global cereal supply. However, irrigation is water and carbon intensive. On-farm pumping and transporting water for irrigation accounts for 70-80% of global water use. The energy required to pump the water varies by irrigation system; in United States it is estimated that 20% of on-farm energy use is used for pumping. Irrigation methods such as sprinkler and drip provide a strategy for increasing farm profits as result of increase in energy and water use efficiency. In addition, carbon dioxide emissions are reduced associated with lower energy demand. Water and carbon emissions savings can be as high as 25% and 40% under sprinkler and drip methods, respectively, compared with conventional irrigation methods.

Project Drawdown's *Irrigation Efficiency* solution estimates global carbon emissions reductions as a result of increased use of energy efficiency under the micro-irrigation system over low efficient conventional-flood- irrigation system. The estimates consider updated global irrigated area, adoption of sprinkler and drip irrigated, energy demand and application efficiency.

The results were estimated for three adoption scenarios based on the regional linear trends.

Total adoption of the improved irrigation practices in the *Plausible* Scenario is 189 million hectares in 2050, representing 59 percent of the total suitable land for nutrient management. Of this, 138 million hectares are adopted from 2020-2050. The emissions reduction impact of this scenario is 1.24 gigatons of carbon dioxide-equivalent between 2020-2050. The operational Net saving is $330.79 billion 2014 USD.

Total adoption in the *Drawdown* Scenario is 287 million hectares in 2050, representing 89 percent of the total suitable land. Of this, 235 million hectares are adopted from 2020-2050. The emissions reduction impact of this scenario is 2.20 gigatons of carbon dioxide-equivalent between 2020-2050. Net operational savings is 585.92 billion 2014 USD.

Total adoption in the *Optimum* Scenario is 320 million hectares in 2050, representing 100 percent of the total suitable land. Of this, 269 million hectares are adopted from 2020-2050. The emissions reduction impact of this scenario is 2.89 gigatons of carbon dioxide-equivalent between 2020-2050. Net operational savings is 769.38 billion 2014 USD.

1. LITERATURE REVIEW

1.1. STATE OF THE PRACTICE

Irrigated agriculture accounts for nearly 70% of freshwater withdrawal globally (WWDR, 2012). This represents almost a fifth of the total cultivated land, however it contributes more than one third of total food production (FAO, 2012). Surface and groundwater are the primary sources of irrigation, although their usages vary from region to region. Both of these resources, particularly groundwater, have been exploited significantly in order to meet the high demand of hybrid crop varieties and higher amounts of fertilizer application in the past century. Groundwater withdrawal in selected countries in past few decades is shown in Figure 1.
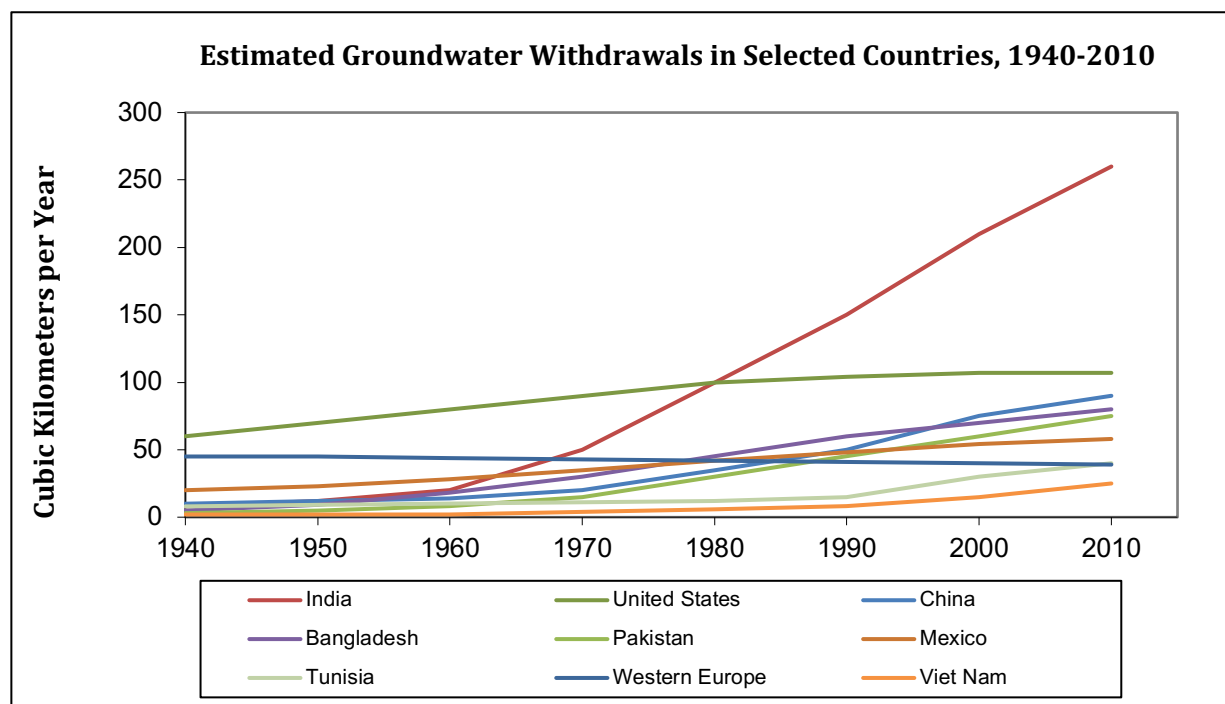
Figure 1.1: Groundwater withdrawal (cubic kilometers per year) in selected countries between 1940 and 2010. Data from: http://www.earth-policy.org/data_center/C26

An increase in irrigation water use in the past few decades has also increased the energy consumption in agriculture sector, largely to meet the pumping demand. Narayanamoorthy (2007) reports a close nexus between irrigation water use (primarily groundwater) and electricity use in Indian agriculture. Groundwater

irrigation in India has increased from 8.65 Million hectares in 1965-66 to 33.64 Million hectares in 2002-03 with an electricity increase of from 1892 million kwh to 84486 million kwh (Narayanamoorthy, 1999).

Increased use of electricity in the irrigation sector increases the carbon emissions from this sector. According to (Rao, 2015) carbon emissions from irrigation pumping in India emits 14.38 million tonnes (MMT) of emissions, representing 4-6% of India's total emissions (Shah, 2009). Similarly, groundwater irrigation in Pakistan results in the emission of 3.8 MMT CO_2 (Qureshi, 2014). China accounts for 50-70% of its total agricultural emissions from the water pumping and conveyance (Rao, 2015). Another study reports 36.72–54.16 MMT CO_2 emissions from irrigation in China (Zou, Li, Li, et al., 2013). A study conducted in the US estimated 290 million tonnes (MMT) of carbon dioxide equivalent from water-energy dynamics (Griffiths-Sattenspiel & Wilson, 2009). The emissions from well irrigation in Spain (0.24 Mt) was found to be three times higher than Egypt (0.082 MMT). In Iran groundwater irrigation results in the emission of 4.9 million Mt of carbon representing 3.6% of its total emissions (Karimi et al., 2012). The regional pattern of CO_2 emissions from power irrigation[1] (fig 2), clearly reflects the high proportion of Asia over others, as the former has the largest area under irrigated agriculture.

Figure 1.2: Carbon dioxide emissions (Gg per year) from power irrigation, average 1995-2010. Data taken from FAO Aquastat

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[1] Emissions from area equipped for irrigation where pumps are used for water supply from the source to the scheme.

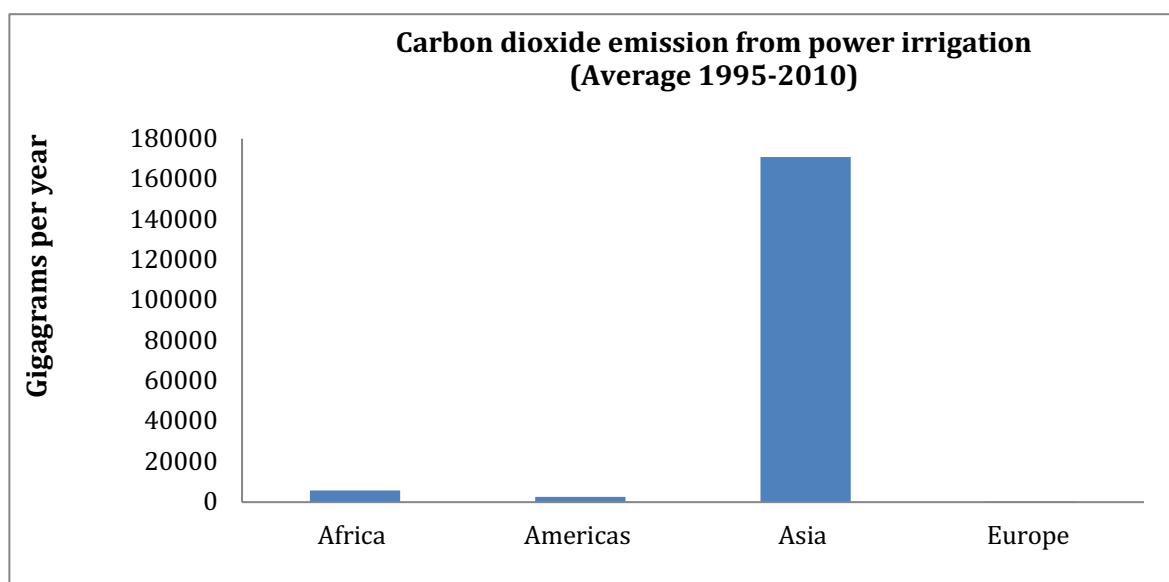Overexploitation of groundwater resources has led to a worldwide groundwater stress, prominently in the Asian and Arabian region. The International Water Management Institute (IWMI) has projected global physical[2] and economic[3] water scarcity by 2025, considering the current usage of both surface and groundwater resources in all of the sectors.

Given the carbon emissions and global water scarcity aspects of irrigation, there is an urgency for optimizing energy and water use efficiency. The irrigation application efficiency of the conventional system is less than 50%. This implies a wastage of 50% of water with investment of 100% of energy. Thus, current irrigation practice is increasingly seen as wasteful and highly inefficient (Hsiaoet al., 2007). The sprinkler and drip irrigation system with higher irrigation efficiency have significant potential to minimize water consumption in the agriculture sector.

Sprinkler irrigation is defined as a method of applying irrigation water where water is distributed through a system of pipes and then sprayed into the air through sprinklers so that it breaks up into small water drops which fall into the ground. Sprinkler irrigation functions like that of rainfall, it evenly sprinkles sufficient amount of water. This reduces the water loss through runoff and evaporation and saves significant amount of water compared to conventional surface/flood irrigation methods.

Drip irrigation method involves dripping water into the soil at a very low rate (2-20 litres/hour) from a system of small diameter plastic pipes fitted with outlets called emitters or drippers. Since drip irrigation supplies water directly to the root zone, the water losses occurring through evaporation and distribution are completely absent (Dhawan et al., 2002; INCID, 1994; Narayanamoorthy, 1999). Thereby it is considered as the most efficient irrigation method available today.

Application efficiency of drip and sprinkler irrigation is 90% and 70% respectively. Moreover there are studies conducted in different regions of the world where effectiveness of micro-irrigation methods to save water and reduce carbon emissions are well-reported (Liet al., 1998, Denget al., 2006; Guan, 2004; Ma & Feng, 2006). According to (Duivenboodenet al., 1999) sprinkler and drip systems leads to 50% water savings compared to conventional irrigation system. Study (Zouet al., 2011) conducted in China shows that micro-irrigation system has led to 96.85 Gm3 water saving and 34.67 Megatonns of carbon dioxide emissions reduction in three years (2007-2009). As study conducted by (Accountinget al., 1999) has

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[2] Water resource development is approaching or has exceeded sustainable limits.

[3] Human, institutional, and financial capital limit access to water even though water in nature is available locally to meet human demands.

reported a decline of 40% in energy consumption and carbon dioxide emissions with the use of efficient irrigation methods. Similar findings have been reported from an Indian study (Narayanamoorthy, 2007), where energy consumption was reported 2.21 and 1.89 times lower in drip irrigated sugarcane and grape field respectively compared to conventional irrigation. Thus efficient irrigation method holds greater potential for tackling water scarcity and global warming issues (Hanjra & Qureshi, 2010; Tejeroet al., 2011; Zouet al., 2013).

During the past few decades, sprinkler (commenced in 1950s) and drip (commenced in 1970s) irrigation systems owing to their capability to apply water efficiently, low labor requirement, and increase in quantity and quality of crop yield/produce have made a breakthrough in many countries around the globe (Kulkarni, 2000). The current adoption of sprinkler, drip and surface irrigation in different regions of the world is shown in Figure 5. Conventional irrigation usage is highest in Asia followed by the OECD countries. However, adoption of both sprinkler and drip irrigation has been found at its highest in OECD 90 and its lowest in Asia. Adoption of drip in Europe was found to be very low compared to other regions.
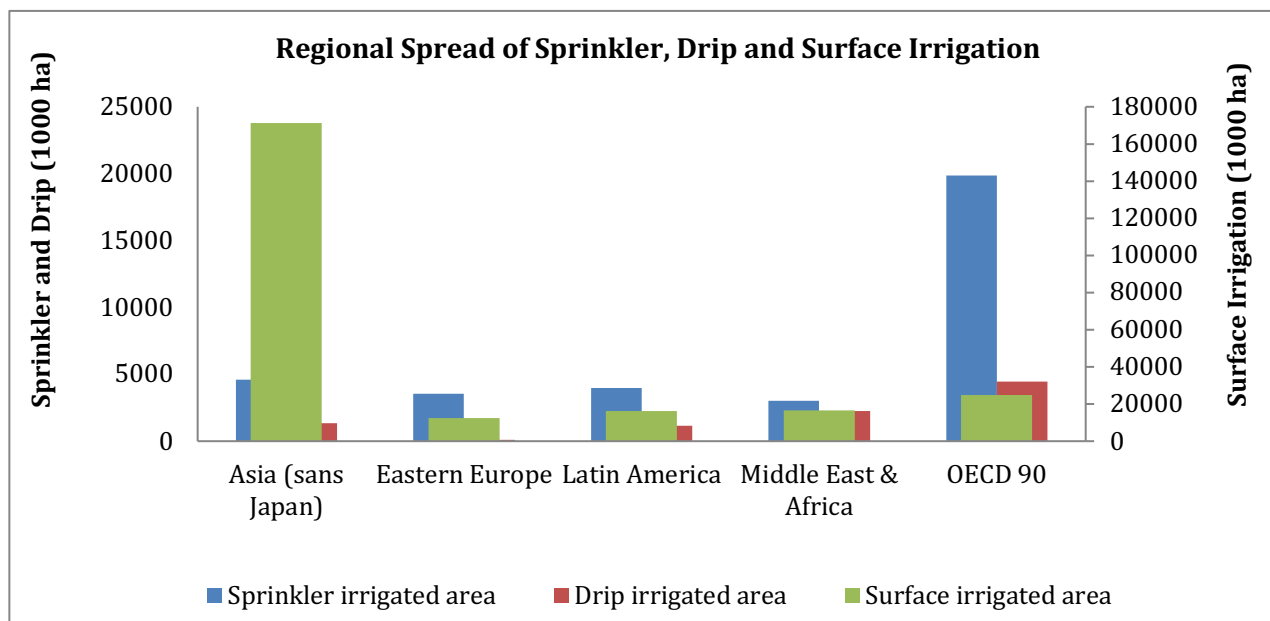
Figure 1.3: Adoption of sprinkler, drip and surface irrigation in five world regions circa 2010, based on data from FAO Aquastat, and ICID.

Co-benefits

- Increase in crop productivity: Experimental studies from India reports an increase in productivity by 20-90% in different crops with the use of drip irrigation (Narayanamoorthy, 2007). A case study from Pakistan (Kahlown et al., 2007) reports an increase of 18% in rice yield along with savings of

35% irrigation water use under sprinkler irrigation. The increase in productivity under improved irrigation methods is attributed to the continuous and uniform application of water across the field.

- Decrease in cost of cultivation: Improved irrigation also reduces the cost of cultivation especially the energy and labor cost required for irrigation and weeding (Narayanamoorthy, 2007). A study reported by (Bhamoriya & Mathew, 2014) estimates electricity saving of 278 kWhr/ha for wide-spaced orchard crops and 100 kWhr/ha for closely grown crops under drip irrigation.

- Soil erosion and pest control: As improved irrigation method minimizes surface runoff, it prevents soil erosion. Also these methods reduce atmospheric humidity which may reduce the occurrence of pests and plant diseases (Andal, 2011; Bhamoriya & Mathew, 2014).

- Utilization of saline water resources: Increasing soil and groundwater salinity globally limits the crop productivity. However, with drip irrigation method, crops can be irrigated with saline water as drip creates low soil moisture tensions in the root zone that dissolves the salts that accumulate at the periphery of the wetted soil mass thereby leading to moisture uptake by the roots. The method can sustain salinity of more than 3000 mg/litre TDS, which would be unsuitable for use with other methods (Karlberg et al., 2007; Minhas, 1996; Rajak et al., 2006; Sharma & Minhas, 2005). However, there are studies which report ineffectiveness of drip irrigation system using saline water (Burt et al., 2003; Hanson et al., 2003). Although it has been also reported that when irrigating with saline water using drip irrigation system, it is advisable to place the dripper lines shallower in order to prevent salt accumulation in the root zone (Marais, 2001) and by adopting other management strategies like smaller and more frequent irrigation spells (Karlberg et al., 2007; Lamm et al., 2002). A study conducted by (Nielsen et al., 1966) reports three times higher water demand to reduce soil salinity in flood irrigation than sprinkler systems.

- Use on marginal fields: With the help of improved irrigation methods, it becomes possible to cultivate the marginal unproductive lands.

- Reduction N2O and CH4 emissions: Improved irrigation methods especially subsurface drip irrigation leads to reduction in N2O emissions compared to conventional furrow irrigation (Kallenbach et al., 2010; Kennedy et al., 2013). Also, application of improved irrigation methods in rice cultivation will significantly reduce CH4 emissions.

- Universal applicability: Improved irrigation methods are well suited to all soil types and undulating terrains as the water flow rate can be controlled (INCID, 1994).

- Usage in greenhouse coverage: Improved irrigation methods have also been used for greenhouses and irrigation of lawns, parks and golf courses. Currently it is being used for about 0.75 Mha greenhouse cover around the world (Kulkarni, 2000).

Trade-offs

- High capital cost: Both sprinkler and drip irrigation systems are quite expensive and beyond the reach of the average farmers in developing countries (Service & Shock, 2013). However, to overcome these issues, most of the countries are giving heavy subsidies on these systems. As discussed above IDE and other similar organization are developing low cost improved irrigation systems, although maximum efforts are laid on development on LCDI. There is need to also develop low cost sprinkler devices as well.

- Plant development issues: Some crops may not develop properly under drip irrigation in some soils and climates. For example, peanuts may not grow properly in dry soil. Moreover, tree crops may benefit from a larger wetting pattern (Lamm et al., 2002).

- Filtration issues: Water filtration is a critical issue for the proper functioning of the improved irrigation systems, particularly, for the long-term subsurface drip irrigation system.

- Other maintenance issues: Improved irrigation systems are not as robust as conventional irrigation system. They require timely and consistent maintenance and repairs (Service & Shock, 2013).

- Operational issues: The improved irrigation methods expect farmers to have good understanding of the crop water demand in order to apply water only when it is required. Unlike conventional irrigation, soils doesn't remain in wet condition for a longer duration under the improved irrigation methods. To overcome these issues, these improved irrigation systems are coming along with the soil moisture device that aid in determining the correct timing of water applications.

1.2. ADOPTION PATH

The area under improved irrigation has increased six-fold in the last 20 years, from 15 million hectares to more than 51 million hectares. Currently improved irrigation methods are being practiced in nearly 112 countries (Kulkarni, 2000, FAO Aquastat, 2019). In developed countries (e.g., USA and few European

countries) the area under improved irrigation is more than 55% of their total irrigated area, while in countries like China and India the improved irrigation practices account for less than 10% of irrigated arable land.

1.2.1 Current Adoption

The area under improved irrigation has increased six-fold in the last 20 years, from 15 million hectares to more than 51 million hectares. Currently improved irrigation methods are being practiced in nearly 112 countries (Kulkarni, 2000, FAO Aquastat, 2019). In developed countries (e.g., USA and few European countries) the area under improved irrigation is more than 55% of their total irrigated area, while in countries like China and India the improved irrigation practices account for less than 10% of irrigated arable land.

1.2.2 Trends to Accelerate Adoption

International Development Enterprises, a non-profit organization specializing in affordable small scale irrigation (IDE4), was the first organization who has worked on the development of low-cost improved irrigation system. Based on their field tests, they introduced the low-cost drip irrigation (LCDI) systems for small farmers. They were successful in reducing the price by 80% compared to the existing drip irrigation system. This resulted in enormous uptake of these devices soon after its introduction. Over 100,000 LCDI systems were purchased by small farmers in India, Nepal, Sri Lanka, and Zimbabwe in its initial years of introduction. A study conducted in India reports adoption of LCDI in around 260,000 ha area in less than 10 years (Kulkarni, 2000). The LCDI systems are also suitable for small fields (0.02 to 0.4 ha); representing the holding of the vast majority of the farmers in developing countries. According to (Kulkarni, 2000) report, LCDI has been adopted on some 50,000 ha by over 250,000 smallholders mainly in developing countries. In Nepal, LCDI was adopted by 2,250 farmers within 4 years of introduction (Westarpet al., 2004). (Polaket al., 1997) suggests that lowering the capital cost of improved irrigation system (eg from $2500 to $250 a hectare) will double adoption, with greater adoption by the small farm holders. (TLet al., 2009) has proposed improving the application efficiency of these methods. This is with special reference to sprinkler systems, where the irrigation application efficiency is close to 75% under experimental setup; however, it is slightly less in the farmer's fields.

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[4] IDE, International Development Enterprises, a non–profit organization specializing in affordable small-scale irrigation

In United States adoption of improved irrigation methods can be encouraged by 1) new laws that can restrict access to labor required to manage flood systems; 2) the water saved by switching from conventional to improved irrigation system can be leased or sold to other growers or other users including municipalities for and 3) impose fees/fines for excess water use or drainage. Economic analyses conducted in the US indicate that shifting from flood to center pivot is a viable option.

1.2.3   Barriers to Adoption

As mentioned above the high cost of installations and operations that is beyond reach for many farmers is a key barrier in adoption of improved irrigation practices. Soil type is also a limitation, as finer-textured soils minimize the impact of sprinkler systems (Brown, 2008)

1.2.4   Adoption Potential

Current area of irrigated land is 320 Million hectares (average value of FAO Aquastat, ICID (2018), Meier et al., 2018 and Global Map of Irrigation Area), we assume that the adoption potential of improved irrigation is 246 million hectares by 2050.

1.3   ADVANTAGES AND DISADVANTAGES OF FARMLAND IRRIGATION

1.3.1   Similar Solutions

Improve irrigation practices are closely linked to improved rice cultivation, system of rice intensification solution and farmland restoration.

1.3.2   Arguments for Adoption

The conversion of the old hand-shift irrigation system to a high efficiency sprinklers and drip irrigation system can result in water savings, as well as an overall reduction in greenhouse gas emissions. Economic modelling also indicated that there is a net benefit of adoption of the improved irrigation system (Marasseni et al., 2012). In addition, better control over the timing and level of water applied by water efficient sprinklers and drip irrigation can help protect crops from weather extremes such as drought stress or frost.

1.3.3   Additional Benefits and Burdens

Farmland irrigation (improved irrigation practices) is compared with other solutions in the food production cluster for farm, ecosystem, and social impacts. Establishment cost is relatively high, but delayed profit period is very short.

Table 1.1 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
Farmland irrigation	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 1.2 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

	Ecosystem Services	Social Justice Benefits	Climate Impact/ha	Global Adoption Potential
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

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[5]) is what constituted the results.

Agency Level

The farmer 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.

2.2 DATA SOURCES

In the case of agricultural water consumption, energy used to irrigate is one of the key source of carbon dioxide emissions. The carbon dioxide emissions are proportional to the amount of water withdrawal and vary depending on different irrigation systems. The emissions are high with conventional irrigation systems (BAU) where irrigation application efficiency is low (less than 50%). The emissions are low when the application efficiency gets improved to 75% and 90% in case of high efficiency sprinkler and drip irrigation system. Thus, farmland irrigation solution include improved irrigation methods (sprinkler and drip) as potential solution to reduce carbon dioxide emissions from the agriculture sector.

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[5] 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.

The methodology estimates carbon dioxide emissions at the regional level, based on existing regional data on total irrigated area available from FAO Aquastat, Meier et al., 2018, Global Irrigation Map Area and ICID (2018), data on sprinkler irrigated area, drip irrigated area are derived from FAO Aquastat, ICID and National Statists. Business as usual (BAU) application efficiency, sprinkler application efficiency, drip application efficiency data are based on metanalysis of the case studies from different countries, and total demand/need for energy used to irrigate one hectare of land taken from Stout (1990) and country-specific estimates.

The emissions from irrigation vary from region to region and are dependent on energy used for irrigation. We have first calculated the energy (KWH/ha) used to irrigate one hectare of land under sprinkler and drip irrigation system using equation 1. The application efficiency under BAU, sprinkler, and drip are based on the average values of the application efficiency reported in different sources.

$$Energy\ of\ Scenario = Energy\ BAU * (1 - [Application\ Efficiency\ \{OPT - BAU\}]) \dots \dots eq\ 1$$

The energy calculated under sprinkler and drip was then used to calculate future energy consumption under different adoption scenarios as discussed in the following section. Thus, the annual CO2 reductions was estimated by multiplying the calculated energy unit savings by region under the adoption scenarios by the emissions factor of the energy unit by region and year (equation 2).

$$Annual\ CO2\ emission\ reduction\ = Annual\ energy\ saved * Emission\ Factor \dots\dots eq\ 2$$

Financial indicators, the capital costs and net profit margin of the adoption scenarios were also estimated and compared with the BAU scenarios in order to assess the financial implications of this solution

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.

Total available land for *farmland irrigation* is 320 million hectares. Current adoption of improved irrigation is estimated at 51 million hectares.

2.4 ADOPTION SCENARIOS

Two different types of adoption scenarios were developed: 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.

Future adoption projections for *farmland irrigation* is based on current adoption of sprinklers and drip irrigation including following assumptions:

Assumption 1: The study is based on the "Top-Down" approach as the adoption of optimum scenario was analyzed at the regional level.

Assumption 2: It was assumed that in future the area under total irrigation will remain the same.

Assumption 3: In the study, we have analyzed only "avoided emissions" under optimal solutions as there is not any literature available reporting significant "carbon sequestration" using microirrigation systems.

Assumption 4: Only "sprinkler and drip" irrigation methods have been considered as microirrigation systems in the study.

Assumption 5: It was assumed that the irrigation energy requirement are largely met through the "electricity" because of the limitation of data available for diesel energy.

Assumption 6: Carbon dioxide emissions calculation using electricity energy requirement for one hectare irrigation was based on single source of information (FAO Aquastat). However, this is the most cited and used data by other researchers and is based on the Stout 1990 book (Handbook of energy for world agriculture). The data was also verified with the data available for the Indian context (shah 2008).

Assumption 7: The country level data was not available for few of the countries, so in the study, it was assumed that they will implement in the same manner as their region will implement in future.

2.4.1 Reference Case / Current Adoption[6]

We assume that total land available for irrigation is currently 320 Million hectare and current adoption of drip and sprinklers irrigation is estimated to be 51 million hectares.

Project Drawdown Scenarios

Seven Project Drawdown scenarios (PDS) consider that future adoption of solutions is based on current adoption (based year), i.e. area under micro-irrigation systems and the total irrigated area

1.**Scenario: Low growth** - In this scenario, it is assumed that the micro-irrigated area will be doubled from the current adoption value in each region by 2050, except OECD 90, where it will grow by 1.5 times, as it already has a high current adoption value.

2. Scenario: High growth - In this scenario, it is assumed that 50% of the total irrigated area of all regions except OECD will adopt micro-irrigation systems, while it will be 70% in OECD as the current adoption value of OECD is already more than 50%.

3. Scenario: Aggressive high growth - In this scenario, it is assumed that 70% of the total irrigated area of all regions except OECD will adopt micro-irrigation systems, while it will be 100% in OECD as the current adoption value of OECD is already more than 50%

4. Scenario: Aggressive max growth -This scenario assumes a 100 % adoption of this solution by 2050 in all regions

5.**Scenario: Aggressive Max Early growth -**This scenario assumes a 100 % adoption of this solution by 2050 in all regions, with 80% of that adoption to be achieved by 2030

6. Scenario: Annual growth based on historical trends in adoption of sprinklers irrigation. In this scenario, we assume that annual growth rate of sprinklers adoption is 4.16% in all countries, this rate corresponds with average growth rate over the period 1990-2017 in 112 countries.

7. Scenario: Annual growth based on sprinklers irrigated history. In this scenario, we assume that annual growth rate of drip irrigation adoption is 6.11%, this rate corresponds with averaged growth rate estimated between 1990-2017 in 104 countries.

Seven PDS scenarios were combined into three main scenarios, to compare the impact of an increased adoption of the drip and sprinkles irrigation to a reference case scenario, these scenarios are:

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[6] 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.

Plausible Scenario – *A conservative approach is adopted for the plausible scenario, and future growth of the solution is estimated based on the "average of all" custom adoption scenarios as listed above.*

Drawdown Scenario – *For the drawdown scenario, an ambitious approach is adopted, and future growth of the solution is estimated based on the "high of all" custom adoption scenarios as listed above.*

Optimum Scenario – *For the optimum scenario, custom adoption scenario that is giving maximum growth based on the existing prognostication is considered, which is represented by the "custom scenario 4.*

2.5 INPUTS

2.5.1 Climate Inputs

Energy efficiency of sprinklers and drip irrigation is 74 % and 88%, while energy needed to irrigate 1 ha of land is 1641 KWh for sprinklers and 1311 KWh for drip irrigation. These estimates are global averages (Stout, 1990). However, these global averages masks important country and regional differences that are driven by type of water source (surface vs ground water), water table depth, irrigation method and volumetric water demand determine the energy needed for abstraction (pumping) and application. The energy needed for irrigation thusvary substantially from farm to farm.

To illustrate this difference, we collected farm/country specific energy demand (15) points for different crops, waters sources and countries. On average the energy needed to irrigate 1ha of land was 4734 Kwh/ha, with lowest value 1786 KWh for sprinklers, while for drip irrigation the average value of 15 data points was 3645 KWh/ha with lowest value was 768KWh/ha. This demonstrate that large variability exist among countries, regions and farms, yet consistent data at country or region are not available. Therefore our estimates (Table 2.1) consider established value of Stout (1990) used by FAO.

Table 2.1 Climate Inputs

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Total irrigated land	*Mha*	367-308	320	5	4
Irrigated efficiency BAU	*%*	47	5	15	5
Irrigation efficiency	*%*	74	67-83	21	5

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
sprinklers					
Irrigation efficiency drip	%	88	85-94	19	7
Energy needed to irrigate 1ha of land - sprinklers	Kwh/ha	1403-1712	1641	5	1
Energy needed to irrigate 1ha of land - drip	Kwh/ha	1121-1356	1311	5	1

2.5.2 Financial Inputs

Averaged first cost of farmland irrigation was estimated to be $641 while the first investment cost for more efficient drip and sprinklers irrigation is $1575 per hectare. To calculate the operating cost of conventional irrigation per functional unit we determined how much of the total water withdrawal is used on the area irrigated using conventional practices and use the percentage of the total withdrawal and the total cost of withdrawal to determine the cost of conventional irrigation per hectare. Similar approach was applied to calculate operational cost of the solution.

Table 2.2 Financial Inputs for Conventional Technologies

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
First costs (Conventional)	US$2014/ha	$210-$1132	$641	13	11
Operating Cost (Conventional)	US$2014/ha	NA	$214	NA	NA

Table 2.3 Financial Inputs for Solution

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
First costs (Solution)	*US$2014/yr*	$775-$2376	$1575	37	21
Operating Cost (Solution)	*US$2014/yr*	NA	$151	NA	NA

2.6 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 irrigation 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.

2.7 LIMITATIONS/FURTHER DEVELOPMENT

Our approach is primarily limited by lack of energy and water withdrawal. Further development of the model would be enhanced by including more accurate figures on fuel use and energy used per hectare of agriculture land at country level or regional level.

3 RESULTS

3.2 ADOPTION

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

Total adoption in the *Plausible* Scenario is 189 million hectares in 2050, representing 59 percent of the total suitable land. Of this, 137 million hectares are adopted from 2020-2050.

Total adoption in the *Drawdown* Scenario is 287 million hectares in 2050, representing 89 percent of the total suitable land. Of this, 235 million hectares are adopted from 2020-2050.

Total adoption in the *Optimum* Scenario is 320 million hectares in 2050, representing 100 percent of the total suitable land. Of this, 268 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 irrigation	Mha	51.46	138	235	269
	% Total Land Available	16.1%	59%	89%	100%

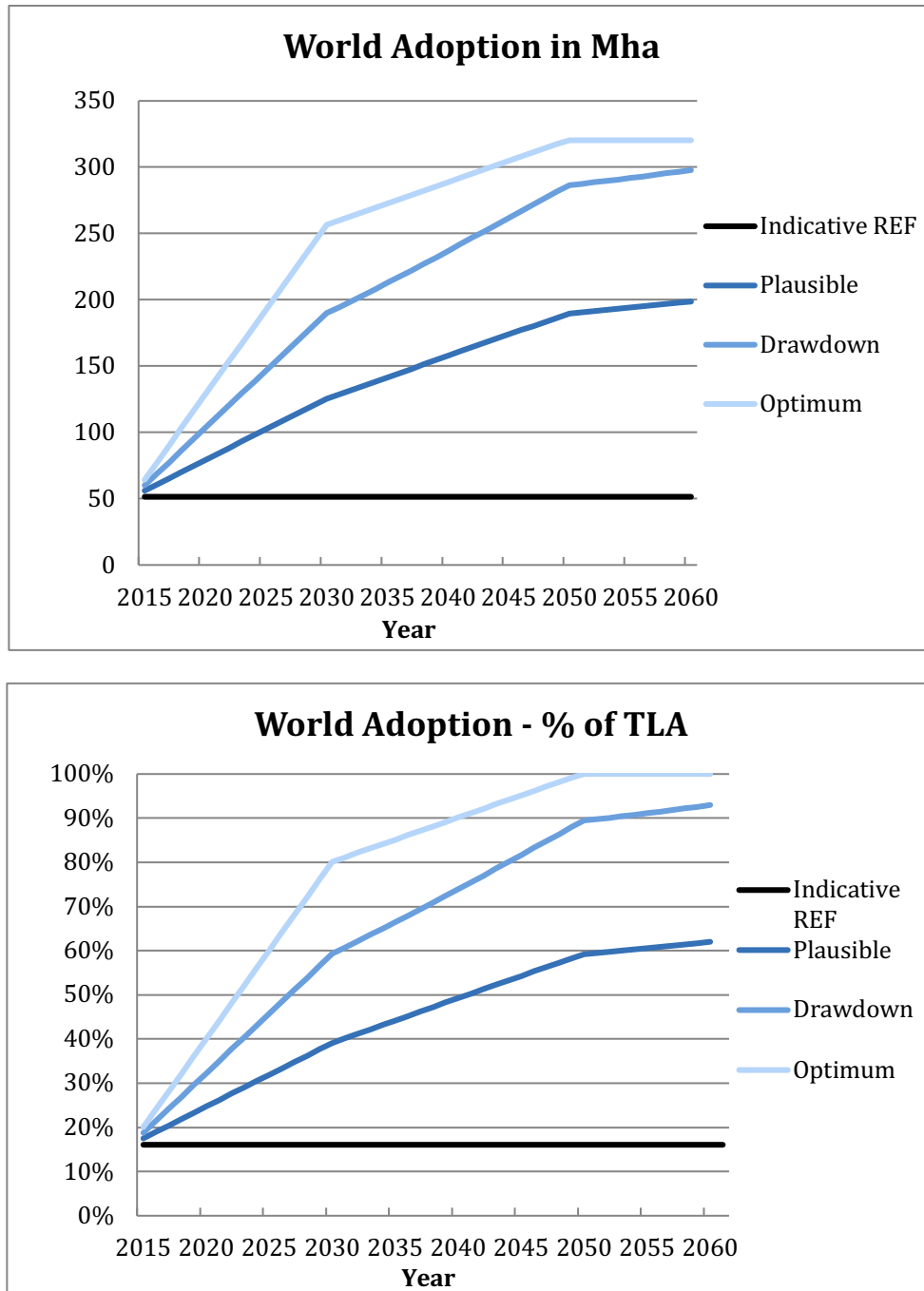**World Adoption in Mha**

World Adoption - % of TLA

Figure 3.1 World Annual Adoption 2020-2050

3.3 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.

Emissions reduction impact is 1.24, 2.20, and 2.89 gigatons of carbon-dioxide equivalent in the *Plausible, Drawdown,* and *Optimum* Scenarios respectively.

Table 3.2 Climate Impacts

Scenario	Maximum Annual Emissions Reduction	Total Emissions Reduction	Max Annual 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	0.06	1.24	-	-	1.24	0.03	0.06
Drawdown	0.11	2.20	-	-	2.20	0.06	0.11
Optimum	0.12	2.89	-	-	2.89	0.10	0.12

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

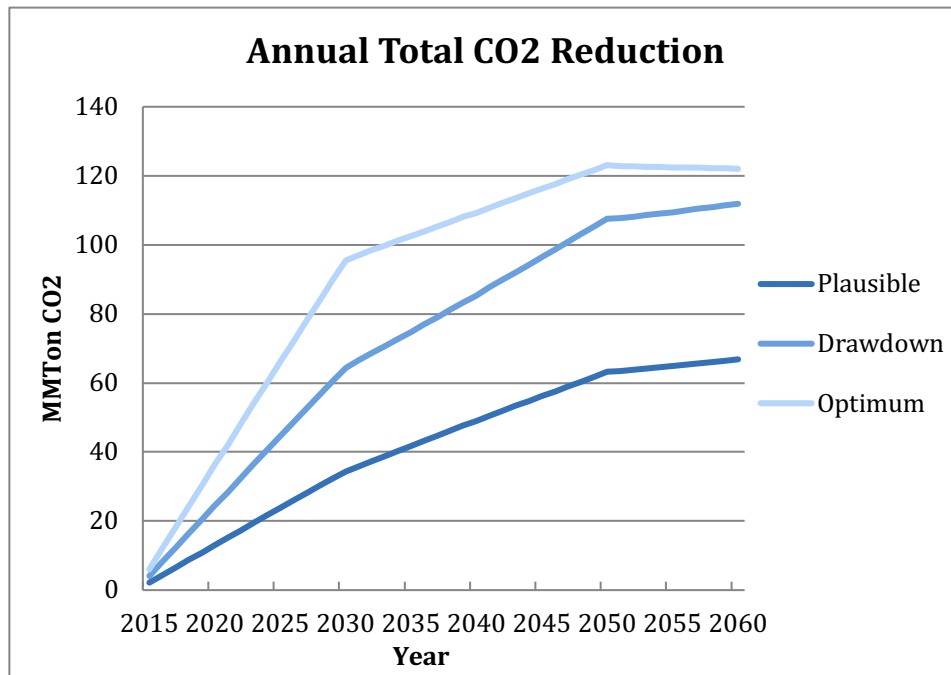| Scenario	GHG Concentration Change in 2050	GHG Concentration Rate of Change in 2050
	PPM CO$_2$-eq (2050)	*PPM CO$_2$-eq change from 2049-2050*
Plausible	0.103	0.005
Drawdown	0.182	0.008
Optimum	0.236	0.009

Figure 3.2 World Annual Greenhouse Gas Emissions Reduction

3.4 FINANCIAL IMPACTS

Below are the financial results of the analysis for each scenario. For a detailed explanation of each result, please see the glossary.

Note that the financial results have changed from those published in the first edition of the *Drawdown* book. There is no net profit margin for this solution. The solution is about efficient use of farm water management, thus the savings are only in the form of operational cost.

For the *Plausible* Scenario, cumulative first cost is US$ 253.85 billion. Marginal first cost is the same as cumulative first cost. Net operating savings is US$ 330.79 billion. Net profit margin is US$0 billion, and lifetime profit margin is US$0. Lifetime cashflow savings NPV is -$12.60.

For the *Drawdown* Scenario, cumulative first cost is US$ 438.59 billion. Marginal first cost is the same as cumulative first cost. Net operating savings is US$ 585.92 billion. Net profit margin is US$0 billion, and lifetime profit margin is US$0 billion. Lifetime cashflow savings NPV is- $22.88 billion.

For the *Optimum* Scenario, cumulative first cost is US$ 524.75 billion. Marginal first cost is the same as cumulative first cost. Net operating savings is US$769.38 billion. Net profit margin is US$0 billion, and lifetime profit margin is US$0 billion. Lifetime cashflow savings NPV is -$31.79 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	$253.85	$253.85	$330.79	$0.00	$0.00	-$12.60
Drawdown	$438.59	$438.59	$585.92	$0.00	$0.00	-$22.88
Optimum	$524.75	$524.75	$769.38	$0.00	$0.00	-$31.79
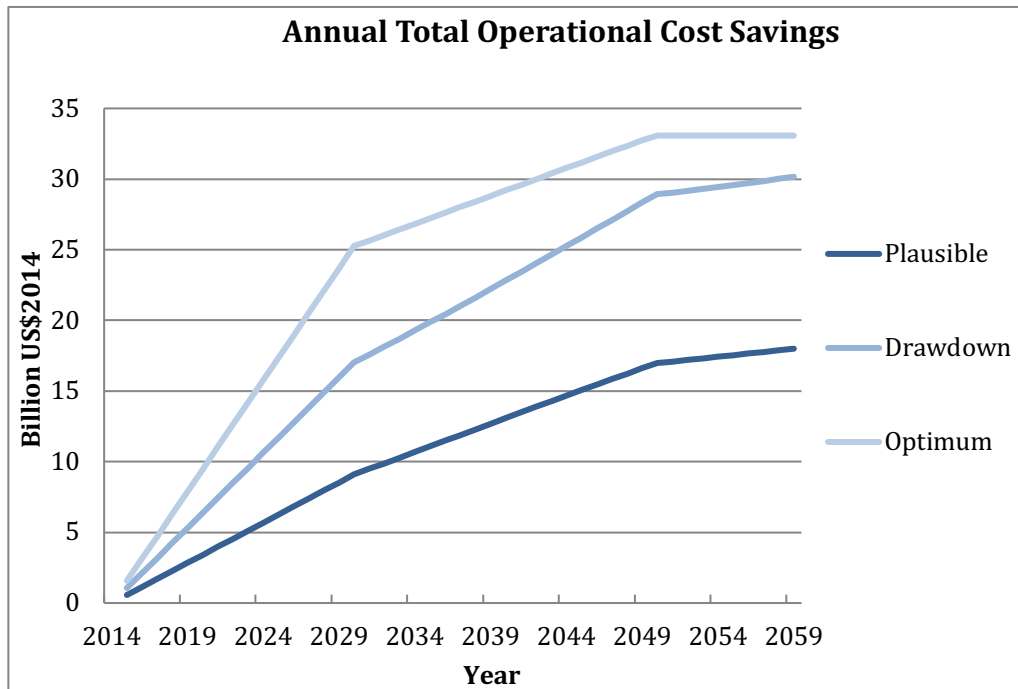
Figure 3.3 Net Operational cost savings

4 DISCUSSION

Improved irrigation methods possess a significant potential for saving irrigation water. Sprinkler and drip irrigation are the prime one having high rate of water application efficiency. These methods not only save water but also help in saving energy used for irrigation. The savings in energy is the key of reducing carbon dioxide emissions from irrigation.

Research conducted at the global level advocated the efficacy of the solution, thus calls for higher adoption. These solutions which were evolved in past few decades have not been implemented to a wider extent. High capital cost is the primary reason for the lower adoption of these solutions along with few operational and maintenance issues. Therefore there is a need to give focus on reducing the capital cost of these solutions and addressing the challenges being faced by farming communities in operating these devices. These problems were well-realized by the manufacturing companies and many of them are now working on developing low cost micro irrigation systems with the lead taken by IED. Apart from these many countries are giving heavy subsidies on these systems, which will also help in increase the adoption of these solutions. However, a significant amount of effort is also required to educate and equip farming communities with the correct knowledge and training on these solutions, so that they can efficiently utilize the benefits of these solutions. Lowering capital costs and building the capacity of farming communities are the two factors most affecting the large-scale adoption of these solutions. Under the high adoption scenarios in this study, we are assuming that both these criteria will be met.

The study concludes that improved irrigation methods can reduce water use while providing modest emissions reduction and financial gains. The solution holds special importance as irrigation is one of the key consumers of scarce fresh water resources globally. Thus, savings in water in irrigation not only helps in reducing carbon dioxide emissions from this sector but also saves a lot energy which goes into the purification, transfer and supply of water as the saved water under optimal solutions can be used in other sectors.

4.2 LIMITATIONS

The study can further be improved with updated estimates on the emissions factor for carbon dioxide emissions and irrigation cost of water to estimate reduced operational cost. More data points on these two parameters will further make the study more robust.

4.3 BENCHMARKS

The global studies that estimates carbon dioxide emissions from irrigation are still lacking, thus we do not provide comparison. More studies are needed to empirically quantify the global warming potential for of the improved irrigation relative to a conventional irrigated system.

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GLOSSARY

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

Approximate PPM Equivalent – the reduction in atmospheric concentration of 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