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Building the Methodology for the First Certified Agricultural Green Bond

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Institutions for Development Sector

Connectivity, Markets, and Finance Division

TECHNICAL NOTE Nº IDB-TN-1668

May 2019

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Cataloging-in-Publication data provided by the
Inter-American Development Bank
Felipe Herrera Library

Pratt, Lawrence.
Protected agriculture in Mexico: building the methodology for the first certified agricultural green bond / Lawrence Pratt and Juan Manuel Ortega; editors, Enrique Nieto and Isabelle Braly-Cartillier.
p. cm. — (IDB Technical Note ; 1668)
Includes bibliographic references.
1. Crops and climate-Economic aspects-Mexico. 2. Greenhouse plants-Economic aspects-Mexico. 3. Agricultural productivity-Environmental aspects-Mexico. 4. Agricultural productivity-Economic aspects-Mexico.
I. Ortega, Juan Manuel. II. Nieto, Enrique, editor. III. Braly-Cartillier, Isabelle, editor. IV. Inter-American Development Bank. Connectivity, Markets and Finance Division. V. Title. VI. Series.
IDB-TN-1668

http://www.iadb.org

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Abstract

The issuance of green bonds has grown rapidly in the past several years. However, agricultural green bonds have lagged far behind, because of the difficulties of developing international certifications, such as those of the Climate Bond Initiative (CBI). These certifications are essential, but demand the creation of comparable criteria and a certification approach that is applicable across several financial asset classes. This has proven to be methodologically and analytically complex in the case of agricultural green bonds because of the difficulties of assessing environmental and social benefits from different technologies in varying geographic and climatic regions. This paper describes the approach, methodology, analysis, and recommendations used to support a green bond for specific protected agricultural technologies in select crops in Mexico. The paper concludes with recommendations for defining minimum technological criteria that provide reasonable assurance to stakeholders that the expected environmental and social benefits will be achieved.

JEL Codes: O13, Q12, Q15, Q18, Q54, Q56

Keywords: agribusiness, agricultural finance, agricultural policy, carbon, certification, climate, climate change, desertification, drought, emissions, energy efficiency, environment and development, environment and growth, environment and trade, FIRA, food production, global warming, green growth, greenhouse gas, greenhouses, IDB, materials efficiency, Mexico, protected agriculture, protected cultivation, renewable resources

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About the Project

In 2017, The Inter-American Development Bank (IDB), through its Connectivity, Markets, and Finance Division, launched a new technical program to support national development banks in their efforts to raise private funds at adequate maturities in local and international capital markets by issuing green bonds or sustainable bonds. Green bonds are used to raise capital for the financing of green projects. Globally, the green bond market took off in 2014 with US$36.6 billion issued, triple the amount issued in 2013 of US$11 billion. Since then it has grown steadily, reaching US$167.3 billion in total green bond issuance by the end of 2018. Because green bonds attract national and international institutional and impact investors, they impact the issuer's ability to diversify sources of funding, while promoting low-carbon investments or other types of investments with demonstrable and significant environmental or social impacts. By the end of 2018, the program was working with 10 institutions and had supported 4 issuances.

The land-use sector (agriculture and forestry) still represents a very small portion of the climate-aligned bond universe—just over 3 percent in 2018 according to the Climate Bond Initiative. Green projects in agriculture have proven to be challenging for green bond issuers and certifiers, as there are few systematic methodologies available to characterize "green" agricultural and other land-use investments. This study develops and applies one such methodology to identify green investments to transform the production of tomatoes (and, by extension, crops with similar characteristics) from open-field cultivation to protected cultivation.

This effort is being carried out to support Trust Funds for Rural Development (Fideicomisos Instituidos en Relación con la Agricultura, or FIRA)—one of the beneficiaries of the IDB technical assistance program—to issue its first green bond. Established in 1954 by Mexico's federal government, FIRA is a second-tier development bank that offers credit and guarantees, training, technical assistance and technology-transfer support to the agriculture, livestock, fishing, forestry and agribusiness sectors in Mexico. The IDB supported the development of a methodology to assess the environmental impacts of protected cultivation in Mexico. Based on this effort, FIRA issued the first internationally certified agricultural green bond in October 2018.

The FIRA bonds were the first agricultural bonds to receive certification from the Climate Bond Standards. They were also reviewed by Sustainalytics, which provided a positive Second Party Opinion. Both organizations reviewed and considered the methodology proposed in this paper and its application to Mexican protected cultivation. This document presents the results of this work and the methodology developed.

Acknowledgements

This report required the input of many people from different organizations and areas of expertise to whom we are indebted for their valuable contributions and perspectives. The authors and editors wish to express their appreciation to Carmen Fernandez Diez and Maria Netto of the IDB, as well as the FIRA team including Erick Rodriguez Maldonado, Artemio Vasquez Aguilar, Ernesto Fernandez Arias, Jose Renato Navarrete Pérez, and Nancy Lorena Flores Garcilazo. Mario Steta of Driscoll Strawberries and President of Asociación Mexicana de Horticultura Protegida (AMHPAC); Mario Alvarado Chávez, President of the Asociación Mexicana de Constructores de Invernaderos, and José Ignacio Moreno of AGROS S.A. de C.V., provided critical guidance on the protected agriculture industry in Mexico.

The authors also extend special thanks to Andrew Seidl (Colorado State University), Francisco Alpizar (CATIE), Salvador Gonzalez (independent consultant), and Christine Negra (Versant Vision LLC) for their valuable reviews and comments on technical aspects of the report.

This work was conducted as part of a technical assistance program executed by the IDB with support from the International Climate Initiative (IKI) of the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) of the Federal Republic of Germany.

Acronyms and Abbreviations

BAU	Business as usual
CBI	Climate Bonds Initiative
Conagua	Comisión Nacional de Agua (Mexican National Water Commission)
EPA	Environmental Protection Agency
ENSO	El Niño Southern Oscillation
FAO	United Nations Food and Agriculture Organization
FDA	Food and Drug Administration
FIRA	Fideicomisos Instituidos en Relación con la Agricultura (Trust Funds for Rural Development)
GHG	Greenhouse gases
IDB	Inter-American Development Bank
LCA	Life cycle analysis
PA	Protected agriculture
SERMANAT	Secretaría de Medio Ambiente y Recursos Naturales (Mexican Secretariat of Environment and Natural Resources)
SIAP	Servicio de Información Agroalimentaria y Pesquera (Food and Fisheries Information Service)
UNFCCC	United Nations Framework Convention on Climate Change
USDA	United States Department of Agriculture

Scope of Work and Methodology

The consultant was tasked with designing a methodology to evaluate the environmental and other benefits of protected agriculture (PA), considering the need to meet the eligibility criteria of issuers of green bonds, or climate bonds. Green bonds are used to raise capital to finance green projects.

Globally, the green bond market took off in 2014 with US$36.6 billion issued, triple the amount issued in 2013 of US$11 billion. Since then it has grown steadily, reaching US$167.3 billion in total green bond issuance by the end of 2018. The land use sector (agriculture and forestry) still represents a very small portion of the climate-aligned bond universe—just over 3 percent in 2018, according to the Climate Bond Initiative (CBI). Green projects in agriculture have proven to be challenging for green bond issuers and certifiers, as there are few systematic methodologies available to define “green” in the agricultural area.

Scope of Work

This study develops and applies one such methodology to identify green investments in transforming the production of tomatoes (and, by extension, crops with similar characteristics) from open-field cultivation to protected cultivation. The authors sought to understand and document the differences between a business-as-usual (BAU) scenario, defined for the purposes of this study as open-field agriculture, and protected agriculture (using various technologies) across a range of relevant environmental and social criteria.

The goal of this effort was to understand, and to the extent possible quantify, the difference between scenarios along a number of relevant environmental and social variables. The authors did not seek to conduct life-cycle analysis (LCA) for the different scenarios, as this was not part of the requirement. Rather, they studied the changes in a select set of variables that are of greatest interest and relevance to the Mexican government, national and regional development banks, and certifiers and issuers of environmental and socially oriented bonds.

Methodology

This approach is not strictly a new methodological approach in the sense that different production

systems are compared side by side. It is similar to approaches generally taken for climate bonds or in green investment criteria to determine the marginal differences between different approaches (e.g., comparing a renewable energy investment to a baseline fossil fuel investment). The principal differences in the approach employed by the authors in this paper lie in the selection of the comparative criteria (particularly the range), the normalization approach on production output (the norm in agriculture is usually land-driven), and the range of alternative technologies.

This approach is considered appropriate for this analysis. First, the biological systems for planting, growing, and harvesting are virtually identical as they are based on the same agricultural product in all scenarios (with relatively minor differences among varieties). Second, all production is in the same country. While there can be significant geographical differences, these are somewhat limited by the plant biology. However, all scenarios are framed in the same policy context, with the same energy mix, virtually identical input types and costs, very similar construction materials and technologies, similarly trained agronomists, and others. The biological conditions and country context control substantially for a wide range of exogenous factors, permitting the study to focus on the differences between the production system scenarios.

The methodology was divided into two steps. The first was to determine the appropriate set of environmental and social criteria upon which to compare the different production technologies. For this first step, the authors established environmental and social criteria based on the most common variables of interest or concern in agriculture, incorporating the proposed criteria of the Climate Bond Initiative for land-use-related climate change impacts (mitigation and adaptation) to increase alignment with emerging climate bond and green bond criteria (a critical reference point) in established preliminary criteria documents. Additional criteria were added based on standards widely used by agricultural certification organizations and development finance institutions' green lending programs, as well as those suggested in the limited literature published in this area. The list of criteria was distributed for comment to the IDB, the Climate Bonds Initiative (CBI), and several experts in the field to validate their relevance.

The second step was to examine the specific characteristics of the various production technologies as applied to each of the environmental and social criteria to generate comparative data for each criterion. Data collected and analyzed were used to populate a comparative matrix, which permitted direct comparisons to be made. The data were normalized for more direct comparison, generally to output variables (kilograms or tons of production). To the extent possible, quantitative data are used, with qualitative data added to complement or clarify the data points.

Data Sources

The main challenge for this effort was that there is scant published literature comparing PA and conventional open-field agriculture that takes environmental and social considerations into account. Publications that do exist are generally focused on agronomic factors, particularly productivity-related variables, and are generally not specific to Mexico. Consequently, the methodology was established to secure information from the following sources:

- Review of the literature for directly relevant information
- Review of the literature for potentially relevant data that could be extrapolated (e.g., from productivity and production costs to environmental footprint) or used to validate data points from local experts and Mexico specifically
- Interviews with individuals in Mexico experienced in protected agriculture (research agronomists, and technical field experts involved in financing)
- FIRA documents related to PA financing
- Senior managers of PA-oriented production companies

High-technology PA – Production Hall.

- Official sources of policy information and field data

Literature Review

The formal peer-reviewed literature is extremely limited on the environmental impacts of greenhouse agriculture. Most publications on PA focus on the productivity aspects, detailed agricultural parameters (for example, fertilization, and water strategies or cultivar comparisons). The most relevant publications for this effort include Torrellas et al. (2013), who developed an input/output methodology to calculate various environmental emissions based on production inputs and for different cultivated products. Torellas et al. based much of their model on tools developed by the Euphoros project,[1] a European Union-supported agricultural project seeking to identify strategies to greatly reduce the life-cycle impact of PA. Country-specific papers such as Boulard et al. (2011), on France; Antón et al. (2010) on the Netherlands; and Moreno Reséndez et al. (2011) on Mexico, examine the impacts on technologies employed in context, and very specific environmental impacts. Gołaszewski et al. (2012) compiles energy profiles across the EU for different production systems (including some PA) to estimate energy consumption per unit of product output. The only published paper identified that explicitly attempts comparisons of open field and protected agriculture systems in a production region is Muñoz et al. (2008), which examines GHG profiles of tomato production in the southern Mediterranean.

All of these sources provided important instructive input into the approach taken for this paper. The findings of these studies were used frequently to compare and validate some of the findings for this paper. The papers cited had several limitations for this effort, which made direct use or incorporation of their methodologies unviable. Most notably,

[1] https://www.wur.nl/en/Research-Results/Projects-and-programmes/Euphoros.htm.

they tended to focus on a narrow set of parameters (such as GHGs) and were almost entirely on geographies and agricultural contexts that were different from those found in Mexico. In addition, the established purpose and needs of the clients for this effort required a high-level understanding of a number of variables rather than an extremely detailed understanding of the target variables of much of the technical literature.

Other Data Sources

In the absence of detailed studies, many quantitative points reported by practitioners and researchers, or presented in technical guidance documents or official sources, are indicative. The Secretary of Agriculture's Food and Fisheries Information Service (Servicio de Información Agroalimentaria y Pesquera, or SIAP) database provided high-quality data from the field, collected by extension agents throughout the country. While this database does not provide information specifically on environmental variables, it was critical in understanding the nature, scale, location, and product selection for PA. The data on catastrophic crop loss provided much of the underlying basis for the vulnerability reduction estimates.

The authors interviewed or received input from more than 20 experts in PA in Mexico, including researchers, practicing agronomists, and managers of PA companies in different parts of the country. PA expansion and technological evolution are moving quickly, and far more quickly than academic researchers are able to research and report. Where it was not possible to secure quantitative data, comparative and qualitative data are presented to provide insight into current understanding of the variables. The authors based the data collection and analysis on current best practices for each technology.

Background

Protected agriculture is the term used to describe a series of cropping techniques that fully or partially control the micro-climate surrounding the plant body according to the requirements of the species during their growth period.[2] Specifically, it refers to technologies and techniques that can be used to protect crops from certain environmental, biological, and climatological elements to improve production. These techniques contrast with the present BAU scenario of open-field production, which refers to more traditional agricultural techniques in natural soils and with direct exposure to sunlight, wind, rain, pathogens, and other elements of the production system. This is the conventional modern farming method in Mexico, which is practiced on the vast majority of farms and determines the production capacity for the products discussed in this paper.

Scale and Distribution

Protected agriculture has grown rapidly in Mexico and spread geographically. In 2000, there were only 790 hectares in production. By 2015, the government reported 23,251 hectares in PA, representing a compounded 25 percent annual growth rate over this period. Approximately 80 percent of production is destined for export markets (almost exclusively the United States). The Mexican Association of Protected Agriculture reports that production is highly concentrated in a few products: 70 percent tomato, 16 percent bell peppers, 10 percent cucumbers, and less than 2 percent berries. Nearly all PA is concentrated in the map shows eight states (out of 31), with just over half in only three states: Sinaloa, Jalisco, and Baja California (FIRA, 2016a).

Commercial Drivers

The underlying principle of PA is to provide control over conditions that are difficult, if not impossible, to control in open-field agriculture. The main

2 "Protected cultivation" and "controlled-environment agriculture" are synonymous terms. Economists frequently use the former to clarify that the concept refers to the use of production techniques that are protected, and not agricultural markets that are protected by tariff and non-tariff trade barriers. Researchers increasingly use the latter term to more accurately describe the technological logic.

conditions that it controls are the horizontal nature of soil-based farming, water/rainfall, temperature, weather and climatic conditions, pathogens, and their various vectors. The higher the technology, the more variables that PA controls. The highest-tech hydroponic greenhouse processes more closely resemble manufacturing operations than traditional agricultural operations.

The principal commercial drivers for protected agriculture in Mexico are:

- Higher and more consistent productivity
- Greater efficiency in the use of land, water, fertilizers, pesticides, labor, and in many instances energy
- Ability to meet demand profitably during colder months in Mexico (lower aggregate production, higher prices) and particularly in the U.S. winter season for export crops
- Better control over sanitary and phytosanitary conditions to meet market requirements and reduce crop risk and damage (damaged crops lead to lower prices and sales)
- Reduced vulnerability and related risk to weather/climate, particularly severe weather (heavy rainfall, hail, drought) which negatively affect crops, soil, quality, and sanitary and phytosanitary conditions
- Better capacity to respond to increasingly demanding consumer requirements with respect to pesticide use, sanitary conditions, and worker protection, primarily for international markets, but increasingly for domestic markets as well

National Policy Drivers

In Mexico, business and government have driven and promoted PA as a business strategy to increase production of high-value export products, and by extension more and better jobs and higher foreign exchange earnings.

The government has also aggressively subsidized PA throughout the country, particularly in its lower-technology variants, through its national development financial institutions such as FIRA. The aim is to help farmers increase their productivity and reduce their vulnerability to severe weather and numerous pathogens.

The government specifically cites PA in its Special Program for Climate Change 2014–2018 (SEGOB, 2014), where it states: “Strategy 2.3: Implement sustainable agricultural, forestry and fishing practices that reduce emissions and decrease ecosystem vulnerability.” Action Area 2.3.2 states: “Technify agricultural area through irrigation and protected agriculture to reduce climate vulnerability and increase food security.” This strategy is fully aligned with FAO policy recommendations and guidance on sustainable intensification of agricultural production.[3]

In addition, in Mexico’s UNFCCC-filed planning, the country commits to “…build quality infrastructure, employ state-of-the-art techniques, and strengthen operations for guaranteeing water availability for agriculture.” The benefits in climate change response are being increasingly recognized—particularly with respect to vulnerability reduction relating to water (SEMARNAT and INECC, 2016). Much of Mexico faces chronic water stress, and much of the country is believed to be experiencing increased frequency of severe weather events (heavy rain, droughts, hailstorms) consistent with climate change modeling. A Mexican government study in 2011 estimated 3.5 to 4 percent GDP losses from climate change impacts, with a significant portion in the agriculture sector (Estrada et al., 2013).

[3] See, for example, http://www.fao.org/policy-support/policy-themes/sustainable-food-agriculture/en/.

Characterization of Protected Agriculture Technology in Mexico

Protected agriculture in Mexico is generally divided into three categories—high-technology, low-technology, and shade houses—and a fourth intermediate category, depending on the technology used. These technologies are used most frequently on the high-value cash crops discussed previously, and increasingly on leafy greens primarily for the local market. While there is no official unified definition of these technologies, all experts and documents consulted agreed on the definitions.[4] Annex 1 presents demonstrative images of the different technologies.

The authors elected to base the data and analysis on current best practices for each PA technology. This decision was made to more accurately reflect forward-looking scenarios for PA, and to be more representative of the requests to, and desired financing from, financial institutions. Consequently, some variables in this report—notably productivity—are based on current expert opinion and observed data and are considerably higher than averages reported in official sources.

High technology. High-technology PA in Mexico uses completely enclosed greenhouses isolated from the soil and surrounding air; inert substrates[5] instead of soils; drip, microspray, or ferti-irrigation precision irrigation, and automation of water, precision fertilizer, and other chemicals used, with constant adjustment during the crop cycle and to account for changes in weather (short- and long-term). In most edible crops (tomato, bell pepper, cucumber, leafy greens) the systems are hydroponic (i.e., nutrients are delivered in solution in the irrigation water). This technology is highly capital intensive, is based on adaptations to principally Dutch technology, and is used on crops primarily destined for export markets. The business case is that higher productivity with a higher-quality product provides higher income, justifying the investment.

The key driver is the U.S. market for tomato, cucumber, bell pepper, berries, and other products, especially during the northern winter season, when prices for these products increase

[4] SIAP uses slightly different nomenclature in its statistical records, but the categories are the same.

[5] Substrates are different types of organic or inorganic material in which the greenhouse plant grows, instead of soil. Advantages include improved pest management, water flow, and nutrient transfer.

High-technology PA.

substantially in the United States but growing conditions in Mexico permit production. The higher-tech controlled environment also allows growers to manage and meet more demanding sanitary and phytosanitary requirements, respecting USDA sanitary and phytosanitary requirements, and Environmental Protection Agency (EPA) and Food and Drug Administration (FDA) requirements on pathogens, pesticides, and chemical residues. In contrast with northern European systems, in Mexico the growing spaces are generally not heated. In some growing regions, additional heat to maintain growing conditions is used on a limited basis during nighttime hours in the coldest months, generally through radiated circulated water heated with natural gas. Use of this heating avoids crop losses, ensures production when prices are highest, and allows year-round employment. Year-round employment is highly beneficial to workers and increasingly important for greenhouse operators, who require highly skilled laborers and, in many geographic areas, are competing to attract and retain them.[6]

Note that for measures of productivity and the later normalization of other variables for high-tech PA, the numbers presented are for current new technology "best practices." The authors consider this the relevant reference production level as it most accurately reflects recent investments (previous few years) and what is currently being developed in Mexico and therefore most likely to the object of new financing.

Low technology. Low technology refers to rudimentary protective structures (i.e., plastic tunnel structures on semi-rigid supports) that protect crops against the hard rains, drought, excessive sun and heat, and other adverse conditions. The crops produced on farms employing this technology are almost without exception for local market consumption. This technology has been promoted aggressively to improve farm income

[6] High-tech growers in the state of Queretaro commented that they compete directly with automobile industry workers for their core workforce.

through productivity increases and reduced vulnerability, primarily as a mechanism to maintain the viability of small-scale farmers. Farmers can expect significant productivity increases, but the economic advantage lies mostly in the ability to maintain quality and prices.

Shade houses. This category, a specific version of low-tech PA, is an increasingly common approach taken by producers. Generally financed in larger-scale operations, it consists of putting protective, permeable cover over land, nearly always previously in extensive open-field (BAU) production systems, to increase productivity and decrease various production risks. For open-field producers, this is a common first step in PA. For a relatively low investment, producers achieve significant benefits, including decreased vulnerability, higher productivity, increased water and chemical input efficiency, and better capacity to serve the profitable winter market in the United States. Along with high-tech operations, it is currently the fastest-growing technology in Mexico (in terms of hectares and total investment). The technology consists of erecting a structure that holds a permeable mesh over existing open-field (BAU) production land, nearly always with drip irrigation. The structure reduces risk from insect infection, wind, and hail damage and allows growers to use more productive “indeterminate” varieties.[7]

Medium technology. This broad category encompasses everything between the more easily categorized high- and low-technology approaches. In general, medium technology refers to production systems that are completely or nearly completely enclosed to air and rain using shading mesh cover, frequently producing with substrate or a combination of substrate and soils. Water use is controlled not always automated, and precision nutrition, but not usually hydroponic, is applied. The crops produced are generally for domestic consumption but may sometimes be exported through consolidators when they meet sanitary standards for pathogens and pesticide type and residues.

Differences between Mexican and Northern European Greenhouse Systems

Greenhouses in Mexico, particularly high-tech operations, are generally adaptations of technology from The Netherlands. While some aspects are very similar (e.g., structure type and materials, water systems, hydroponic approaches, pathogen management, etc.) the greatest difference is energy consumption. Dutch and German systems employ nearly year-round heating to maintain the temperature needed to grow produce. In Mexico, the required growing temperatures occur naturally year-round. Only simple ventilation is required during the hottest periods and increasingly water-circulated radiated floor heating for limited use when cold temperatures threaten crop viability or severely impact growth (Table 1).

7 “Indeterminate” plants grow, flower, and set fruit over the entire growing season. “Determinate” plants grow to a certain height and then stop. They also flower and set all their fruit within a relatively short period of time.

TABLE 1: Indicative Energy Consumption for Greenhouse Tomato Production

Country	Productivity (tons/ha)	Energy input GJ /Ton	kwh/kg
Germany	200	63.30	17.58
Netherlands	640	23.60	6.56
Portugal	200	2.23	0.62
Greece	230	1.12	0.31
Mexico	500	0.78	0.22

Sources: Gołaszewski et al. (2012). Data from Mexico compiled by authors from various sources on high-technology PA systems.

Crops and Relevant Differences

Both FIRA and the IDB wanted to highlight crops produced in large volume in PA systems that are relevant from the standpoint of both financing and national policy impact. However, nearly all published data and expert opinion focuses on tomato production, given the very high economic importance of this crop and its preponderance in PA in Mexico (and generally worldwide).

The PA experts consulted and the available literature concur that while the absolute numbers may vary, regardless of whether BAU or AP approaches are used to grow tomatoes, bell peppers, and cucumbers, almost no difference is observed in variables such as productivity, water use, chemical input use, waste, and worker aspects, and the results are "very similar" for berries. The authors therefore believe that the findings in this report, which are substantially based on data from and oriented toward tomato production, are equally valid for all of the above-mentioned crops (which represent at least 90 percent of all PA production in Mexico) in terms of direction and strength of impact in all environmental and social variables. A notable exception is the production of leafy greens, such as lettuce and spinach, which have significantly different production profiles and are not considered in this effort. Specifically, these products require different climate control conditions, production geographies, scale, BAU scenarios, water usage, and chemical strategies, which render them less comparable. A separate study is required to characterize these products, even considering the same methodology.

Comparative Criteria

The authors included environmental and social criteria based on the most common variables of interest in agriculture and incorporated the proposed criteria of the Climate Bond Initiative to increase alignment with emerging climate bond and other green bond and social bond criteria.

The following variables were selected for comparison:

- Productivity
- Land and soil requirements
- Water use
- Vulnerability
- Chemical inputs (fertilizers and pesticides)
- Energy use
- Waste
- Labor issues
- GHG footprint

To the extent that published methodologies and quantitative data availability permit, these are used. Where it was not possible to obtain quantitative data, comparative and qualitative data are presented to provide insight into current understanding of the variables.

Principal Findings

All data and all expert opinion point to PA being a highly favorable strategy for the following:

- Improving farm income (through productivity increases, improved price based on quality and seasonality, reduced crop damage and loss)
- Increasing efficiency, particularly in water, land use, fertilizer, and labor
- Greatly reducing vulnerability and increasing resilience to changing meteorological conditions and related physical and pathogen (insects generally, and in the case of high-tech PA also bacteria and fungi) impacts
- Opportunities to reduce water consumption through efficiency and recovery and even use lower-quality desalinized (non-drinking-quality water) for tomato production
- The possibility of a range of new technologies for even greater improvement in environmental and social impact (safer chemicals, reduced water impact, waste).

For more high-tech operations, the following additional benefits were identified:

- Worker economic stability through better compensated, year-round employment
- Higher salaries for agricultural workers and better working conditions (in medium- to high-tech)
- The potential for much greater future improvements in productivity, safety, and water management (as distinct from BAU strategies, which hold little prospect for significant improvement)
- Generally lower GHG footprint per unit of production. While PA increases some impacts versus BAU, notably waste from plastics, this impact is compensated in other areas when examining the entire production system, and particularly when considering ongoing versus embedded emissions

All experts consulted and all data identified are remarkably consistent in the above points. Differences of opinion on data interpretation are relatively minor. There is no apparent disagreement on the direction of impacts or the nature and magnitude of benefits and costs. There are important contextual differences (Mexico vs. Mediterranean vs. Northern Europe) that require careful consideration. However, the findings in Mexico are consistent with the findings of the published research in other geographies, and when controlling for climate, growing conditions and technology employed in Mexico, there is a high level of alignment and consistency.

The environmental and social benefits of PA versus BAU are directly and highly correlated with technological variables/choices and discrete management decisions. This should allow standards to be set based on observable criteria. For example, type of infrastructure and technology employed appear to be satisfactory as conditions that determine reduced impact. This would provide simple investment guidelines/criteria and would require only simple verification.

Analysis of Findings

This section presents the principal findings of the data-gathering efforts for each of the impact matrix criteria.

Productivity

The greatest difference between PA and BAU relates to the productivity of the production system. This drives much (if not most) of the shift toward PA in Mexico. Productivity is measured in kg of product per year per hectare of land. The productivity gains come primarily from pure productive capacity, but also increased production from avoidance of losses due to severe weather and pathogens. However, the productivity gains also derive from the efficiency of fertilizers, water, labor, and other variables, that are addressed in other criteria below.

Tomato productivity is used for this comparison, though experts confirmed nearly identical strength of impact in bell pepper and cucumbers, and likely even greater in berries due to their susceptibility to pathogens and sensitivity to temperature and fungi.

For measures of productivity and the later normalization of other variables for high-tech PA, the numbers presented in Table 2 are for current new-technology best practices. The authors consider this to be the relevant reference production level because it most accurately reflects recent investments (last few years) and what is currently being developed in Mexico.

The productivity numbers in Table 2 do not include expected losses due to severe weather experienced primarily in open-field production, discussed in the vulnerability section below. Thus, these productivity numbers overstate BAU productivity and understate PA on an expected value basis.

Land-Related Variables

The key issues related to land have to do with soil needs and erosion. Soil needs are tied to the agronomic requirements for the specific crop. Tomato in open-field production requires deep, loamy (high organic content) soil, with good drainage, quite flat, with an optimum pH between 6.2

TABLE 2: Land Productivity (metric tons of tomato per year per hectare of land)

BAU (open-field)	High-tech (current best practices)	Low-tech	Shade house	Medium-tech
22 tons/ha rainfed	500–800 ton/ha	100 to 300 tons/ha	Seasonal 120 to 150 tons/ha	400 ton/ha (estimated median)
40 tons/ha irrigated			Year-round 250 to 300 tons/ha	
	(12x to 35x improvement vs BAU)	(2.5x to 13x improvement vs BAU)	(3x to 14x improvement vs BAU)	(10x to 18x improvement vs BAU)

Sources: FIRA (2009; 2016b); Carlos Torres Barrera, FIRA, Interview, September 2017; Katia Montero, Protected Agriculture Expert, Interview, March 2018. Note that high-tech productivity data are for current best practices" for year-round production.

and 6.8. This is premium agricultural land that is degraded through use and must be replenished with nutrients and organic matter. Low-tech PA and shade houses (and the approximately 60 percent of medium-tech PA using natural soil) require these same general conditions. High-tech operations and medium-tech using substrates instead of soils have no required soil conditions. These PA operations can be located on any type of land, as long as it on a slope of less than 2 percent. In practice, natural soils are covered with thick plastic in high-tech operations to ensure the soils and the microbes contained in them do not enter the growing envelope. The growing conditions are created biochemically in the growing substrate. The trend in medium-tech is to move away from soils toward substrates to reduce variability and pathogen exposure. There is ongoing research on improving substrates to improve nutrient delivery, water management, and growing conditions.

In the case of erosion, for high-tech farms there are effectively no losses to erosion because the production system is not connected to the soil. For open-field operations, the authors could not find any specific data on erosion losses in the literature, although it is mentioned in documentation from FIRA and others among the principal reasons farmers should consider switching to a PA system. For medium-tech systems that use substrates, there is no loss to erosion. For medium-tech systems that use natural soils, there could be some erosion but this would be relatively infrequent and minimal, particularly compared to open-field and even low-tech PA. Low-tech production, including shade houses, would still be subject to erosion losses from rainfall washover and river rises (where exposed), but erosion from direct impact of rainfall is greatly reduced as the plastic cover blocks the direct impact and splash and bounce from heavy rain (Table 3).

TABLE 3: Land-Related Variables

Variable	BAU (open-field)	High-tech (current best practices)	Low-tech	Shade house	Medium-tech
Type of land	Deep, loamy, good drainage, quite flat, pH 6.2 to 6.8 (slightly acidic for tomato)	Any land that can be covered, with less than 2% slope. Growing medium is substrate.	Same as BAU	Ideally the land must have drainage and a slight slope to avoid pests	Approximately 60% on soils, same as BAU. 40% in substrates, same as high-tech
Erosion	Frequently identified as a concern	None from agricultural operations	Considerably less than BAU, but still a concern	Considerably less than BAU, but still a concern	Considerably less than BAU to none.

Sources: FIRA (2009; 2011); various experts interviewed.

TABLE 4: Water Variables in PA versus BAU

Variable	BAU (open field)	High-tech (current best practices)	Low-tech	Shade house	Medium-tech
Cubic meters per ton of tomato	75 m^3 /ton	16 m^3 /ton (approx. 80% improvement over BAU)	59 m^3 /ton (approx. 20% improvement over BAU)	50–70 m^3 /ton (approx. 7–33% improvement over BAU)	35 m^3 /ton (median approx. 50% improvement over BAU)
Water source	Rain and surface water, wells.	Water from deep wells. This assures water availability in quantity and year-round.	Water can be obtained from surface water or a well which help ensure quantity and year-round.	Rain, water from deep wells, surface waters.	Water from well (underground). This assures water availability in quantity and year-round.
Water delivery	Traditional Irrigation (pump and sprinkler)	Drip irrigation, with pumping and precision dosing system	Rain-fed, or stream-fed with high power pump.	Rain, traditional, irrigation, drip irrigation.	Drip irrigation, with pumping and dosing system. Rain-fed during wetter seasons.

Sources: FIRA (2010; 2011); Carlos Torres Barrera, FIRA, Interview, September 2017; Katia Montero, Shade House Protected Agriculture Expert, Interview, March 2018; various other experts consulted.

Water Use

Improved water management is one of the most notable characteristics of PA. In open- field production, rainfall or irrigation (usually by high volume pumps) meet water needs. Watering is by routine schedule, and most water is lost to soil, runoff, or evaporation. In high-tech and many medium-tech operations, water is specifically allocated based on plants' real-time requirements using drip and micro-aspersion irrigation systems, frequently with sensors and computer controlled. Evaporation is minimal, and little water is lost. The systems are so efficient from an energy standpoint that they can be (and increasingly are) driven by small, low voltage and amperage motors (by contrast, open-field production requires gasoline or diesel pumps of at least 2 horsepower). In addition, high-tech operations and more sophisticated medium-tech operations use hydroponic systems whereby nutrients are delivered through the water. Lost water is also lost nutrients. This economic driver encourages very efficient use and incentivizes recovery and reuse of lost water. High-tech operations require extremely reliable water supplies, so they tend to use deep wells to ensure year-round quantity and quality. Open-field and low-tech production methods use a mixture of rainfed, surface water-fed (pumped) irrigation and occasionally wells in drier climates. However, shade houses that are well capitalized use precision irrigation systems and require reliable water supplies, similar to higher-tech operations (Table 4).

The final disposition of used water is highly variable in Mexico, depending on specific local conditions. Due to generally warm temperatures, there is significant evaporation in open-field production. While technically much of any excess watering will recharge through the soil or move downstream for other use, evaporation loss is considered important though difficult to quantify. However, since the principal water issue in Mexico, and the principal focus of national policy concern is water scarcity, its efficient use is considered to be the principal variable of concern.

Vulnerabilities

The principal vulnerabilities in Mexican agriculture are water stress and severe weather.

Water Stress. Water is one of the most critically stressed resources in Mexico and is the country's

principal national vulnerability concern. One of the Mexican government's top vulnerability reduction priorities is to move toward more technical approaches to water management in agriculture to increase water efficiency.

Large parts of the country are desert, semi-desert, or arid. More than two-thirds of the country (representing over 80 percent of the population) is classified under "strong" or "very strong" water stress (SEMARNAT, 2012). Agriculture is by far the largest consumer of water in Mexico, representing 77 percent of water consumption (FAO-Aquastat). Nearly one-fourth of all agriculture is irrigated, and nearly all of that with extremely low water efficiency. PA offers an important mechanism to mitigate water stress while maintaining or increasing agricultural output.

Severe weather. Open-field agriculture is very vulnerable to severe weather. Like most of Latin America, Mexico is expected to suffer significant changes in weather conditions due to climate change. Broad climate change impacts, particularly rising temperature and sea level, drive Mexico's vulnerability. Moreover, most of Mexico is highly vulnerable to changes in the El Niño Southern Oscillation (ENSO), which is projected to lead to increased incidence of droughts, severe rain and flooding events, and altered seasonality of rains.[8]

According to data from the Secretary of Agriculture's SIAP database, between 2008 and 2016, open-field farmers suffered a total loss of their harvests on an average of 4.4 percent of all land each year. The comparable number for medium- and high-tech production is less than 0.2 percent for the past five years, representing a 20-fold improvement for PA versus BAU. The data for shade houses is not complete enough in the SIAP database to assert a number. However, the actual number is likely to be somewhat less than

[8] Existing research suggests that one third of agricultural yield variability is already attributable to climate change. See Ray et al. (2015).

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open-field because of the additional protection provided by the infrastructure and cropping techniques. In addition, open-field farmers suffer significant quality loss once every two or three years due to weather and pathogens (driven by weather conditions), which can reduce the price received for their product by 50 percent or more for a large part of their harvest (Cedillo, Lamas).

In 2011, severe cold waves affected northwestern Mexico. High-tech greenhouses were hard hit, and tomato crops suffered extreme losses. Perhaps as much as 30 percent of the winter crop was lost in that region, representing nearly 10 percent of all greenhouse tomato production (SIAP Database, Moreno, I, Cedillo). Producers responded with the increased use of emergency heating, primarily through water-circulated radiated heat in the flooring.

Agro-chemical Inputs

The two principal chemical inputs in agriculture are fertilizers (nutrients) and pesticides. PA systems allow for a much more precise use of both, dramatically increasing the efficiency of chemical use per unit of output.

Fertilizers: In open-field agriculture and very low-tech PA, fertilizers are applied according to a schedule and linked to total land area. Most fertilizer does not reach the target plant, instead going into the soil where it may or may not be absorbed by the plant and may be washed away by water. In high-tech and most medium-tech systems, nutrients are supplied directly to the plant either through water (in solution in hydroponic operations), or in the individual plant's bag or pot. This ensures that a much higher percentage of the fertilizer reaches the plant, decreasing waste, improving productivity, and also decreasing available nitrogen that could convert to greenhouse gases (GHGs). In shade houses, fertilizers are applied directly to the plants, but with greater precision. The principal fertilizers used in tomato production are calcium nitrate, potassium nitrate, magnesium sulfate, and phosphoric acid. The related emissions are discussed in the section below on GHG footprinting.

Pesticides. Tomato, bell pepper, cucumber, and berry crops are affected by dozens (perhaps hundreds) of fungal and bacterial pathogens, as well as insects, most notably whitefly (*Trialeurodes vaporariorum*), particularly in northwestern Mexico. In general, the same pathogens affect the products regardless of production system. Shade houses, medium-tech, and high-tech are all effective at greatly reducing insect presence and damage. However, only sealed high-tech operations and some more sophisticated medium-tech operations that are nearly completely sealed (non-permeable envelope) to the outside environment dramatically reduce the vectors of infections introduced by air, water, or carried in by workers on shoes or clothes. These higher-tech production facilities are isolated from soils, water is controlled (or cleaned if needed, as in the case of re-use), workers follow protocols for shoes and clothing before entering, and the air is separated or the facility positively pressured when opened. In open-field and low-tech PA operations, however, pathogens come in literally on whatever the wind blows in, whatever happens to be in the water, or wherever workers recently walked.

In open-field and low-tech PA, pesticides are usually applied by "rule of thumb" (preventative or routine). Because the higher-tech PA systems are so closely controlled and monitored, the decision to use pesticides, and the selection of type, is more precise and sophisticated. In many cases, outbreaks are anticipated (e.g., based on weather conditions) and non-chemical strategies are employed. For example, if the weather has been very humid or rainy, the most effective action is to generate a greater circulation of air in the space to avoid the proliferation of certain diseases or bacteria. An example of this is the pathogen called *Clavibacter michiganensi,* which aggressively attacks tomato crops and is capable of damaging entire crops in a week. In open-field production, these bacteria are treated with aggressive and dangerous (red band) chemicals across the entire farm. In high-tech PA operations, these bacteria can be managed almost

completely by controlling temperature and humidity through simple ventilation. The strategy employed by the agronomists in these PA operations is: (i) constantly monitor temperature and relative humidity to avoid conditions that enable or promote pathogen growth, (ii) protect against entry of pathogens via air, water, and workers, and (iii) use chemicals (biologicals where possible) early during outbreaks to prevent the spread of infection.

There are some management-related points on pesticide selection that should also be considered. All high-tech PA operations, many of the more sophisticated medium-tech operations, and most of the larger-scale shade house operations, which are generally oriented toward export production, select pesticides to ensure that products can enter the United States. They use only products approved by the EPA (for use on crops) and FDA (for trace amounts on food) and are monitored and audited for compliance, as failure to use approved substances can result in rejection of a company and potentially even the entire growing area's access to the U.S. market. According to several experts consulted, when the product is intended for the Mexican market, farmers and buyers tend to be much less selective on chemical choice, and dangerous red-band chemicals are frequently used. An additional point raised by agronomists consulted and a manufacturer is that PA allows much greater use of low- (or zero) toxicity products. In open-field production, rain washes away the product, rendering it much less effective (or effective over a shorter period). Under PA, biological agents and those based on surface contact remain on the leaves and fruit longer, allowing their protected and corrective action to continue and reducing the need for more dangerous and systemic chemical pesticide products.

Table 5 summarizes data on agrochemical inputs used in the different PA technologies.

TABLE 5: Agrochemical Inputs (tomato as reference)

Variable	BAU (open field)	High-tech (current best practices)	Low-tech	Shade house	Medium-tech
Kg of fertilizer per ton of tomatoes	364.5	121.5	243	300	318.5
Kg of total nitrogen per ton of Tomatoes	31.1	10.4	20.7	24.88	27.2
Active ingredient of pesticide (kg per ton of product)	5.1 kg (24 applications per four-month cycle)	1.7 kg (maximum eight applications per four-month cycle) (approx. 65% improvement over BAU)	Likely to be similar to BAU based on farmer habits	2 kg (10 applications, 1 per month cycle) (approx. 65% improvement over BAU)	Enclosed operations with substrate likely to be similar to high tech. Non-sealed likely to more similar to BAU
Types of chemicals	No selective use. High incidence of red band.	U.S. approved. Green band with occasional yellow band. Potential for biologicals.	No selective use. High incidence of red band.	U.S. approved for export-oriented operations. Green band with occasional yellow band. Some potential for biologicals. For local market, highly variable.	Higher-tech using specifications to access U.S. market. Lower-tech variable.

Sources: Director of a high-tech PA Company, Interview, September 2017; Eugenio Cedillo Portugal, Agricultural Researcher with FIRA, Interviews, September and October 2017; numerous articles on use of restricted pesticides in Mexico, corroborated in multiple interviews (e.g., Pérez-Olvera et al., 2011).

Energy for Operations

In BAU, very little additional energy (beyond sun and human) is used, except for irrigation. The principal products subject to this study use very little equipment in open-field operations. The sensitive nature of the plants, and particularly their fruit, require manual work. There is little to no use of harvesters or tractors. Motorized carts are used to gather harvested product for storage. In open-field operations, where irrigation is employed, water pumping is required and is quite energy intensive in gasoline or diesel to power the pumps. In low-tech PA, farmers may employ more efficient drip irrigation systems that use less water and likely less energy than open-field systems.

In high-tech PA, energy is used for: pumping water from a well or other source, powering generally very energy-efficient drip irrigation, ventilation to maintain temperature and humidity, and heating as needed. Higher-tech operations are connected to the national electric grid, and they use grid electricity, diesel for pumps and backup generators, and natural gas for heating water when needed. Shade houses, medium- and lower-tech operations use energy primarily for pumping water. When using precision irrigation systems, energy consumption in these operations is considerably lower than with BAU (Table 6).

Waste

The main waste produced by greenhouses beside reusable and degradable biomass from expired plants, and the only significant increased environmental impact identified from PA versus BAU, is the plastic sheeting or netting that is used to cover the plants. The quantity and impact are quite significant. The plastic must be changed every three years for most plastics used. Some producers are finding it more cost effective to buy higher-quality films that need to be changed every four to five years. In 2016, SIAP reported that 24,600 hectares operate under plastic cover (low, medium and high tech), in tomato, cucumber, and strawberry alone. Assuming a three-year cycle, this means there were nearly 8,000 hectares of used plastic removed from PA cover in 2017, not including cover that was damaged by severe weather or accidents. Similarly, shade house cover is made of plastic, with a similar expectation of three- to five-year useful life, depending on quality.

According to three experts interviewed, for low-tech and some medium-tech operations, the old plastic covers are frequently re-used as ground cover and particularly as growing containers (plastic buckets) for plants. Larger growers generally discard shade house cover when large holes and tears appear. Smaller-scale farmers then take the material to use in smaller pieces. In spite of the recycling and re-use, field experts confirmed that nearly all low-tech operations and most medium-tech operations outside major production areas are probably not providing adequate disposal of plastics.

The government is clearly aware of the potential impact. It reportedly passed a legal requirement that this plastic must be recovered for re-use or recycling. Implementation is increasing, but still limited. All experts consulted reported that there are now recycling companies in major growing areas (Sinaloa, Jalisco, and Querétaro were specifically named) specializing in this plastic recovery.

TABLE 6: Energy for Operations (kWh per ton of product)

BAU (open field)	High-tech (current best practices)	Low-tech	Shade house	Medium-tech
743[a]	216[b]	600	518–698[b]	385

Source: Author´s calculations from various tables and annexes.

[a] Information generated by the consultant analysis, Annex 4 includes the calculations and assumptions.

[b] Information provided by a PA High Technology company.

[c] Authors' calculation based on expert inputs.

TABLE 7: Waste Streams

Variable	BAU (open-field)	High-tech	Low-tech	Shade houses	Medium-tech
Annual plastic sheeting waste	0.0/ha	0.33 ha/ha	0.33 ha/ha	0.33 ha/ha	0.33 ha/ha
Waste water	Most water lost	Less than 5% lost	Most water lost	Most water lost	ND

Sources: Various sources from operating companies and researchers.

Sources also stated that the companies that sell new plastic sheeting are now increasingly being asked (and complying) with PA companies' request that they take back the old plastic as a condition of sale (reported in Queretaro). These companies are driving the business of the recyclers. For shade houses in Sinaloa, experts consulted believed that there is likely recycling taking place, as the Secretary of Agriculture has set up waste collection centers for pesticide container waste and other wastes, including shading material. Several sources report that plastic recycling is growing very quickly.

While there is no hard data on the amount of plastic recovered, it is unrealistic to assume that more than half is currently recycled or reused. In addition, there are other plastic waste materials, such as pipes, drip belts, and plastic bottles of agrochemical inputs, that can be substantial but are relatively minor compared to the plastic sheeting.

The other waste created by PA is liquid waste. Compared to BAU, the amount of water and chemicals lost to waste is a small fraction. Many high-tech operations are actively recovering residual water and the nutrients it contains. The water is filtered and subjected to ultraviolet light to remove bacteria and re-injected into the process. Wastewater in these operations is now reported as generally limited to water used for cleaning and repairs.

In the case of medium technology, there may be wastewater that passes through some type of filter or decanter, although no information is available to explain more detail. In low technology, the final liquid wastes are discharged directly into the soil. Liquid waste from shade houses is similar to BAU, except for the more efficient use of fertilizers, which would translate into a proportionate reduction in fertilizer runoff. Other production waste from all technologies are organic matter from pruning or plant renovation. These can be included in composting chambers or placed in open fields without further treatment.

Table 7 summarizes findings on waste profiles for the different PA technologies.

Labor

PA can offer substantial labor advantages over BAU, particularly in the higher-tech applications. However, as PA employs greater technology, fewer workers are required per hectare, and the types of workers required are quite different when moving to medium- and high-tech operations. This creates a challenge in the sense that there will be fewer manual labor jobs, usually seasonal jobs for field workers (nearly 100 percent unskilled men). However, the jobs created are much better paid, equally suitable for women in most job descriptions, are permanent and year-round, and are considerably safer.

High tech, most medium-tech, and some shade house operations operate 12 months per year. High-tech and most medium-tech operations require reliable workers who can read and write and can follow technical protocols. These companies must invest substantial resources in training personnel for growing operations, harvesting, maintenance, supervision, quality control, record keeping, and other skilled areas. Consequently, worker turnover is costly, and companies must provide competitive salaries and benefits to retain good workers. In the state of Querétaro, the CEO of a major high-tech PA company stated, "It is

TABLE 8: Labor Variables

Variable	BAU (open-field)	High-tech	Low-tech	Shade house	Medium-tech
Workers per hectare at full operation	21–30	10	21	21	14
Work type	Hard manual, low-skilled field labor	Resembles manufacturing; semi-skilled	Same as BAU	Same as BAU. In year-round production, the labor requires some skill	Resembles manufacturing; some skill
Labor term	Not year-round, not permanent/ Frequently daily or piece rate	Permanent, year-round, usually social benefits included	Same as BAU	Seasonal or year-round.	Frequently year-round and permanent
Safety	Low injury rate due to lack of machinery Extensive exposure to high- risk agro-chemicals	Low injury rate due to lack of machinery Indoor working conditions Limited exposure to relatively low-toxicity chemicals	Low injury rate due to lack of machinery Extensive exposure to high-risk agrochemicals	Low injury rate due to lack of machinery Exposure to chemicals could be high or low depending on market orientation	Low injury rate due to lack of machinery Mostly indoor work Exposure to chemicals could be high or low depending on market orientation
Gender	Nature of work apt primarily for men	Most jobs appropriate for women	Nature of work apt primarily for men	Nature of work apt primarily for men	More work for women than BAU

Sources: Eugenio Cedillo Portugal, Agricultural Researcher with FIRA, Interviews, September and October 2017; various sources, including experts and operating company managers interviewed.

tough and expensive to attract and keep good workers here. We are competing head to head with a growing automotive industry. We can find good workers, but they are indifferent as to whether they are working in our greenhouses or on automobiles, since the work is more or less the same." Women reportedly make up a substantial and growing part of the workforce in high-tech operations in some growing areas.

Table 8 summarizes findings on the labor-related variables for the different PA technologies.

GHG Footprinting

The authors have calculated relevant estimates of GHG emissions and normalized these estimates to kgCO_2e per kg of tomato production. Emissions factors are based on industry standards (see Annex 2), and, where possible, on the actual ground conditions reported in Mexico (most notably for fertilizers).

The footprint has been broken down by infrastructure (embedded footprint) in the construction of the PA structures, and cultivation. For each, the principal GHG sources are addressed. While there are other minor sources of GHG emissions, the categories presented are believed to represent nearly all the relevant emissions sources. Annexes 2 and 3 provide more detail on how these estimations were calculated.

The items described above are fixed or medium-term variables (in the case of plastic). The GHG footprint from agricultural operations is presented below.

The estimated reductions shown above for GHG from fertilizers in high- and medium-tech production and shade houses are likely very

TABLE 8A: Estimated GHG Footprint for PA Infrastructure

	Concrete	Metal	Plastic	kg of CO_2e per ton of tomatoes
Open-field	0.00	0	0	0
High	0.87	10.88	63.78	75.52
Medium	1.73	21.75	127.56	151.04
Shade house (year-round)	2.31	29.00	10.05	41.36
Shade house (seasonal)	4.62	58.00	14.98	77.6
Low	6.93	87.02	30.16	124.11

Source: Authors´ calculations based on emissions factors found in Annex 2, and use factors found in Annex 3.

conservative: real reductions are likely to be considerably more favorable. In open-field and lower-tech production, fertilizer is applied broadly across the farm. This means only a small portion actually reaches the plant, with a far greater amount exposed to soil, water, air, and runoff. All of this makes a much greater percentage of the nitrogen in the fertilizer available to convert to 2+ nitrous oxides (NOx). In higher-tech operations (particularly hydroponic), nearly 100 percent of the fertilizer reaches the plant, either in the initial application or reapplied after capture. Consequently, much less nitrogen is released into the environment to become NOx. In technical terms, the IPCC nitrogen conversion factor discussed in Annex 4 is likely considerably lower in PA operations. However, since there is no available research on conversion factors in PA, the authors used the accepted IPCC number to err strongly on the side of conservatism in these estimates.

The estimations show that medium- and high-technology PA yield considerably lower GHG footprints, even when including plastic. Shade houses also show a clear reduction in year-round production and modest reductions in seasonal production. There are arguments for considering plastic as embedded infrastructure, because it is an integral piece of the physical structure and not directly related to the cultivation of the crop. However, unlike steel and concrete components, plastic requires replacement every three to five years, and is a recurring cost that could reasonably be considered part of operations. Consequently, the authors present different scenarios above for clarity and consideration depending on the methodologies preferred by different investors. As in most aspects of PA, it is the extraordinary efficiency gains that provide the GHG benefits. More efficient use of energy, water, and chemical inputs lead to an advantageous GHG profile versus BAU.

TABLE 8B: Estimated GHG Footprint for Cultivation of Tomato in Mexico

	Irrigation	Fertilizers[a]	kg of CO_2e per ton of tomatoes
Open-field	337.32	0.39	337.71
High	98.06	0.13	98.19
Medium	174.79	0.26	175.05
Shade house (year-round)	235.63	0.31	235.94
Shade house (seasonal)	316.89	0.31	317.20
Low	272.40	0.34	272.74

Source: Authors' calculation based on Table 8a.

[a] Annex 5 provides more information about the factors and calculation of CO_2 emissions for fertilizers.

TABLE 8C: Estimated Total GHG Footprint of Tomato (three scenarios)

	Total (Cultivation plus infrastructure)		Alternative total (Cultivation plus plastic only)		Cultivation only	
	kg of CO_2e per ton of tomatoes	Difference versus BAU	kg of CO_2e per ton of tomatoes	Difference versus BAU	kg of CO_2e per ton of tomatoes	Difference versus BAU
Open-field	337.71		337.71		337.71	
High	173.71	–49%	161.97	–52%	98.19	–71%
Medium	326.09	–3%	302.61	–10%	175.05	–48%
Shade house (year-round)	277.30	–18%	245.99	–27%	235.94	–30%
Shade house (seasonal)	394.80	17%	332.18	–2%	317.20	–6%
Low	396.85	18%	302.90	–10%	272.74	–19%

Source: Authors' elaboration with source data found in Annexes.

Discussion of Findings

There is a strong case to be made for promoting PA as an environmentally and socially preferable alternative to open-field agriculture. In nearly every economic, environmental and social variable, PA technology shows improvements over BAU scenarios.

Productivity. The principal economic driver for agricultural producers of moving from BAU to PA is the increase in on-farm productivity. Increased production efficiency, additional or extended growing seasons, and markedly decreased crop losses lead to higher yield per unit of production. This result appears to be true for all technological levels of PA, regardless of geography. This result is consistent with studies from other countries (see, for example, Abukari and Tok, 2010). Productivity gains increase significantly as the level of technology rises.

Land and soil requirements. BAU requires high-value land and soils to be productive. Increasing levels of protection enable farmers to use less optimal land and soil. Even low-tech production allows for shading to cool temperatures and increased moisture retention. With high-tech methods, production can take place virtually anywhere, as it has no land or soil requirements other than to be on level ground.

Water use. Increased efficiency in water use is a critical priority for the Mexican government due to the moderate to extreme water scarcity in most of the country. Water is the critical limiting factor in increasing agricultural production, particularly in the poorer areas of the country, where agriculture competes directly with human consumption. The efficiency gains in water productivity are a necessary condition both for increasing production and improving the long-term viability of local stocks. PA uses less water and loses much less to evaporation and overwatering. Moreover, investment in increased water efficiency brings ancillary benefits, such as energy efficiency (less water to pump) and permits more sophisticated management of chemical inputs such as fertigation and optimized timing of pesticide application.

One area of potential concern is that in areas where PA is highly concentrated, the cumulative effects of increased production on the watershed could potentially offset the gains achieved in water efficiency. While the Mexican government's water-permitting process is quite rigorous,

the potential cumulative effects should be considered and assessed in areas of very high concentration of production.

Vulnerability. This variable is the most compelling. The reduction in catastrophic crop losses from the use of PA strategies in Mexico is stunning, even for the most rudimentary technologies. All technological levels of PA appear to significantly reduce vulnerability to damage from climatic and biological sources. The physical barriers used in PA protect crops and soils from hard rain, help retain moisture, and provide protection against pathogens. PA technologies reduce crop losses in the short term and help to increase longer-term viability of the farm. While the advantages are significant for all technologies, higher-tech approaches control more production variables, isolating the production operations to a greater degree from the sources of potential harm.

To the extent that PA technologies improve water efficiency per unit of output, this contributes positively to reducing vulnerability. PA technology is not better than BAU when BAU is entirely rain-fed. However, for tomato and other primary PA crops and most growing regions in Mexico, rainfed production is usually viable for limited parts of the year. Crops grown most of the year or year-round require irrigation from surface water or wells. PA approaches that use precision methods (drip, aspersion, fertigation) can safely be assumed to be better than any traditional irrigation.

Chemical inputs (fertilizers and pesticides)

- ***Fertilizers***. The ability to apply fertilization in a more precise and controlled manner is one of the key drivers of farmer income in moving to PA. Less fertilizer is lost to rain or erosion, and the same quantity of fertilizer benefits more produce due to the increased concentration of produce in the growing system and lower crop loss. The benefit is observed at all technological levels but increases substantially with higher technology. In high-tech and hydroponic systems, virtually all fertilizer reaches the plant, either initially or when it is recovered and recycled. The more fertilizer that reaches and enters the plant, the less it contributes to eutrophication, soil degradation, and off-gassing (in the case of nitrogen in fertilizers, off-gassing creates a GHG). In technical agronomic terms, quantity and type of fertilizer is a farm management variable. In theory, a farmer could apply more fertilizer than is needed, reducing or negating benefits. However, in reality, this is extremely unlikely because one of the critical benefits justifying the investment in PA is more efficient fertilization. Producers would have to act directly counter to all available technical guidance and their own financial interests on one of the single largest cost items in their farm´s operating budget.

  One issue that emerged in the review process warrants further investigation that is beyond the scope of this paper. In shade house and medium-tech production where natural soils are the growing medium, the use of fertilizers per hectare increases dramatically, even though the use per ton of output decreases significantly. It is theoretically possible that leakage (fertilizer that reaches something other than the target plant-growing environment) could present an increase in per hectare terms with possible adverse local implications, such as impact on local water sources in areas with a large concentration of this production.
- ***Pesticides***. The two most important dimensions for pesticides are selection and use. In lower- to medium-tech PA, pesticide use presents similar conditions and drivers to those for fertilizers. There are important efficiencies in their application that can lead to significantly lower use per unit of produce. With greater control over growing conditions found in high-tech (and some of the more sophisticated medium-tech) production, there are additional gains. The non-permeable barriers and ventilation systems of high-tech, by design, make it much more difficult for pathogens to reach or establish themselves on plants. This enables less pesticide to be used and much less harmful pesticides to be

Higher-tech Shade House Production (photo courtesy hortalizas.com).

employed more effectively (including biological control). Since pesticides are expensive inputs (the product itself as well as the costs related to worker protection, storage, and disposal), producers have compelling incentives to reduce their application. The selection of chemicals presents challenges. The most toxic substances, referred to as "red band" in World Health Organization (WHO) nomenclature, are highly effective, usually inexpensive, and widely available. Despite efforts to ban and phase out these chemicals worldwide, many are still available and used more widely than their legal registration indicates. These red-band substances are not used in the export sector in Mexico because buyers in the United States, the principal importers of Mexican produce, do not accept them. The United States requires that imported products meet U.S. standards on pesticide use and trace presence. U.S. buyers insist on, and even audit to ensure, that only products registered in the United States are applied to crops in order to avoid produce being rejected at the border or by customers. It is therefore safe to assume that exporters are using substances that meet international requirements. The concern when considering Mexico is that environmental performance in pesticides may not improve (though likely would not weaken) as a result of a transition to PA if the producers do not make decisions to use less harmful chemicals, either of their own volition or in response to more demanding requirements from domestic[9] or foreign buyers.

Energy use. Energy use is the most problematic variable for this analysis. Agriculture is a relatively low-intensity user of additional energy (beyond sunlight and the potential energy stored in fertilizers). The most rudimentary agricultural technology uses virtually no additional energy other than

9 Several of those interviewed commented on recent new requirements on chemical use by some domestic buyers.

manual labor and draft animals. With increased technology, water pumps and machines such as tractors are also used. In the extreme case (PA in northern Europe), energy intensity is extremely high, as external energy sources are used to create the required growing conditions for the crops. For this analysis, the authors received detailed input on actual, observed energy consumption from producers and researchers in the PA field in Mexico. For PA, energy is used primarily for ventilation (in high-tech and higher end of medium tech), water movement, and heating for protection against cold snaps. The BAU scenario assumes that a producer is pumping water with conventional pumping equipment to obtain additional production in non-rainy seasons. The authors believe this comparison to be valid, as what is being compared against PA are marginal additional production units. In this case, for BAU, this is output from intensification of the existing farm by extending production into non-rainy seasons. A standard pump size and run time observed in semi-arid growing conditions in Costa Rica was used as the reference.

This analysis is highly sensitive to the assumptions for BAU. For example, a hypothetical growing region that had year-round optimal rainfall and growing temperatures would likely not show much (if any) improvement in its energy profile per unit of output. There are, however, a few growing regions with these characteristics, and one of the national goals is to expand agricultural production in more challenging zones.

Waste. PA is more material-intensive than open-field agriculture. Infrastructure (ranging from wood poles and simple plastic covering in low tech, to steel and concrete with glass/plastic covering in high-tech) is introduced into the system to control growing conditions. Organic waste from the plants is similar. Liquid discharge (i.e., water containing soil or chemicals) is significantly reduced in high- tech PA, although lower- and medium-tech approaches should be investigated to validate improvement. The principal waste stream of concern in PA is the use of plastic covering. Whether permeable mesh found in low-tech, shade houses, and some medium tech, or non-permeable sheeting and ground covering, PA produces substantial plastic waste. The waste footprint is substantial. All sources consulted with knowledge of the local situation stated that the pristine plastic used in the shade houses and higher-tech operations, after it finishes its useful life, is repurposed for other uses or on other farms. In addition, several experts interviewed reported increased recycling rates, particularly in areas with high concentrations of growers. Ensuring a reasonable and rational post-PA use for the plastic coverings is an important element of waste management.

Labor. Rising technology levels lead to improved working conditions. There are multiple dimensions to these effects. First, higher levels of PA technologies are more likely to provide year-round employment. Second, higher technologies levels are associated with less intensive use of agrochemicals and the use of less harmful substances. As higher-tech export-oriented operations are more regularly audited, it is reasonable to assume that safety protocols are more likely to be followed. Higher levels of technology require higher skill levels, which pay substantially higher wages than lower tech or BAU options. And finally, the higher tech PA technologies create more opportunities for women's employment as jobs require skills where women are equally or better qualified, rather than BAU, where physical strength and endurance are the principal basis for employment.

GHG footprint. This parameter is the most complex to interpret. GHG footprint is significantly determined by two variables: emissions associated with the embedded footprint of the PA infrastructure (concrete, plastic, metal, rubber) and the productivity levels of the production system. Higher levels of technology require more infrastructure, with its associated footprint. However, the productivity gains from this higher technology, on balance, more than compensate for the increased infrastructure footprint. There is an inherent policy decision in emissions accounting regarding the extent to which the embedded emissions in the production infrastructure should

be included or excluded and, if embedded emissions are included, the time period over which the embedded emissions should be amortized.

Table 8c summarizes the comparison of different levels of PA, with different infrastructure inclusion assumptions. All the infrastructure assumptions are quite conservative in that the concrete, steel, and rubber infrastructure is assumed to survive a considerably shorter time than is observed in practice. In addition, as noted previously, NOx emissions from fertilizers are likely overstated for all PA scenarios. The useful life assumptions for plastic sheeting are moderately conservative, as they assume the minimum range provided by the manufacturers and producers. Further, no allowance is made for recycling or re-use of any of the materials.

Productivity of the production system is determined by the technological level (higher versus lower technology) and the seasonality of production. GHG benefits are lower when production is seasonal, meaning that the total annual productivity of the production system is lower.

The other key variable to consider is the BAU baseline, which assumes substantial water pumping. This variable substantially determines the GHG benefits, particularly for shade houses. As discussed previously, the relevant comparison for PA GHG footprint is increased BAU production. As the marginal agricultural frontier in Mexico has severe water constraints, substantial water movement (via pumping directly by the farmer or local authorities) is the most realistic scenario, and therefore the relevant comparison.

Considering all these points, the only scenarios that do not lead to decreased GHG footprint are low-tech production and seasonal shade houses when all embedded infrastructure admissions are included. All other scenarios appear to range from roughly neutral to highly beneficial. Greater GHG benefits occur with higher productivity, whether through higher levels of technology, a longer growing season, or some combination of the two (with the highest benefits deriving from year-round high-tech production).

Conclusions

There is a strong case to be made for promoting PA as an environmentally and socially preferable alternative to open-field agriculture for a significant number of cash crops in Mexico. In nearly every environmental and social variable, PA technology shows a large positive improvement over BAU scenarios. Only increased solid waste (plastic) shows lower performance, and productivity gains compensate for the increased GHG footprint in nearly all systems, and considerably so in higher-tech technologies. Further, there are policy efforts as well as significant commercial incentives to improve plastic recovery and reuse.

The observed and expected improvements in productivity, water efficiency, vulnerability reduction, chemical use, and working conditions are compelling in all scenarios with all technologies. The GHG benefits are strongly favorable with higher technologies, and neutral to positive in nearly all other scenarios.

The opportunities for ongoing improvements in technology are encouraging. Protected agriculture, even in its high-tech form, offers additional potential for large improvements in productivity and energy use, particularly in pesticide selection and strategy. In comparison, BAU is largely a technological dead end, with only marginal improvements considered possible.

The confidence for making the case is high. While there is little published peer-reviewed literature on the environmental impacts of PA systems, and none specific to Mexico or comparing PA and BAU, there is a wealth of experience and gray literature that are all consistent and data-driven. It is also important to note that all peer-reviewed literature consulted in the specific areas of interest is consistent with the expert opinion and gray literature. The authors did not find any literature contradicting the direction or strength of impact for any of the variables.

The environmental and social benefits of PA versus BAU are directly and highly correlated with technological variables/choices and discrete management decisions. This should allow for the setting of standards based on observable criteria. For example, type of infrastructure and technology employed appear to be satisfactory as conditions that determine reduced impact. This would provide for simple investment guidelines/criteria and would require only simple verification.

Recommendations for Investment Criteria

The case for PA is compelling in virtually every variable, for several technological platforms. Overall the data present a strong case for PA being considered as a sustainability oriented investment.

The strength of the arguments for PA as a favorable sustainability strategy in Mexico is overwhelming. All technologies considered are transformative for agricultural producers, vulnerability reduction, workers, and water resources. From a policy perspective, the government of Mexico should consider the rapid and large-scale expansion of PA under its existing policy mandates for agriculture, water resources, and climate change mitigation and adaptation. The broader social benefits (beyond those to private actors) are found to be significant enough to warrant policy interventions, including subsidies and other mechanisms to promote the broader adoption of PA.

With respect to climate finance, PA technologies appear to meet all conceptual criteria considered "transformative" technology by the Climate Bonds Initiative (CBI).[10] First, PA provides dramatic and compelling advantages in vulnerability reduction in all technologies and scenarios. Second, in most scenarios, the GHG footprint is reduced compared to BAU, even considering embedded emissions. Third, PA has been established as an explicit strategy priority for Mexico for GHG and vulnerability reduction. Fourth, PA strategies are consistent with FAO policy guidance on Sustainable Intensification as an approach to ensure food security within climate constraints.

While the relative difference between high-tech and other technologies versus BAU is substantial, all technologies considered could easily be considered transformative. There is compelling evidence that much medium-tech production also meets CBI criteria, as does production in the larger and more sophisticated shade house systems, most notably when they are engaged in production throughout most of the year. Substantially greater productivity and more efficient fertilizer and water use lead to a considerably lower GHG footprint. These technologies reduce vulnerability considerably, similar to the high-tech operations.

[10] CBI is a leader in the certification of financial instruments based on climate change impact, including GHG footprint reduction and vulnerability reduction.

Open-field Agriculture.

The challenge for financial institutions financing PA is how to provide reasonable certainty, during the evaluation and approval processes that the PA project to be financed is likely to actually produce the expected benefits over an extended period. Several characteristics of PA are highly favorable for this purpose.

First, it is largely the investment itself in PA infrastructure (the objective of the financing and the use of the capital) that determines the improvement over BAU scenarios. Consequently, the project's purpose and objectives—higher productivity, better market access, and greater water and other input efficiency—are perfectly aligned with the goals of financial institutions (likelihood of repayment of the loan and interest), and the potential environmental and social goals of the financial institution and its capital partners (lower GHG, reduced vulnerability, and improvements in multiple other variables). In practical terms, this means that an investment in PA with an agreed upon set of infrastructure characteristics, as long as it continues to operate with that infrastructure, can very reasonably be assumed to be achieving the desired agronomic goals, financial return targets, and environmental and social performance levels.

Second, there is no incentive for the owner to cease using the infrastructure. For example, there is no advantage to changing back to BAU once the investment is made. The infrastructure has no real salvage value outside of PA, and the investment in time, energy, and commercial relationships would be pointlessly lost. This is in contrast to many other environmental investments, such as wastewater treatment plants, where an owner could theoretically reduce operating costs by ceasing to operate.

Third, there is relatively little that operational changes (intentional, oversights, or errors) could do to change or diminish the expected positive differences versus BAU. For example, changing plastic cover more frequently (which would increase GHG from plastic waste) is costly, and

all major PA companies are constantly seeking ways to extend the life of plastic. Similarly, producers are continually seeking water and fertilizer efficiencies, which are achieved precisely because of the use of the infrastructure. The possible areas of counterproductive incentives are pesticide selection, working conditions, and post-use management of plastic waste. These could be addressed in covenants, complementary agreements, or other commitments between the financial institutions and the project promoters.

The authors conclude that it should be reasonable to assume that if the loan is performing in financial terms as approved with appropriate conditions, it can reasonably be assumed to be performing in agronomic as well as environmental and social terms. Annual visits should be sufficient to verify that operations are being carried out in accordance with the investment in the infrastructure.

From the standpoint of the Mexican government, any investment in any type of PA can be expected to yield significant nationally defined high-priority environmental and social benefits and should be promoted as a sustainable investment. However, from FIRA's perspective, with its goal of supporting ongoing lending, primarily through financial intermediaries throughout the country, financial viability criteria are a critical consideration. As such, FIRA should focus its investment criteria on PA that has demonstrated financial viability. These include shade house operations of moderate to large scale, and medium- and high-tech operations of virtually any scale. If the financing deal is viable, there is near certainty of achieving multiple benefits without any significant risk of harm. Plastic waste management is a variable to consider for all production systems. Pesticide use and selection is also a variable to consider when the operation is for domestic production. These points could be addressed with lending covenants.

Beyond its own lending criteria aligned with Mexican government goals and priorities, FIRA wishes that most (if not all) its lending portfolio conform to CBI criteria, which have not yet been established for agriculture of any type. CBI is currently considering criteria for a Mexico-specific PA standard based on its established frameworks. The authors recommend the following investment criteria to align the broad benefits of PA for Mexico with the more specific climate-change criteria required for CBI. The following infrastructure requirements would provide a high degree of certainty of the climate change benefits sought by CBI in its certification programs, while also providing broader

Recommended Infrastructure Requirements to Align CBI, FIRA, and Government of Mexico Priorities

Requirement	Comment
1. Operations that are completely enclosed (full roof and walls) with permeable or non-permeable air envelope.	Provides significant control over growing conditions, allowing for greater productivity, controlled water and chemical use and protection against erosion and soil degradation.
2. Operations must be designed and operated for year-round (or substantially year-round, multi-cycle) production.	Provides the necessary productivity to ensure GHG footprint benefits.
3. When water sources other than direct rain-fed are used, water must be supplied by precision irrigation methods (drip, micro-aspersion, or fertigation) with monitoring.	Achieves the primary vulnerability reduction goal of the Mexican government, and minimizes energy use for water movement.
4. Heating only for defense against cold in winter months. Heating may not be used to provide growing conditions.	Ensures reduced GHG footprint.
5. Passive cooling only, active ventilation is permitted only for managing heat and relative humidity.	While extremely unlikely that operations will use refrigerants due to cost considerations, this point covers the issue to avoid any possible GHG footprint from either increased energy use or refrigerants.

Requirement	Comment
1. Sealed operations with non-permeable soil cover and integral (non-permeable) air envelope	Provide maximum control over growing conditions, with greatly reduced pathogens, chemical use, and water use and improved working conditions, productivity, and GHG footprint
2. Production in substrates	Permits production in areas where soil conditions do not permit production, increased productivity, reduces water and chemical use.
3. Water recovery and reuse systems	Increase water efficiency, decrease chemical use, and GHG emissions from fertilizers

Lending condition requirement	Comment
1. PA operator shall have a written policy promoting (and measuring advances) for re-using, re-cycling, and proper disposal of plastic waste.	Improved management of plastic waste is a national goal. This covenant commits PA operator to consider this point explicitly in planning and have measurable data to assess.
2. PA operator shall not use active ingredients that are listed in Classification Ia or Ib in the WHO recommended Classification of Pesticides by Hazard (the red band)	Promotes the use of safer chemicals for worker safety and environmental protection. This is consistent with existing Mexican legal requirements and would encourage greater compliance.

benefits to Mexico and a significant lending base for FIRA to achieve scale and impact.

These points are easily verified prior to a lending operation in the technical review and due diligence phases with a minimum of technical ability. They can be stipulated and documented in the lending contract and easily verified post-construction and in periodic reviews.

Recommended Preferred Practices for Higher Levels of Transformative Impact

As discussed above, one of the most interesting and promising aspects of PA is the opportunity to improve and upgrade production technologies. Higher technology is associated with benefits across all environmental and social variables examined. FIRA should consider mechanisms to promote investment in higher levels of technology, including recognition within its lending criteria. The following infrastructure requirements are considered state-of-the-art and provide even greater transformative benefits.

For all PA financing, lending institutions should include conditions or covenants in their lending agreements to promote greater alignment with national goals and provide assurances to stakeholders that these goals are being pursued.

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ANNEX 1

Emissions Factors Used for GHG Calculations

Variable	Value	Unit	Notes
Concrete	0.15	kg CO_2/Kg of Concrete	Industry standard[a]
Galvanized steel	2.90	tons CO_2/ton of Iron	Assumed US profile[a]
Polyethylene (PE)	2.40	kg CO_2/kg of PE	Industry standard
Chemical fertilizers	1.25	kg CO_2/kg of N Fertilizer	IPCC Fertilizer guidelines for Nitrogen[b]
Diesel	2.60	kg CO_2/liter	Standard based on formulation in Mexico[c]
LPG	1.58	kg CO_2/liter GLP	Standard based on formulation in Mexico[c]
Electricity	0.45	tons CO_2/MWh	Standard based on formulation for Mexican grid[d]

Sources:
[a] City of Winnipeg (2012);
[b] IPCC (1997); Mosier et al. (1998); Smith, Bouwman, and Braatz in IPCC (1999);
[c] INECC (2014);
[d] SERMANAT (2015); Global CCS Institute (2013).

ANNEX 2

GHG Calculations for PA Infrastructure

The life expectancy of the concrete and steel is assumed to be 20 years, the plastic 3 years.

Principal Materials for Structure and System Included in the Inventory

Materials	Components	Quantity/ha	Quantity/ton tomato	Unit
Structure				
Concrete	Cement, sand, and gravel	42.00	0.05	m^3
Ground cover	Ground cover	10,000.00	12.50	m^2
Screen	Anti-aphid screening	4,450.00	5.56	m^2
Plastic sheeting	700 cal plastic sheeting	13,500.00	16.88	m^2
Steel	Pillars, reinforcements, gutters, shafts, profiles, arches, ventilation, plant supports	60,000.00	75.00	Kg
Motors and electrification	Operation of windows	20.00	0.03	Units
Supporting equipment				
Bags	Substrate bags	28,000.00	35.00	kg
Substrate	Perlite complex	28,000.00	35.00	Liter
Irrigation component	Microtube	30,000.00	37.50	Each
Irrigation component	Brace	30,000.00	37.50	Each
Irrigation component	Drip/sprayer	30,000.00	37.50	Each
Irrigation component	Distributor	15,000.00	18.75	Each

(*continued on next page*)

(*continued*)

Principal Materials for Structure and System Included in the Inventory

Materials	Components	Quantity/ha	Quantity/ton tomato	Unit
Irrigation component	Controller systems (pumps, valves, controls) 28,000.00 35.00 Sistema			
Irrigation component	PVC tubing	300.00	0.38	m/l

Sources: The original format table was taken from IRTA, Producción Vegetal1 and adapted for this research by Mario Alvarado Chávez, President of the Asociación Mexicana de Constructores de Invernaderos, February 2018; Torrellas (2011).

Weight of the materials (kg)										
Structure	High-tech		Medium-tech		Low-tech		Shade house (seasonal)		Shade house (year-round)	
Concrete	92,400.00	43%	92,400.00	43%	92,400.00	59%	92,400.00	60%	92,400.00	59%
Ground cover	4,000.00	2%	4,000.00	2%	0.0%	0%	0.0%			
Screen	311.50	0%	311.50	0%	311.50	0.2%	311.50	0%	311.50	0.2%
Plastic sheeting	2,497.50	1%	2,497.50	1%	2,497.50	1.6%	2,497.50	2%	2,497.50	1.6%
Steel	60,000.00	28%	60,000.00	28%	60,000.00	38%	60,000.00	39%	60,000.00	38%
Motors and electrification	400.00	0%								
Supporting equipment	—		—		—		—		—	
	—		—		—		—		—	
Bags	28,000.00	13%	28,000.00	13%		0%		0%		0%
Substrate	—		—		—		—		—	
Irrigation component	150.00	0%	150.00	0%	150.00	0%	0.00	0%	150.00	0%
Irrigation component	300.00	0%	300.00	0%	300.00	0%	0.00	0%	300.00	0%
Irrigation component	300.00	0%	300.00	0%	300.00	0%	0.00	0%	300.00	0%
Irrigation component	150.00	0%	150.00	0%	150.00	0%	0.00	0%	150.00	0%
Irrigation component	28,000.00	13%	28,000.00	13%		0%		0%		0%
Irrigation component	60.00	0%	60.00	0%	60.00	0%	0.00	0%	60.00	0%
	216,569.00	100.0%	216,169.00	100%	156,169.00	100%	155,209.01	100%	156,169.00	100%

Source: Authors´ elaboration based on previous table (Chaves, IRTA).
Note: The table above shows the mass (kg) present in each technology category per hectare and the percentage composition of the total mass of infrastructure.

Variable	BAU (open field)	High-tech		Low-tech		Shade house		Medium-tech	
Infrastructure intensity (approx. weight per m^2 of construction)		21.66 kg/m^2		15.62 kg/m^2		15.62 kg/m^2		21.62 kg/m^2	
Materials Mix		Plastic Metal Concrete	29.45% 27.70% 42.67%	Plastic Metal Concrete	2.41% 38.42% 59.17%	Plastic Metal Concrete	2.41% 38.42% 59.17%	Plasticos Metal Concrete	29.50% 27.76% 42.74%
Mass per component (kg/m^2)		Plastics Metal Concrete	6.38 6.0 9.24	Plastics Metal Concrete	0.38 6.0 9.24	Plastics Metal Concrete	0.38 6.0 9.24	Plastics Metal Concrete	6.38 6.0 9.24
Emissions factors (kg CO_2/kg Material)		Plastic Metal Concrete	2.4 2.9 0.15	Plastic Metal Concrete	2.4 2.9 0.15	Plastic Metal Concrete	2.4 2.9 0.15	Plastic Metal Concrete	2.4 2.9 0.15

Source: Authors´ calculations.
Note: This table categorizes the types of materials in order to convert to GHG footprint using the factors presented in Annex 2.

Tons of CO_2/ha		Concrete	Metal	Plastic	Total tons of CO_2/Ha
BAU	Open Field	0	0	0	0
Technology	High	13.86	174.02	153.07	340.95
	Medium	13.86	174.02	153.07	340.95
	Shade house (year-round)	13.86	174.00	9.05	196.91
	Shade house (seasonal)	13.86	174.00	6.74	194.60
	Low	13.86	174.03	9.05	196.94

Source: Authors´ calculations.
Note: This table presents the tons of CO_2 embedded emissions per hectare of tomato. It assumes the total of CO_2 emissions during the life expectancy of each material (concrete and steel is assumed to be 20 years, plastic 3 years).

kg of CO_2/ton of tomato		Concrete	Metal	Plastic
BAU	Open field	0	0	0
Technology	High	0.87	10.88	63.78
	Medium	1.73	21.75	127.56
	Shade house (year-round)	2.31	29.00	10.05
	Shade house (seasonal)	4.62	58.00	14.98
	Low	6.93	87.02	30.16

Source: Authors´ calculations.
Note: This table summarizes the results of the analysis of CO_2 emissions during the life expectancy of the infrastructure with respect to annual production (tons of tomato/ ha) by technology.

Annual Yield of Production

PA Technology		Tons of tomato /ha
BAU	Open Field	22
Technology	High	800
	Medium	400
	Shade house (year-round)	300
	Shade house (seasonal)	150
	Low	100

Source: Authors´ calculations.
Note: This table presents yields of tomato production assumed for each technology for the results of the preceding table.

ANNEX 3

Emissions from Irrigation

The amount of GHG emissions from irrigation is determined by the amount of energy used for pumps and the general equipment that needs to be supplied with power depending on the PA technology used. In these case analyses, there are two scenarios:

a. Open-field irrigation. In this context of agriculture, the authors assumed the use of a pump of 5 HP (3.73 kW) power capacity that works 12 hours per day during the year. It is not suited to a specific condition or cycle; it is for general purposes.

The following table summarizes the scenario.

Pump	
5	HP
3.73	Kw
Energy (kWh)	
12	Hours per day
16337	kWh/year
Annual Tomato Production	
22	ton/ha
Energy – Production	
742.6	kwh/ton

Source: Authors´ calculations based on manufacturer information on pump, and assumed pumping needs in open-field, semi-arid climate.

b. High-tech irrigation. For the analysis of this scenario, a PA high-technology company provided the following information.

Tomato Production(Kg/m^2)	63
Total Production (ton)	12600
Total surface (m^2)	200000
Diesel consumption per ton (liters of diesel)	0.314
Consumption per ton (kWh)	212
Total Energy (kWh /Ton of tomato)	216

Source: Authors´ calculations based on pump specifications and Conversion factor: 1 liter of diesel = 11 kWh.

In both cases, the data on water per ton of tomato are used in a simple extrapolation method. The energy consumption is then estimated for PA medium, low-tech, and shade house.

Technology	kwh/Ton of tomato
Open-field	742.6
High	215.68
Medium	385.38
Shade house (year-round)	519.33
Shade house (seasonal)	697.95
Low	599.71

Source: Authors´ calculations.

CO_2 Emissions

The CO_2 factor devised by Mexico's Department of the Environment and Natural Resources (Secretaría de Medio Ambiente y Recursos Naturales de México, or SERMANAT) is used to calculate CO_2 emissions.

CO_2 factor: 0.45 tons of CO_2/MWh

This factor is related to Mexico's electrical grid, which uses 25 percent renewable energy and 75 percent fossil fuels generation. Access to the electrical grid in Mexico is about 99 percent, according to the World Bank and Mexico's Federal Electricity Commission.

GHG Irrigation		kg of CO_2/Ton of tomato
BAU	Open-field	337.32
Technology	High	98.06
	Medium	174.79
	Shade house (year-round)	235.63
	Shade house (seasonal)	316.89
	Low	272.40

Source: Authors´ calculations.

ANNEX 4

Emissions Factors Used for Fertilizers

The principal GHG concern from fertilizers relates to the creation of nitrous oxides (NOx) when nitrogen in fertilizer is made available to air through soil and water to combine with oxygen atoms. The actual emissions factor—that is, how much each gram of nitrogen leads to how much NOx—depends on many variables, including temperature, soil, crop and other variables and is a topic of ongoing scientific study. The authors have adopted the default emission factor suggested by IPCC of 1.25 percent of applied organic or synthetic N by mass. (See IPCC, 1997; Mosier et al., 1998; Smith, Bouwman and Braatz, n.d.).

To calculate the potential fertilizer impact, the authors calculated the total mass of nitrogen in the various fertilizers reported as being used for tomato in Mexico to derive a nitrogen factor. The various technical experts reported that the same fertilizers are generally used in open-field and PA operations, and that while the timing and ratios may vary in practice, the differences were minimal. Based on the technical specification sheets shared by a high-tech PA grower, the consultants calculated that 8.53 percent of all fertilizer mass applied per ton of tomatoes is elemental nitrogen. (Note: blank components are confidential items that have no nitrogen content).

The table below presents the structure of calculations to arrive at a normalized kg of CO_2 per ton of tomatoes, based on reported fertilizer usage and productivity levels of the different technologies discussed previously.

Fertilizer component	g or ml per ton of tomatoes	% total	Nitrogen % of the molecule	Nitrogen added (g or ml)
Calcium nitrate	45,896.13	37.66	17.1	7,835.73
Potassium nitrate	15,470.49	12.70	13.9	2,143.33
Calcium chloride	4,525.67	3.71	0	0.00
Potassium chloride	4,073.19	3.34	0	0.00
Magnesium sulfate	20,366.26	16.71	0	0.00
Potassium sulfate	9,474.86	7.78	0	0.00
Urea	4.57	0.0037	31.8	1.45
Iron chelate	665.18	0.55	1.4	9.58
Monopotassium phosphate	4,256.00	3.49	0	0.00
Micronutrient chelate	850.95	0.70	0	0.00
Ammonium molybdate	7.49	0.01	7.2	0.54
Copper sulfate	10.10	0.01	0	0.00
Magnesium sulfate	68.68	0.06	0	0.00
Zinc sulfate	61.61	0.05	0	0.00
Boramine	19.75	0.02	4	0.86
Micronutrient complex	25.21	0.02	0	0.00
Humic/fluvic acid compound	21.94	0.02	0	0.00
Calcium chelate	14.19	0.01	0	0.00
Boric acid	252.83	0.21	0	0.00
Green phosphoric acid	11,318.95	9.29	0	0.00
Nitric acid	1,786.52	1.47	22.2	397.13
Sulfuric acid	2,690.12	2.21	0	0.00
Total	121,861	100	8.52	10,389

	Open-field	High-tech	Medium-tech	Low-tech	Shade house (seasonal)	Shade house (year-round)
Reported bags de fertilizer	7.29	2.43	4.86	6.37	6	6
kg per bag	50	50	50	50	50	50
Ton of tomatoes/ ha per year	40	800	400	100	150	300
kg of fertilizer per ton of tomatoes	364.5	121.5	243	318.5	300.7	300.7
kg of nitrogen per ton of tomatoes (8.53% N/total conversion)	31.1	10.4	20.7	27.2	24.9	24.9
Emission Factor CO_2	1.25%	1.25%	1.25%	1.25%	1.25%	1.25%
kg of CO_2 per ton of Tomatoes	0.388	0.129	0.259	0.339	0.31	0.31

Source: Authors´ calculations.

ANNEX 5

Total GHG Summary

Yield of production tons/ha per year	kg of CO_2 per ton of tomato		Infrastructure			Cultivation		
			Concrete	Metal	Plastic	Irrigation	Fertilizers	Total kg of CO_2 per ton of tomato
22	BAU	Open-field	0	0	0	337.32	0.39	337.71
800	Technology	High	0.87	10.88	63.78	98.06	0.13	173.71
400		Medium	1.73	21.75	127.56	174.79	0.26	326.09
300		Shade house (year-round)	2.31	29.00	10.05	235.63	0.31	277.30
150		Shade house (seasonal)	4.62	58.00	14.98	316.89	0.31	394.80
100		Low	6.93	87.02	30.16	272.40	0.34	396.85
	Material life expectancy (years)		20	20	3			

Source: Authors' calculations.